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Climate of the Past Discussions

Multivariate statistic and time series analyses of grain-size data in Quaternary sediments of Lake El'gygytgyn, NE Russia

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Abstract

Lake El'gygytgyn, located in the Far East Russian Arctic, was formed by a meteorite impact about 3.58 Ma ago. In 2009, the ICDP Lake El'gygytgyn Drilling Project obtained a continuous sediment sequence of the lacustrine deposits and the upper part of the impact breccia. Here, we present grain-size data of the past 2.6 Ma. General downcore grain-size variations yield coarser sediments during warm periods and finer ones during cold periods. According to Principal Component Analyses (PCA), the climate-dependent variations in grain-size distributions mainly occur in the coarse silt and very fine silt fraction. During interglacial periods, accumulation of coarser grain sizes in the lake center is supposed to be caused by redistribution of clastic material by a wind-induced current pattern during the ice-free period. Sediment supply to the lake is triggered by the thickness of the active layer in the catchment, and the availability of water as transport medium. During glacial periods, sedimentation at Lake El'gygytgyn is hampered by the occurrence of a perennial ice-cover with sedimentation being restricted to seasonal moats and vertical conducts through the ice. Thus, the summer temperature predominantly triggers transport of coarse material into the lake center. Time series analysis that was carried out to gain insight in the frequency of the grain-size data showed grain-size variations predominately on Milankovitch's eccentricity, obliquity and precession bands. Variations in the relative power of these three oscillation bands during the Quaternary imply that climate conditions at Lake El'gygytgyn are mainly triggered by global glacial/interglacial variations (eccentricity, obliquity) and local insolation forcing (precession), respectively.

1 Introduction

The Polar Regions are known to play a crucial but not yet well understood role within the global climate system (Washington and Meehl, 1996; Johannessen et al., 2004), influencing both the oceanic and the atmospheric circulation. The recent global warming trend has been, and is predicted to be, most pronounced in the Arctic (ACIA, 2004; Serreze and Francis, 2006). However, rather little is known about the natural and environmental variability on geological timescales. Our current knowledge on the Cenozoic climate evolution of the Arctic for long was based on sparse, often discontinuous marine and terrestrial paleorecords of the Arctic Ocean and adjacent landmasses (Thiede et al., 1998; Backman et al., 2005; Moran et al., 2006; Axford et al., 2009; Pienitz et al., 2009; Zech et al., 2011).

The first continuous Pliocene/Pleistocene sediment record in the terrestrial Artic was recovered in 2009 during a deep drilling campaign of the International Continental Scientific Drilling Program (ICDP) at Lake El'gygytgyn in the Far East Russian Artic (Fig. 1; Melles et al., 2011). Pilot studies on Lake El'gygytgyn sediments covering the last 2–3 glacial/interglacial cycles had already demonstrated the usability of this archive for paleoclimate reconstructions (e.g. Brigham-Grette et al., 2007; Melles et al., 2007; Niessen et al., 2007). Initial results from the upper part of the 318 m long sediment record in central parts of the lake (ICDP site 5011-1) provided first details of Quaternary history, focusing on interglacial variability during the past 2.8 Myr (Melles et al., 2012).

Here, we present new results of granulometric analyses on ICDP core 5011-1 throughout the past 2.6 Myr, which were analyzed by a Principal Component Analyses (PCA) to detect dominate variations in the grain-size distributions. Building on recent studies on the modern climatological, hydrological, and sedimentological settings (Fedorov et al., 2012; Nolan et al., 2012; Wennrich et al., 2012), the data is used to reconstruct dependencies of the grain-size distribution in the center of Lake El'gygytgyn to climate variability over time. Time-series analyses of the granulometric data furthermore yield information about the influence of orbital vs. global ice-volume forcing on the sedimentation in Lake El'gygytgyn.

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2 Site information

Lake El'gygytgyn is located in the Far East Russian Arctic, in the central part of the Chukchi Peninsula (67° 30′ N, 172° 05′ E, 492 m a.s.l.; Fig. 1). It is formed within a meteorite impact crater (e.g. Dietz and McHone, 1977; Gurov et al., 1979) dated to about 3.58 Ma (Layer, 2000). The lake has a nearly circular shape with a diameter of about 12 km and a depth of about 175 m (Nolan and Brigham-Grette, 2007), whereas the catchment confined by the crater rim measures about 18 km in diameter (corresponding to 293 km^2). Today, the lake is not located in the center of the crater but slightly displaced to the southeast, resulting in an asymmetric catchment area (Fig. 1).

The El'gygytgyn crater region is part of the Central-Chukchi sector of the Okhotsk-Chukchi volcanic belt (Gurov and Gurova, 1979; Gurov et al., 2007). It is dominated by acid volcanic rocks, ignimbrites and tuffaceous clastic rocks of the Late Cretaceous (e.g. Gurov et al., 2007; Stone et al., 2009). The lake is surrounded by continuous permafrost, whose onset can presumably be traced back to the Late Pliocene (Glushkova and Smirnov, 2007), and which is assumed to have a thickness of about 330–360 m with an unfrozen talik underneath the lake today (Mottaghy et al., 2012). The recent geomorphologic shape of the lake catchment is predominantly affected by permafrost and by modeling processes of the lake itself (Glushkova and Smirnov, 2007). Distinct lake-level variations during the Mid Pleistocene to Holocene resulted in various accumulative and erosional terraces at 35–40 m, 9–11 m and 2.5–3.0 m above as well as 10 m below the modern lake level (Glushkova and Smirnov, 2007; Juschus et al., 2011).

The catchment of Lake El'gygytgyn is dissected by approximately 50 ephemeral inlet streams (see Fig. 1, Nolan and Brigham-Grette, 2007), which deliver sediment in the order of ca. 350 $t\,yr^{-1}$ into the lake (Fedorov et al., 2012). In 2003, main sediment discharge occurred during snowmelt in spring and early summer, with maximum values of 24 $g\,s^{-1}$ in June and 0.4 $g\,s^{-1}$ in August (Fedorov et al., 2012). Much of the sediment is trapped in coastal lagoons at the mouths of several inlet-streams, which are dammed by gravelly shore bars generated by ice-floe pressure or storms (Glushkova

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and Smirnov, 2007; Nolan and Brigham-Grette, 2007; Fedorov et al., 2012). The lake is drained by the Enmyvaan River towards the southeast (Fig. 1), which is supposed to be the only discharge during the lake history (Glushkova and Smirnov, 2007; Nolan and Brigham-Grette, 2007).

The regional climate at Lake El'gygytgyn is cold, dry, and windy (Nolan and Brigham-Grette, 2007) with a mean annual air temperature of −10.4 °C and an annual precipitation between 70 and 200 mm measured between 2002 and 2008 (Nolan, 2012). Strong (up to 21 ms^{-1}) and very persistent winds of north-northwestern and south-southeastern directions are dominant (Nolan and Brigham-Grette, 2007).

Lake El'gygytgyn is characterized as monomictic and oligotrophic to ultra-oligotrophic, with a low bioproductivity demonstrated by low diatom accumulation (Cremer and Wagner, 2003; Nolan and Brigham-Grette, 2007). Today, the water column is fully mixed with almost complete oxygen saturation during summer, but a thermal stratification occurs during winter (Cremer and Wagner, 2003). During peak glacial periods, in contrast, anoxic bottom water conditions prevailed, resulting from a perennial ice cover (Melles et al., 2007).

According to initial results from ICDP core 5011-1, the Quaternary sediments in central Lake El'gygytgyn can clearly be differentiated into three pelagic facies (Melles et al., 2012; Cook et al., 2013). Dark grey to black, finely laminated silt and clay with sporadical clasts are linked to peak glacial periods (facies A). In contrast, warm and peak warm ("super interglacial") interglacial conditions are reflected by olive gray to brownish, massive to faintly bedded silt (facies B) and laminated brownish silt (facies C), respectively. Beside these pelagic sediments, eight volcanic ash beds as well as numerous mass movement deposits (MMD) of different type (turbdites, slumps, slides, grain flows, debrites) have been identified (Juschus et al., 2009; Sauerbrey et al., 2013).

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3 Material and methods

Within the scope of this study, 1019 samples of Lake El'gygytgyn sediments originating from pelagic sediments in core composite of ICDP site 5011-1 (862 samples) and the pilot core Lz1024 (157 samples, locations see Fig. 1) have been analyzed for their grain-size distribution with a sampling resolution of 8 cm. Detailed descriptions of the creation of the composite profile, the lithostratigraphy, and MMD's are given by Nowaczyk et al. (2013) and Wennrich et al. (2013), and by Melles et al. (2012), and by Sauerbrey et al. (2013), respectively. The age model of the Lake El'gygytgyn sediment sequence is primarily based on magnetostratigraphic data (Haltia-Hovi and Nowaczyk, 2013), further improved by tuning of sediment proxies to the global marine benthic isotope stack of Lisiecki and Raymo (2005, LR04) and local insolation of orbital parameters by Laskar et al. (2004; Melles et al., 2012; Nowaczyk et al., 2013).

Prior to the grain-size analyses, a multi-step chemical treatment procedure was developed to remove autochthonous sediment components without altering the clastic material. The results of each treatment step were subsequently validated by elemental analyses, Fourier-Transformed Infrared Spectroscopy (FTIRS), X-ray diffraction (XRD), scanning electron microscopy (SEM) and optical microscopy. In a first step, approximately 0.75 g of dry sediment was treated with 15 mL H_2O_2 (30 % v/v, 50 °C, 18 h) to remove organic remains. Afterwards authigenic precipitated vivianite $((Fe)_3(PO_4)_2{}^* 8H_2O)$ was dissolved according to Asikainen et al. (2007) by treating the sediment with 15 mL HNO_3 (0.5M, 50 °C, 5 h, 30 min shaking in between). Finally, biogenic silica (opal), whose content can exceed 50 % in Lake El'gygytgyn sediments (Vogel et al., 2012), was removed by adding 2 × 15 mL NaOH (1 M, 85 °C, 30 min) with manual shaking during the reaction. Between the single pre-treatment steps, the samples were centrifuged and neutralized with DI water. The remaining sediment fraction was dispersed in 60 mL demineralized and degassed water, mixed with $Na_4P_2O_7$ (m/v, 0.05 %) and shaken for 12 h. Prior to the analysis, samples were ultrasonified for one

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minute to remove air bubbles and to achieve re-dispersing, and subsequently sieved to 600 µm.

Grain-size analyses were performed using a Saturn DigiSizer 5200 laser particle analyzer, equipped with a Master Tech 52 autosampler (Micromeritics Co., USA). The analyzer is able to detect particle diameters between 0.1 and 1000 µm. For the measurement, the flow rate was set to $10\,\mathrm{L\,min^{-1}}$ and the obscuration was adjusted to 20 %. The grain-size distribution of three measurements was finally averaged.

Grain-size statistics were calculated with the software GRADISTAT version 8.0 (Blott and Pye, 2001), and are given according to the method by Folk and Ward (1957). Furthermore, a Principal Component Analysis (PCA) was calculated with the software XLSTAT (Addinsoft Corp.). After an initial linear correlation test of the variables and standardization of the data, the PCA was carried out on the volume frequency of each grain diameter measured by the laser particle analyzer. The grain-size fractions as well as the mean, median and mode values were chosen as additional variables to simplify the visualization of the results.

For time-series analysis of the PCA results, the bulk spectrum of the unevenly spaced samples was calculated using the Fortran 90 program REDFIT by Schulz and Mudelsee (2002). Evolutionary spectra of the grain-size data and the benthic marine isotope stack LR04 (Lisiecki and Raymo, 2005) were plotted with the software package ESALAB (Weber et al., 2010).

4 Results

4.1 Grain-size data

In the composite profile of ICDP site 5011-1, variations in the grain-size data are rather small, but still distinct (Fig. 2). The sand content does not exceed 15.5 % with medium sand being the coarsest grain-size fraction that occurs. The average silt and clay contents are about 69.2 % and 27.7 %, respectively, showing minor fluctuations of only

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about 15 % within both fractions. The mean values range between 2.5 µm and 9.3 µm (after Folk and Ward, 1957), and thus, are classified as very fine (2–4 µm) to medium silt (8–16 µm). In general, this corresponds to earlier investigations on the grain-size distributions of the past 65 kyr in Lake El'gygytgyn (Asikainen et al., 2007).

Two characteristic grain-size distribution patterns describe the pelagic sediments of Lake El'gygytgyn at ICDP site 5011-1, exemplary shown on sample 5011-546 (Fig. 3a) and sample 5011-450 (Fig. 3b). Sample 5011-546 (Fig. 3a) is characterized by a poly-modal but nearly symmetrical grain-size distribution, with dominating silt (70.5 %) and lower clay (23.5 %) and sand contents (6 %), and a resulting mean value of 17.6 µm. A typical feature of grain-size distributions of this type is the lack of normal tailing but the occurrence of a peak or coarse-skewed shoulder at approximately 100 µm. In contrast, the sample 5011-450 (Fig. 3b) is remarkably finer and shows a tri-modal distribution including a double peak around 10 µm. The small discrepancy between the mean value (6.8 µm) and the mode value (5.4 µm) indicates a slightly asymmetrical pattern caused by the lack of a normal tailing to coarse sediments and an artificially coarse-skewed shoulder. Sample 5011-450 comprises silt and clay contents of 71 % and 28.5 %, respectively, but is lacking sand.

4.2 PCA

The PCA of the pelagic sediment yield 3 major principal components (PCs) explaining 75.4 % of the total variance in the grain-size data, with PC1, PC2 and PC3 covering variances of 42.8 %, 20.4 %, and 12.2 %, respectively. The plot of the active variables (PC1 vs. PC2, variance: 63.2 %, Fig. 4) clearly shows an arch spanning from clay to very coarse silt (Fig. 4), with highest negative factor loadings of PC1 revealing a grain diameter of 23.6 µm (coarse silt) and highest positives of 1.9 µm (clay to very fine silt). Grain diameters coarser than 44.5 µm (very coarse silt to medium sand) and finer then 0.6 µm (clay) focus to the origin of the diagram, which results in a horseshoe-pattern (Fig. 4). The sample scores of PC1 (plot see Fig. 2) show a high correlation to the mean ($R^2 = 0.93$) and the median values ($R^2 = 0.91$), whereas only a weaker

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correspondence to the mode values (R^2 = 0.56) is noticeable. In contrast, PC2 is highly correlated to medium silt (R^2 = 0.83) and PC3 is not correlated to any grain-size fraction.

4.3 Time-series analysis

To gain insight into the frequency of the grain-size data, time series analyses of PC1 samples scores have been performed. The bulk spectrum yields three important peaks with dominant oscillations at 98.5 kyr, 40.6 kyr, and 22.9 kyr, which exceed the significance level of 99 % χ^2 (Fig. 5).

The evolutionary power spectrum of PC1 sample scores (Fig. 6a) was carried with a window width of 240 ka. Overlapping window segments were used for the calculations, which resulted in a reported time period of 2478 ka to 120 ka. During this period, the evolutionary power spectrum yields distinct variations in the relative power of the three dominate cycles (98.5 kyr, 40.6 kyr, and 22.9 kyr). The 98.5 kyr period is highly variable throughout the analyzed time period with a strong relative power prior to 2300 and from 2100 to 1800 ka, from 1250 to 1000 ka, and after 800 ka, but a weak dominance in the periods 2200 to 2100 ka, 1800 to 1600 ka and 1000 to 800 ka. The 40.6 kyr cycle is more consistent with a strong relative power from 2400 to 1250 ka and from 950 to 670 ka, whereas a low signal occurs around 1750 ka and after 670 ka. The 22.9 kyr cycle occurs from 1900 ka to 1300 ka, from 1100 ka to 900 ka, and during two short time periods at 2250 and 130 ka.

5 Discussion

5.1 Climate dependency

The Quaternary grain-size variability and distribution of core 5011-1 from Lake El'gygytgyn imply a strong climate dependency, with coarse-grained, polymodal

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distributed sediments (Fig. 3a) occurring during warm periods and fine-grained, tri-modal distributed deposits (Fig. 3b) during cold periods. This is confirmed by a comparison of the mean grain-size to other climate-dependent proxies of the Lake El'gygytgyn record. The Si/Ti ratio, which is a measure of the biogenic silica content (BSi) in the sediment, and thus, of the primary production by diatoms (Melles et al., 2007, 2012; Vogel et al., 2012; Wennrich et al., 2013) shows very similar trends as the grain-size data (Fig. 7).

As shown for modern conditions, the supply of clastic material to Lake El'gygytgyn is mainly restricted to the snowmelt during spring and early summer due to the availability of fluvial discharge (cf. Fedorov et al., 2012). Additionally, the thickness of the active layer of the local permafrost is supposed to trigger the availability of clastic material. During snowmelt, even pebble to cobble-sized rocks as well as clumps of tundra are transported to the beach and close to the shoreline in the lake (cf. Asikainen et al., 2007; Nolan and Brigham-Grette, 2007). Coarse material may be filtered by the shore bars, explaining the lack of a normal tailing to coarse sediments in Lake El'gygytgyn deposits. Subsequently, parts of the sediment are re-distributed by a wind-induced current pattern, which triggers the deposition of coarse-grained sediments in the center of Lake El'gygytgyn (Wennrich et al., 2012). The grain-size data of ICDP site 5011-1 suggests that sedimentation processes described for the modern conditions persisted during interglacial periods through the entire Quaternary. Coarser grain-size distributions even do not occur in sediments of facies C (peak warm conditions), most likely because the maximum wind speed and the resulting current speed within the water body is limited. As a result, grain-size distributions from "super interglacials" (facies C), do not differ significantly from normal interglacial deposits (facies B, cf. Figs. 2 and 7). A current speed in the lake may be limited, but is most likely also variable. Currents of varying speed could have resulted in poorly sorted sediments such as indicated by the typical polymodal grain-size distributions of interglacial sediments and the occurrence of the coarse-skewed shoulder or independent peak at ~ 100 µm (cf. Fig. 3a). However, polymodal grain-size distributions could also be triggered by additional sedimentation

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processes, such as eolian or ice floe transportation. For modern conditions, eolian sediment input to Lake El'gygytgyn is calculated to 2 to 5 % of the total sediment deposition (Fedorov et al., 2012). At Lake El'gygytgyn, random ice floe transport could have significantly contributed to the sediment supply to ICDP site 5011-1 as modern observations recorded sediment supply by inlet streams onto the ice cover during snowmelt. Therefrom, the sediment is periodically flushed out when the summer temperature is high enough (Fedorov et al., 2012). Sediment supply onto the ice cover and subsequent redistribution by ice-floe transportation is also described for other seasonally ice-covered lakes, e.g. for Lake Baikal (Vologina et al., 2005).

Gradual transitions from warm to cold conditions on an interglacial-glacial time scale are well reflected by the mean grain-size, and even higher amplitude variations (e.g. between MIS 11 and 10, Fig. 7) are present in the data. This implies gradual rather than abrupt changes of the sedimentation processes at Lake El'gygytgyn during such transitions. The lack of coarse material and the better sorting of sediments from glacial periods predominantly depends on colder summer temperatures at Lake El'gygytgyn. A thin active layer and restricted water as major transport medium hamper the supply of coarse material to the lake. Furthermore, the absence of ice free conditions at Lake El'gygytgyn, which depends on the summer temperature (Nolan, 2012), excludes the redistribution of clastic material by a wind induced current pattern. In general, sediment supply to Lake El'gygytgyn under such climate conditions is widely restricted to seasonal moats around the perennial lake ice, formed in late summer (Asikainen et al., 2007; Melles et al., 2007). Furthermore, material of eolian origin is able to move through the ice along grain boundaries and vertical conducts (Nolan, 2012) whereby it might be compacted to 1–2 mm clasts during cold and dry conditions (Asikainen et al., 2007; Melles et al., 2007).

5.2 PCA

Factor loadings of PC1 results yield the most important grain diameter (fractions) contributing to the grain-size distribution (Fig. 4). High positive or negative factor loadings imply a high importance of the coarse silt and the very fine silt fraction, respectively. As variations in the grain-size data are primarily attributed to climate variability, sample scores of PC1 can be interpreted to represent climate variations. High negative PC1 scores are associated to warmer climate conditions with ice-free conditions during summer and enhanced sedimentation of coarse silt. In contrast, high positive PC1 scores are linked to glacial climate conditions and the enrichment of very fine silt. Silt, in detail medium silt, shows the weakest correlation to PC1 but high factor loading on PC2. The high correlation of medium silt to PC2 is apparently mainly triggered by the occurrence of the horseshoe pattern (Fig. 4). The horseshoe pattern is a mathematic artifact in PCA results (cf. Kendall, 1971; Gauch et al., 1977), which occurs if the analyzed data set is only influenced by one long gradient and each variable (inhere: grain diameter) is successively replaced by the next one, resulting in an unimodal response to the gradient (Swan, 1970; Gauch et al., 1977). Thus, PCA results substantiate the interpretation that grain-size variations of Lake El'gygytgyn sediments are predominatly triggered by climate variability between warm and cold periods. Hence, mathematical methods to remove the horseshoe effect, such as the Detrended Correspondence Analyses (Hill and Gauch, 1980) or the Aitchison's centered logartio procedure (Davis, 2002), were not applied to the analyzed data.

5.3 Time series analysis

To distinguish between time periods, which are dominated by global glacial-interglacial or shorter-term variations, a time series analysis on PC1 sample scores was carried out. As the age model of core 5011-1 was derived by tuning sediment proxies with local insolation and the global marine isotope stack LR04 (Melles et al., 2012; Nowaczyk et al., 2013), the bulk spectrum (Fig. 5) yield dominant oscillations above the 99 % χ^2 confidence level at Milankovitch's eccentricity (98.5 kyr), obliquity (40.6 kyr) and precession oscillations (22.9 kyr). However, the relative dominance of these three oscillations clearly differs during the Quaternary in comparison to LR04 (Fig. 6). Cycles of 98.5 ka and 40.6 ka are interpreted to be a result of global climate variability and variations of

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the global ice volume, such as reflected by marine isotope stack LR04 (Lisiecki and Raymo, 2005, cf. Fig. 6b). In contrast, the 22.9 ka band is triggered by local orbital precession forcing at the latitude of Lake El'gygytgyn, with coarser grain-size distributions associated with high insolation values. Consequently, ice-free summertime is extended during high insolation forcing. These findings are concomitant with results of previous studies on the sedimentation pattern of Lake El'gygytgyns, e.g. magnetic susceptibility and TOC data (Melles et al., 2007; Nowaczyk et al., 2007).

During the early Pleistocene (2600 ka to 780 ka, see also Fig. 2), when global climate conditions were dominated by the 41 kyr band (e.g. Clark et al., 2006), similarities and dissimilarities between 5011-1 and LR04 occur (Fig. 6). The strong oscillation of the 41.7 kyr cycle in the grain-size data of 5011-1 well reflect global climate variability on the obliquity oscillation band at Lake El'gygygtgyn. In contrast, die 98.5 kyr cycle in the grain-size data is more variable, with a strong response to climate forcing between 2450 ka and 2300 ka, between 2100 ka and 1800 ka and a reduced power between 1800 ka and 1600 ka (Fig. 6). These findings partly agree with descriptions of Nie et al. (2008) about the 100 ka band during the early Pleistocene. Following their description of the "late Pliocene-early Pleistocene 100-kyr problem", there is a strong response of climate proxies between 3000 ka and 1800 ka, although forcing is strong between 1300 ka and 2300 ka. However, Lake El'gygytgyn grain-size data indicate only a weak 98.5 kyr cycle between 2300 ka and 2100 ka.

During the early Pleistocene, the 22.9 kyr precession band is strong around 2250 ka and between 1900 ka and 1300 ka when the relative eccentricity or obliquity powers are low. Thereby, the precession band at Lake El'gygytgyn mostly interplays with the eccentricity band and is therefore closely connected with the "late Pliocene-early Pleistocene 100-kyr problem". The absence of the 23 ka band between 3000 and 1000 ka in global benthic isotope records (cf. Fig. 6) despite a strong precession cycle at all latitudes has been explained with an out-of-phase ice-sheet growth and melt at each pole (Raymo et al., 2006). Grain-size data at Lake El'gygytyn is not directly coupled to global ice-volume variability and shows the 23 ka precession band to be important for

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the climate conditions during specific time intervals. Variations on a 23 ka oscillation band during the early Pleistocene are also reported from the Chinese loess plateau (Sun et al., 2006) and African dust records (deMenocal, 1995).

The time periods of the Middle Pleistocene Transition (MPT, see also Fig. 2) and the late Pleistocene are marked by the transition of climate variability on the obliquity oscillation to eccentricity oscillation (e.g. Clark et al., 2006). Thereby, in our data set this transition is rather gradual with an initial onset of the 98.5 kyr cycle at 1250 ka, low power from 1000 to 800 ka and strong power afterwards until at least 130 ka. A weaken of the 100 ka eccentricity band around 1000 ka is also present in LR04 (Fig. 6). At Lake El'gygytgyn, this period until 800 ka is characterized by an initially strong 22.9 kyr cycle and subsequent strong 40.6 kyr cycle. The decreasing relative power of the obliquity oscillation during the late Pleistocene implies that the MPT at Lake El'gygytgyn lasted from 1250 to 670 ka. Such a gradual transition is also described for LR04 with an initial onset at 1250 ka, a disturbance of the eccentricity cycle for 100 kyr around 1000 ka, and a completion of the transition to the 100 kyr world at 700 ka (Clark et al., 2006). The mechanism leading to the emerge of the 100 kyr band are hypothesized to have been triggered by a long-term cooling trend induced by decreasing pCO_2 (Berger et al., 1999; Tizperman and Gildor, 2003) and/or increasing ice-sheet thickness due to exposure of high-friction crystalline bedrock (Clark and Pollard, 1998), whereas orbital forcing can be excluded (Clark et al., 2006).

6 Conclusions

Variations in the grain-size distribution of Lake El'gygytgyn sediments during the past 2600 ka have shown to be mainly influenced by the summer temperature, and thus, by global and regional climate conditions. Main factors triggering the clastic sedimentation in the lake are supposed to be the existence and duration of the annual lake-ice cover, the permafrost stability around the lake and the strengths of fluvial transport processes in the catchment. Studies on the modern sedimentation in the lake have shown

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that a wind-induced current pattern of different strengths triggers the occurrence of coarse-grained deposits at the center of the lake during ice-free periods (Wennrich et al., 2012). Our data suggest that this process persisted through the entire Quaternary. Under glacial climate conditions, sediment supply to the lake is supposed to be restricted to seasonal moats close to the shore and to vertical conducts in the ice.

Principal Component Analysis allowed identifying most important grain-size fractions attributing to variations in the data set. It could be emphasized that coarse silt and very fine silt are the major players in climate-depended variations in the grain-size data whereas medium silt do not show this climate dependency.

Time series analysis reveals major oscillation and their relative dominance in the grain-size data during the Quaternary. It can be concluded that duration of annual lake-ice cover and thickness of the active layer during summer are triggered by global glacial/interglacial cycles (98.5 kyr, 40.6 kyr) as well as by local insolation forcing (precession band, 22.9 kyr). Early Pleistocene variations on a 98.5 kyr oscillation band partly agree with descriptions of the "late Pliocene-early Pleistocene 100-kyr problem" by Nie et al. (2008). Additionally, our data suggest an interplay of the 98.5 kyr and the 22.9 kyr cycles during the early Pleistocene, and thus, reflecting global versus regional climate variability at Lake El'gygytgyn. The MPT is well reflected by our data between 1250 ka and 670 ka.

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Multivariate statistic and time series analyses of grain-size data

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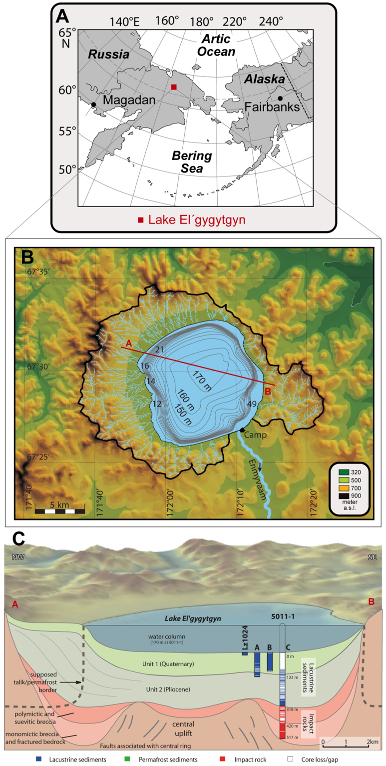

Fig. 1. (A) Location of Lake El'gygytgyn in the Far East Russian Artic, **(B)** Bathymetric map of the lake and topographic map of the catchment area, including the approximately 50 inlet streams and the Enmyvaam River outlet (Fedorov and Kupolov, 2005); red line: profile A to B. **(C)** Schematic profile A to B with the locations of the pilot core Lz 1024 and the three holes (A, B and C) at ICDP site 5011-1 with the Pliocene/Pleistocene boundary penetrated at approximately 123 m, and the transition to the impact breccia at 318 m below lake floor (modified after Melles et al., 2011).

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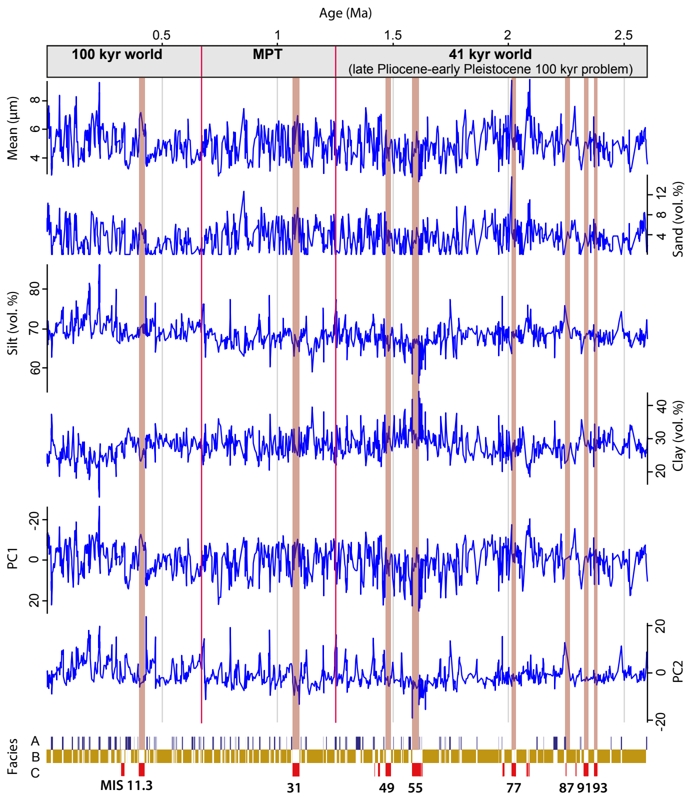

Fig. 2. Selected grain-size parameters (Mean, Sand, Silt, Clay) and sample scores of PC1 and PC2 in the Quaternary sediments of the core composite at ICDP site 5011-1 in central Lake El'gygytgyn. The timing of the Mid-Pleistocene Transition (MPT) from the 41 kyr world, including the Pliocene-early Pleistocene 100 kyr problem after Nie et al. (2008), to the 100 kyr world is derived from the time series analysis (cf. Fig. 6). Facies bar was modified from Melles et al. (2012), Marine Isotope Stages of "super interglacial" facies C (after Melles et al., 2012) are labeled below.

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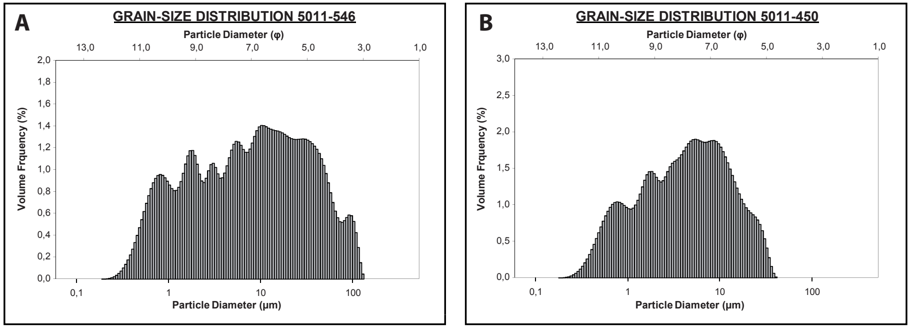

Fig. 3. Grain-size distributions of two representative samples: sample 5011-546 **(A)** extraordinary warm climate conditions (facies C), and 5011-450 **(B)** cold and dry climate conditions (facies A).

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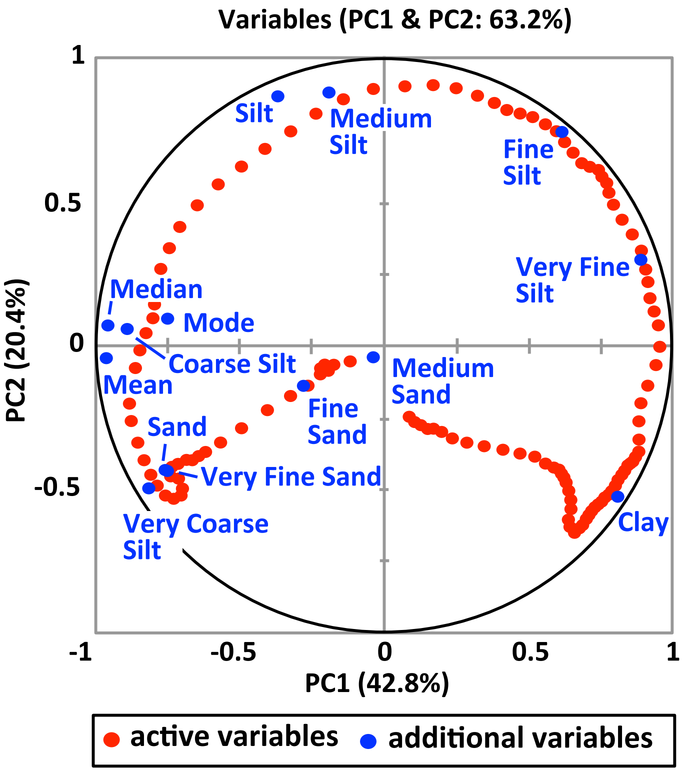

Fig. 4. Results of the PCA of the raw grain-size data (PC1 and PC2). Red dots (active variables) represent specific grain diameters measured by the laser particle analyzer. Selected grain-size fractions and parameters were chosen as additional variables (blue dots) for visualization of the results and are not directly included into the PCA calculations. PC1 (42.8 %) and PC2 (20.4 %) together comprise about 63.2 % of the total variance in the data set. The active variables clearly show a horseshoe pattern (for further explanations see text).

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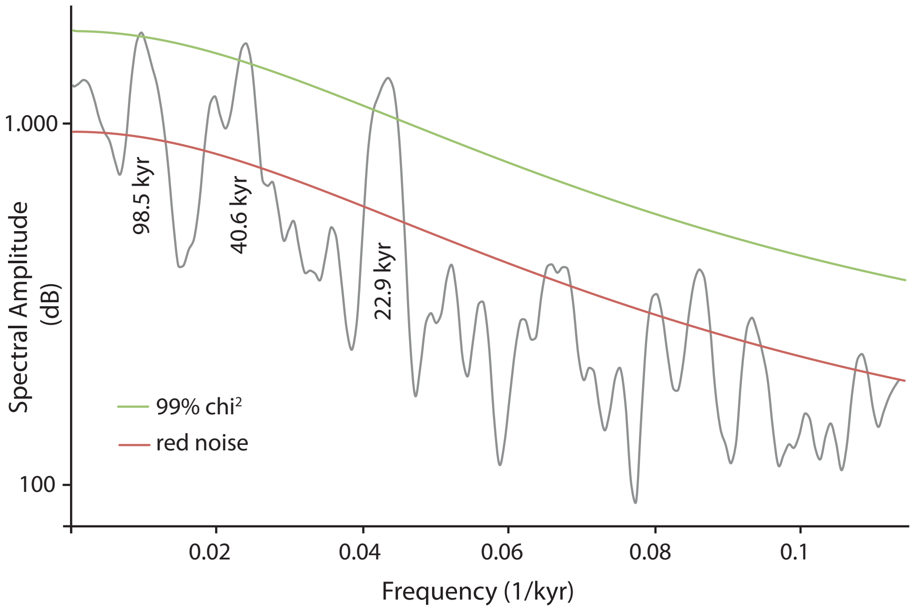

Fig. 5. Bias-corrected spectrum of sample scores of PC1 using the software REDFIT38, applying the Lomb-Scargle periodogram for unevenly spaced time series in combination with the Welch's Overlapped Segment Averaging procedure (Mudelsee et al., 2009). Number of segments n_{50} = 14; window type: boxcar; red line: red noise level; green line: 99 % false-alarm level (χ^2). Significant cycles at 98.5, 40.6 and 22.9 kyr exceed both the red noise and the confidence level.

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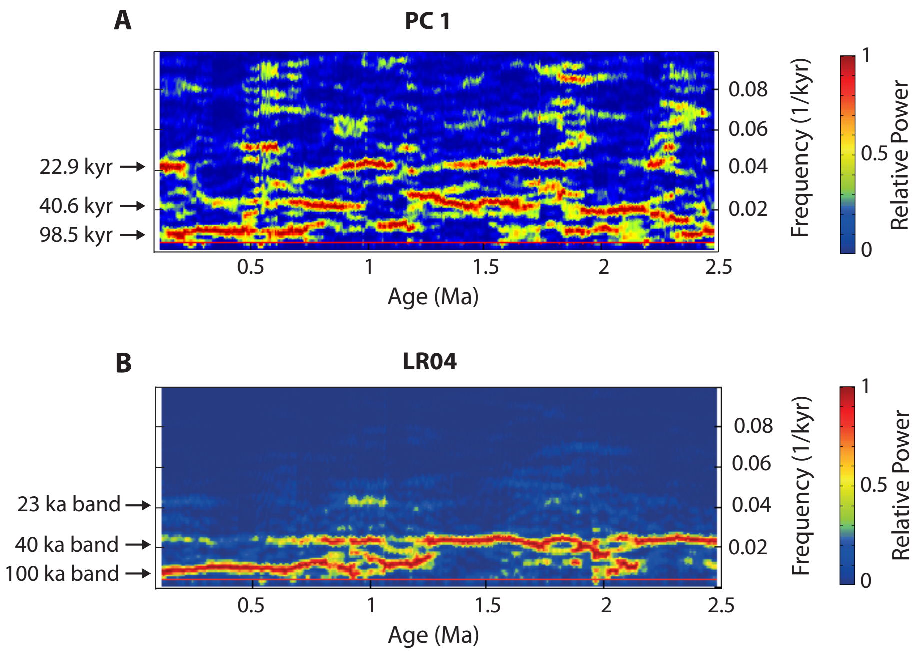

Fig. 6. (A) Evolutionary power spectrum of sample scores of PC1 from 120 ka to 2478 ka, resulting from the chosen window width of 240 ka (window type: boxcar). The used software ESALAB (Weber et al., 2010) is based on the same algorithms as REDFIT38. **(B)** Evolutionary power spectrum of LR04 (Lisiecki and Raymo, 2005) applying the same settings as in Fig. 6a.

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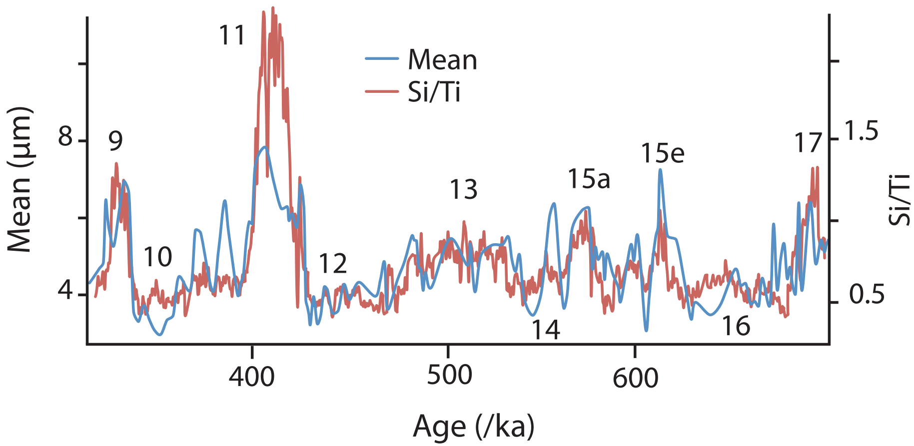

Fig. 7. Comparison of the mean values (after Folk and Ward, 1957) and the Si/Ti ratio as a proxy for bioproductivity in Lake El'gygytgyn between Marine Isotope Stages 17 and 9. Variations on a glacial-interglacial time-scale but also of higher frequency are well reflected by the grain-size data. Grain-size distributions during MIS11 do not differ compared to other interglacials.

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