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Modern sedimentation patterns in Lake El'gygytgyn, NE Russia, derived from surface sediment and inlet streams samples

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Abstract

High Arctic Lake El'gygytgyn/NE Russia holds a continuous 3.58 Ma sediment record, which is regarded as the most long-lasting climate archive of the terrestrial Arctic. Based on multi-proxy geochemical, mineralogical and granulometric analyses of surface sediment, inlet stream and bedrock samples, supplemented by statistical methods, major processes influencing the modern sedimentation in the lake were investigated. Grain-size parameters and chemical elements linked to the input of feldspars from acidic bedrock indicate a wind-induced two-cell current system as major driver of sediment transport and accumulation processes in Lake El'gygytgyn. The distribution of mafic-rock related elements in the sediment on the lake floor can be traced back to the input of weathering products of basaltic rocks in the catchment. Obvious similarities in the spatial variability of manganese and heavy metals indicate sorption or co-precipitaion of these elements with Fe and Mn hydroxides and oxides. But the akin distribution of organic matter content might also point to a fixation to organic components. An enrichment of mercury in the inlet streams might be indicative of neotectonic activity around the lake. The results of this study add to the fundamental knowledge of the in-lake processes of Lake El'gygytgyn and its lake-catchment interactions, and thus, yield crucial insights for the interpretation of paleo-data from this unique archive.

1 Introduction

In spring 2009, the ICDP El'gygytgyn Drilling Project recovered the 318-m long lacustrine sediment record of Lake El'gygytgyn in Chukotka, NE Russia (Melles et al., 2011; Fig. 1; Melles et al., 2012). Long high-resolution lake sediment records are known to well document regional hydrologic and climatic responses to atmospheric changes (Brigham-Grette et al., 2007a), and thereby are rare but valuable archives of climate and environmental changes (Vogel et al., 2010). Given their often continuous sediment sequences, large, old lake basins play an important role in collecting sedimentological

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information providing a continental signature to couple with the marine realm. Thus, these lakes help to close gaps in the knowledge on land-ocean interactions through time. Nevertheless, the profound interpretation of proxy data derived from lake sediment records requires a in-depth knowledge of the lake-specific modern biological and sedimentological processes and their controlling factors (Vogel et al., 2010; Viehberg et al., 2012).

In the high Arctic, Lake El'gygytgyn represents an unique site, because it holds the most long-lasting widely time-continuous climate archive of the terrestrial Arctic (Melles et al., 2011, 2012), reaching back to the time of meteorite impact event 3.6 Ma ago (Layer, 2000). Furthermore, the basin was never overcome by the large Cenozoic continental ice-masses (Glushkova, 2001; Glushkova and Smirnov, 2007), resulting in a continuous sedimentation. The lake is located in a region influenced by both Siberian and North Pacific oceanic air-masses (Barr and Clark, 2011; Yanase and Abe-Ouchi, 2007; Mock et al., 1998), making it very sensitive to reflect regional atmospheric changes. The high potential of Lake El'gygytgyn for globally significant paleoclimate and -environmental reconstructions is confirmed by numerous studies on the lake sediments formed during the past three glacial/interglacial cycles (Brigham-Grette et al., 2007b; Lozhkin et al., 2007; Melles et al., 2007; Minyuk et al., 2007; Nowaczyk et al., 2007; Swann et al., 2010; Asikainen et al., 2007).

Within the framework of the pre-site survey research, modern climatological and hydrological processes in the lake surrounding and in the water column were intensively investigated (e.g. Cremer and Wagner, 2003; Cremer et al., 2005; Nolan and Brigham-Grette, 2007; Nolan et al., 2003; Fedorov et al., 2012), and a variety of modern to sub-recent sample sets were taken for study (Melles et al., 2005).

Here, we present the combined results of a multi-proxy and statistical approach to enhance our understanding of the modern sedimentation of Lake El'gygytgyn by analyzing a set of surface sediment and inlet streams samples, as well as hand samples from the surrounding bedrock. Major goal of this study is to provide information concerning dominant sedimentation patterns in the lake controlled by climate-driven transport processes, bedrock geology, post-depositional processes, but possibly also influenced by tectonic activity. In combination with new climate and hydrology data (Nolan, 2012; Fedorov et al., 2012), these findings will enhance our understanding of fundamental in-lake processes, and thus, forming an important base for the interpretation of the Lake El'gygytgyn paleo-record extending to 3.6 Ma.

2 Study site

High arctic Lake El'gygytgyn (67°30′ N, 172°0530′ E, 492 m a.s.l.; Fig. 1) is located within the Anadyr Mountain Range in Central Chukotka/Far East Russian Arctic. Today, the roughly circular lake has a diameter of ~12 km and a maximum water depth of 175 m (Nolan and Brigham-Grette, 2007; Melles et al., 2007), filling the deepest part of the ~18-km wide El'gygytgyn impact crater (Gurov et al., 2007). With a surface area of ~110 km^2 the lake is fed by 50 ephemeral streams draining a watershed area of 293 km^2 defined by the crater rim (Nolan et al., 2003; Fig. 2a). The outlet stream, the Enmyvaam River at the south-eastern edge of the lake, flows into the Anadyr River, which further drains into the Bering Sea (Nolan and Brigham-Grette, 2007).

The climate in Chukotka is characterized by low mean winter and summer temperatures between −32 °C and −36 °C (January) and between +4 °C and +8 °C (July, August), respectively (Treshnikov, 1985), and a mean annual precipitation of ~ 250 mm (Glotov and Zuev, 1995). In 2002, winter and summer temperature extremes of −40 °C and +26 °C, respectively, were measured at Lake El'gygytgyn (Nolan and Brigham-Grette, 2007). Strong winds either from the north or south with a mean hourly wind speed of 5.6 m s^{-1}, were punctuated by maximum values up to 21.0 m s^{-1} (Nolan and Brigham-Grette, 2007).

Lake El'gygytgyn is an oligotrophic to ultra-oligotrophic and cold-monomictic lake (Cremer and Wagner, 2003), with a yearly ice-cover lasting from mid October until early to mid July (Nolan et al., 2003). While thermal stratification of the water column is today established during the ice-covered season (Cremer et al., 2005), the lake becomes fully mixed by late summer after snowmelt and the initial ice break-up, triggered by the lateral movement of warmer shore-waters and enhanced by strong winds (Nolan and Brigham-Grette, 2007). The residence time of the lake water was calculated to be ~100 yr (Fedorov et al., 2012).

Geomorphological studies in the lake catchment have identified prominent lake terraces at 35–40 m, 9–11 m and 3–5 m above the recent lake level as remains of lake-level high-stands during the lake history (Glushkova and Smirnov, 2007; Schwamborn et al., 2006, 2008a). In addition, an ancient terrace 10 m below the modern water level points out a significant lake-level lowering, likely during MIS 2 (Juschus et al., 2011). Although the existence of higher terraces 60 and 80 m above the recent lake level has been suggested (Gurov et al., 2007; Nekrasov, 1963), their lacustrine origin is questionable.

The El'gygytgyn impact crater was formed in Upper Cretaceous volcanic rocks of the Okhotsk-Chukchi Volcanic Belt (OCVB) (Gurov et al., 2007; Gurov and Gurova, 1979). The bedrock in the vicinity of the lake predominantly consists of ignimbrites, tuffs and andesite-basalts associated to the Pykarvaam, Voron'in, Koekvun' and Ergyvaam Formation (Belyi and Raikevich, 1994; Nowaczyk et al., 2002; Fig. 1b) dated to about 67–90 Ma (Kelley et al., 1999; Stone et al., 2009). The region of Lake El'gygytgyn is affected by continuous permafrost, presumably since the Late Pliocene (Glushkova and Smirnov, 2007). Erosion and detrital sediment transport of bedrock material into the lake basin are mainly triggered by permafrost related cryogenic weathering, as well as slope dynamics, and fluvial outwash in the lake surrounding (Schwamborn et al., 2008b; Fedorov et al., 2012). Thus, climate-driven variations in permafrost stability are believed to have a major influence on the lake sediment composition.

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3 Material and methods

3.1 Field work

During a field campaign in summer 2003, a set of 55 surface sediment samples was collected from the floor of Lake El'gygytgyn (Fig. 1b). The samples were recovered from a floating platform using a gravity corer (UWITEC Corp., Austria) equipped with plastic liners 6 cm in diameter. Sample locations generally correspond to a field determined map grid, except for the shallowest parts of the lake, which were only sampled along a transect at the southern shelf and at three sites along the southeastern shelf. This study is based on the surface sediments of the gravity cores, comprising the uppermost 2 cm (Fig. 2).

To investigate the influence of fluvial sediment supply and the bedrock geology on the modern sediments of Lake El'gygytgyn, additional 30 sediment samples were taken from the major inlet streams entering the lake, and another 11 bedrock samples were collected in the lake catchment (Fig. 1b). These bedrock data were supplemented by data taken from the literature (Belyi and Belaya, 1998).

3.2 Analytical work

Sediments from both the lake bed and the inlet stream samples were freeze-dried in the lab and subsequently split into sample aliquots. Aliquots for geochemical and biogeochemical analyzes were ground to <63 µm and homogenized. Total nitrogen (TN) was measured with an elemental analyzer (vario EL III, elementar Corp.). The content of total organic carbon (TOC) was measured using a METALYT CS 1000S analyzer (ELTRA Corp.), after pretreating the sediment with 10 % HCl in order to remove carbonates.

Major and trace elements were measured by ICP-OES (iCAP 6300 DUO, Thermo Scientific) after $HClO_4$/HF total digestions. Acid digestion was performed in closed Teflon vessels (PDS-6) heated for 6 h at 180 °C by treating 100 mg sample with 3 ml

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HF + 1 ml $HClO_4$. After digestion, the acids were evaporated using a heated metal block (180 °C) and were re-dissolved and evaporated three times with 3 ml half-concentrated HCl, followed by re-dissolution with 2 vol% HNO_3 and dilution to 25 ml. Precision (1σ) and accuracy were checked by parallel analysis of international and in-house reference materials, leading to ≤2.8 and ≤2.6 % for major elements and ≤1.7 and ≤12.1 % for trace metals. Mercury was directly determined at 30–50 mg of dry homogenized sediment using a DMA-80 Direct Mercury Analyzer (MLS instruments). The analysis is based on combustion of the sample and pre-concentration of Hg at a gold trap (amalgam), re-heating and determination of Hg gas by atomic-absorption spectrometry (AAS). The detection limit of the analysis is very low (<1 $\mu g\,kg^{-1}$) and the reproducibility (precision) is ~5 % relative to the standard deviation from the average value.

The major and trace element composition of the bedrock rock samples was determined by X-ray fluorescence (XRF) analysis using a sequential X-ray spectrometer (Phillips PW2400) calibrated with natural and synthetic standards. Prior to analysis powdered samples were heated for four hours at 105 °C before fusion with $Li_2B_4O_7$.

Bulk mineral contents were measured by means of XRD on pressed pellets, using a Philips PW 1820 diffractometer with Co$K\alpha$ radiation (40 kV, 40 mA), automatic divergence slit (ADS), graphite monochromator, and automatic sample changer. Mineral identification was done by means of the Philips software X'Pert HighScore™ and sheet silicates were identified and quantified with the X-ray diffraction interpretation software MacDiff 4.25 (Petschick et al., 1996). Full quantification of the bulk mineral assemblage was carried out using the QUAX software package (Emmermann and Lauterjung, 1990) following the QUAX full pattern method (cf., Vogt et al., 2002). The standard deviation for bulk mineral determination is ±2 % for quartz (Vogt, 1997) and ±5–10 % for feldspars and clay minerals (Vogt et al., 2002).

Grain-size analyses were performed on 1 g freeze-dried sediment. Prior to the measurement, samples were pre-treated according to Francke et al. (2012) to remove organic matter (30 % H_2O_2/50 °C), vivianite nodules (0.5 M HNO_3/50 °C) and biogenic silica (0.5 M NaOH leaching/90 °C). Subsequently, the samples were mixed

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with $Na_4P_2O_7$ solution (0.05 % w/v) as a dispergent agent and finally measured by a Laser Particle Size Analyzer (DigiSizer 5200, Micromeritics Instrument Corp.). The laser-diffractometer uses a 1 MB CCD-sensor and calculates 160 grain-size classes between 0.1 and 1000 µm with average values of three runs. One minute of ultrasonic treatment and flow rates of 10 l min^{-1} re-suspended the sediments prior to detection.

3.3 Statistics

Calculations of grain-size parameters and statistics were performed using the program GRADISTAT (Blott and Pye, 2001). The statistical grain-size parameters were calculated according to the arithmetic method of moments.

To handle and to simplify the element data, and to visualize grain-size dependencies, both a principal component analysis (PCA) and a redundancy analysis (RDA) were carried out. Analyses were conducted using the Microsoft Excel add-in XLSTAT (Addinsoft SARL) with chemical element data as dependent response variables and various grain-size parameters (mean, mode, median, percentages of sand, mud, silt, clay, medium sand, fine sand, very fine sand, very coarse silt, coarse silt, medium silt, fine silt, very fine silt) as explanatory variables, respectively.

4 Results and discussion

The Lake El'gygytgyn surface sediments show a variety of distribution patterns based on grain-size parameters, element concentrations, bulk mineralogy, and organic parameters, which are controlled by transport processes, basin topography, bedrock geology, early diagenetic processes and potential tectonic activity. Thus, the surface sediments provide fundamental data about the dominating transport mechanisms and processes, but also about the sediment sources and post-depositional sediment alteration. These data have a direct impact on the interpretation of paleoclimate record derived from sediment cores from Lake El'gygytgyn.

4.1 Sediment transport mechanisms within the water body

The surface sediments of Lake El'gygytgyn are silt dominated with a mean grain-size ranging between 7.3 and 69.6 µm (Fig. 3d). The spatial distribution of the mean grain-size shows fine-grained sediments in the northern, eastern and western central lake basin, whereas coarser material appears at the southern, northwestern and northeastern edges of the lake (Fig. 3d). Obviously, the grain-size distribution traces the general two-cell wind induced current system in Lake El'gygytgyn as postulated by Nolan and Brigham-Grette (2007), which appears to be triggered by strong winds from north or south. Similar wind-driven two-cell current circulations are common features in Arctic lakes (e.g. Côté and Burn, 2002), often resulting in oriented lakes with an elliptical shape perpendicular to the main wind direction. Coarse-grained areas with high sand content (>63 µm) up to 73.8 % are located in the northwestern and northeastern corners of the lake and along the southern shore (Fig. 3a), where highest erosional forces prevent the deposition of fine-grained material (Nolan and Brigham-Grette, 2007).

Higher silt content (2–63 µm) is observed at the eastern lake shore (Fig. 3b), with maximum values up to 82.3 % at the southeastern edge of the basin near the mouth of creek 49 and 50 (creek numbers accord. to Nolan et al., 2003; Fig. 3a). During snow melt, creek 49 (informally called "Lagerny creek") produces the highest water and sediment discharge of all inlet streams in the range of 6.1 $m^3 s^{-1}$ and 24.0 $g s^{-1}$, respectively (Fedorov et al., 2012). Thus, the high silt content most likely can be traced back to the high flux of fluvial suspension from this major inlet and its northward drift during northern winds along the eastern shore.

Surprisingly, the center of the lake exhibits a tongue of higher mean grain sizes of 15–25 µm extending from the southern shore towards the lake center (Fig. 3d). This feature is mainly due to higher contents of very coarse silt (31–63 µm) of up to 17 %. Since larger inlet streams are missing along the southern shore, a fluvial origin for this tongue can be excluded. Furthermore, the low sand content in the area of the tongue (Fig. 3a) makes is unlikely that ice-rafting transport contributes materials from

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the southern, very sandy shelf. The lack of sand and the selective enrichment of very coarse silt also eliminates an origin for this tongue from turbidity currents, whose deposits are rather abundant in the sediment core of Lake El'gygytgyn but exclude a recent event (Juschus et al., 2009). Thus, the coarser sediment tongue is most likely the result of wave-induced re-suspension and erosion of fine-grained material from the shallow southern shelf shore (water depth <10 m) during heavy storms with northerly wind directions and a subsequent northward transport by sub-surface currents. This suggestion is supported by a very coarse grain-size on the southern shelf (Figs. 3a, d) reflecting erosional and transport processes in this area. The occurrence of such re-suspension processes was observed during a heavy storm from north in August 2003. Wind velocities up to 16.8 ms^{-1} (Nolan, personal communication) and wave heights up to 1 m created a distinct northward reaching suspension cloud ~1 km in length in front of the outlet (Fig. 4). The visible suspension cloud ended just at the shelf edge, implying a further transport and dispersion of the material into the deeper lake basin via intra- and/or underflows. Between 2001 and 2005, similar heavy storms with wind speeds exceeding 10 ms^{-1} and a duration of more than four hours were recorded at the lake between 9 (2001, 2004) and 26 (2002) times during the ice-free season (mid July–mid October; Nolan et al., 2003). The formation of a major suspension fan is likely amplified by the triangular, funnel-shaped morphology of the southern shore of Lake El'gygytgyn (Fig. 1b), focusing the wave activity at the southeastern edge just in front of the Enmyvaam outlet. Furthermore, the similarity in the locations of the coarse grained sediment tongue and a NE-SW oriented ridge structure obvious in the bathymetry (Fig. 1b) indicate a higher sediment rates along the suspension fan.

The bulk mineral composition of the surface sediments is dominated by a mixture of quartz, feldspars (plagioclase and K-feldspars) and clay minerals (Table 1). Although bedrock samples of the catchment contain fairly scattered amounts of quartz ranging from 3.0–27.7 %, the surface samples show a rather heterogeneous quartz distribution with a clear enrichment (up to 34.3 %) at the southern and southeastern shore (Fig. 3f). Conversely, the northwestern shore is characterized by lowest quartz contents. Feldspars, also have high concentration in the surface sediments at the southern and northeastern shores (max. 42.5 %) but differ from quartz by high concentration also at the northwestern shore and a pronounced low in the central and eastern part of the lake (max. 22.8 %; Fig. 3e). These values fit within the concentration range of the inlet stream samples (25.4–40.0 %) and of the bedrock material (15.1–51.4 %; Table 1 and Fig. 3e). In the latter, feldspars occur as phenocrysts of orthoclase ($KAlSi_3O_8$) and plagioclase, mainly of oligoclase and andesine ($(Na, Ca)[Al(Si, Al)Si_2O_8]$), in both the acid and andesitic volcanic rocks (Gurov et al., 2005; Belyi, 2010).

The quartz distribution shows some similarity with the pattern of silt content (Fig. 3b), and the feldspar distribution shows a distinct similarity with the pattern of sand content (Fig. 3a). The obvious enrichments of quartz in the silt and feldspar in the coarse fraction of the sediment can be directly traced back to cryogenic weathering processes within the active layer of the permafrost in the lake surrounding, which promote this grain-size dependent accumulation (Konishchev, 1982; Schwamborn et al., 2008b).

Based on the PCA of the elemental concentrations in Lake El'gygytgyn surface sediments, three dominant element clusters can be defined implying different transport, sedimentation and post-depositional processes. Group I, with high loadings on principle component (PC) 2 and low loadings on PC1, includes Al_2O_3, Na_2O, CaO, K_2O, Ba and Sr (Fig. 5a). As illustrated in K_2O concentrations as high as 6.65 % (Fig. 6a), these elements are typically enriched close to the southern and northern shores, consistent with a similar pattern of feldspar concentrations (Fig. 3e). This composition can be linked to the amount of plagioclase and K-feldspars (Fig. 3e) originating from the surrounding acidic volcanic rocks. The dominance of acidic volcanic rocks is also indicated by the relatively homogeneous distribution of group I elements in the sediments of the inlet streams and the source rocks around the lake. Since carbonate rocks are very rare in the catchment of Lake El'gygytgyn, mostly occurring as vein fillings in the suevite below the lake sediments (Melles et al., 2011), the main sources for strontium can be attributed to Na-Ca-feldspars, replacing sodium or calcium (Cherniak and Watson, 1994), and to K-feldspars, with strontium and barium known to substitute potassium (El Bouseily and El Sokkary, 1975).

Apparently, K_2O concentrations in the inlets (4.50–8.46 %) and at the northern and southern shelves even exceed the concentrations in the source rocks (1.19–4.69 %; Fig. 6a), implying an enrichment of potassium during weathering and/or transport processes. This contradicts a higher grade of chemical weathering of the inlet stream deposits and surface sediments usually causing a depletion especially of Na, but also K and Ca (Nesbitt and Young, 1984). Furthermore, the RDA results of the element concentrations with grain-size parameters as explanatory variables show a clear correlation of the group I elements with the sand fraction (Figs. 5b and 3a). Consequently, elements of group I (e.g. K, Na, or Sr) can be used in sediment cores of Lake El'gygytgyn as an indicator for coarser grain sizes (Wennrich et al., 2012; Francke et al., 2012).

4.2 Indications for sediment sources

The results of the PCA yield a clear cluster of the elements of group II, including Cr, Cu, Zr, TiO_2, Zn, V, Ni, Fe_2O_3, Co and Cd, with high loadings of PC1 and only low negative loadings of PC2 (Fig. 5a). As visible, for instance in the distribution plot of Cr (Fig. 6b), these elements are highly enriched in the southeastern part of Lake El'gygytgyn (e.g. up to 70.3 mg kg^{-1} Cr) and along the eastern shore, whereas the other parts of the basin show relatively low concentrations (6.3–30.5 mg kg^{-1} Cr). The heterogeneous distribution in combination with high concentrations of group II elements in the bedrock samples of the southeastern crater rim (up to 104 mg kg^{-1} Cr) and of sediments from streams 48 to 50 (30.1–154.0 mg kg^{-1} Cr; Fig. 6b) suggest a bedrock source in the southeastern lake catchment. Especially Cr, Ni, Cu and Co, but also Fe_2O_3, were reported to have maximum values in the basaltic rocks (basalts, andesite-basalts) of the Koekvun' Formation (Belyi and Belaya, 1998) that pervasively outcrops along the southeastern section of the crater (Nowaczyk et al., 2002).

The RDA plot of geochemical proxies and grain-size parameters suggests a high correspondence between the group II elements and the coarse silt (16–31 µm) and, to some degree, the medium silt (7–16 µm) and total silt fraction (Fig. 5b), which is also supported by similarities in the spatial distribution patterns of silt (Fig. 2b) and Cr (Fig. 6b). This suggests an origin for the group II elements from fluvial input of "Lagerny Creek". The prevailing northward dispersion of this fluvial material (Figs. 2b and 6b) implies an anti-clockwise circulation pattern at the western lake shore, and thus suggest slightly dominant northerly winds during the ice-free period as drivers of the current circulation system.

According to down-core investigations on ICDP Site 5011-1 (Fig. 1) and pilot core PG1351 in the central part of Lake El'gygytgyn, Ti, Fe_2O_3, but also Cr and Ni typically are enriched during cold stages (Minyuk et al., 2007, 2011, 2012; Wennrich et al., 2012). These sediments are usually characterized by low coarse silt to fine sand but higher clay and fine silt contents (Francke et al., 2012). Neverthelesss, the non-ambiguous results from this study on the surface sediments suggest a particularly high sediment supply to the central lake during cold stages from the southeastern lake catchment (i.e. the Lagerny Creek).

4.3 Indicators of post-depositional processes

A third group of elements, characterized by medium negative loadings of PC1 and high negative loadings of PC2 in the PCA, is comprised of typical heavy metals, such as Pb, Mo, MnO, As, but also P_2O_5, SO_2 and Hg (Fig. 5a). With the exception of arsenic, these elements are typically enriched in the deepest part of the lake basin characterized by high clay content, and are depleted in sediments along the coarse-grained northern and southern shores (e.g. MnO; Fig. 6c). This spatial distribution coincides with the patterns of TOC and TN (Fig. 6e and f), suggesting that group III elements are partly bound to organic matter. Iron shows some similarities to the pattern of group III elements, but the signal is highly overprinted by an enhanced input of Fe-bearing minerals from southeastern inlet streams.

In the oxic surface sediments of fully-mixed Lake El'gygytgyn (Cremer et al., 2005), higher contents of group III elements are presumably linked to the occurrence of

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Fe- and Mn- hydroxides and -oxides, as magnetite (Fe_3O_4), which occur in considerable amounts of up to 6.4 % (Table 1). Carbonate phases, such as siderite ($FeCO_3$) and rhodochrosite ($MnCO_3$), play only a minor role in surface sediments (Table 1). Thus, the iron mineralogy at the sediment/water interface clearly differs from the down-core sediments, where higher Fe concentrations are linked to the diagenetic formation of vivianite ($(Fe)_3(PO_4)_2 \cdot 8\,H_2O$) under reducing pore-water conditions (Minyuk et al., 2007, 2012), with manganese incorporated as an impurity into the vivianite structure (Fagel et al., 2005).

Enhanced concentrations of heavy metals (Pb, As, Mo), but also P_2O_5, in the central basin of Lake El'gygytgyn might also be linked to the enhanced occurrence of Fe- and Mn- hydroxides and -oxides. Observations of recent sediments from Lake Baikal in SE Siberia yielded a typical enrichment of P and As in iron oxides due to adsorption and co-precipitation, whereas Mo typically accumulates with manganese oxides (Müller et al., 2002). On the other hand, phosphorous and sulfur are typical components of lacustrine organic matter (Wetzel, 2001). Molybdenum as a catalyst for nitrogen fixation in living plants is generally accumulated in plant material (Bortels, 1930), but can also be fixed to the organic matter by early diagenetic processes (Robinson et al., 1993).

4.4 Indicators of tectonic activity

Mercury is heterogeneously distributed in the recent sediments of Lake El'gygytgyn. For major parts of the lake basin, Hg values in the surface sediments do not exceed 150 $\mu g\,kg^{-1}$ (Fig. 6d) and are also positively correlated to the TOC contents ($r^2 = 0.61$; Fig. 7). A similar coincidence of Hg and TOC was also observed in surficial sediments from Lake Baikal, where mercury mainly occurs as Hg^0 absorbed onto organic matter (Gelety et al., 2005, 2007). Besides this trend, mercury in Lake El'gygytgyn shows a pronounced local maximum in the northern central lake basin, with 2 sample locations showing 4–5 times higher Hg contents (476 and 576 $\mu g\,kg^{-1}$) compared to the remaining lake sediments. Sediments from the inlet stream yield concentrations of Hg ranging between 14–1142 µg kg^{-1}, with highest values found in creeks 46 to 50 in the southeaster corner of the basin (Fig. 6d).

Although an atmospheric mercury deposition has been observed even for remote lakes (e.g., Lorey and Driscoll, 1999; Cohen, 2003), the high concentration of Hg in both the surface sediments of Lake El'gygytgyn and its tributaries implies a local Hg source. A soil gas mercury survey in the lake catchment in 2003 yielded elevated Hg values in the southeastern region of the El'gygytgyn crater. These were interpreted as tracers of tectonic activity along a NW–SE striking major boundary within the OCVB and/or a fault system associated with the Malyi-Chaun graben zone in this area (Fedorov and Kupolov, 2005). Similar fault-related mercury anomalies in soils have also been reported from the Baikal Rift Zone (Koval et al., 1999, 2006). Although recent seismic activity is reportedly low for the El'gygytgyn region (Fujita et al., 2002), minor faults mapped within the lake sediments during the seismic surveys (Niessen et al., 2007) indicate an ongoing neotectonic activity. Such fault re-activation explains well the elevated Hg values in the inlet stream sediments. Because no obvious transport process exists to explain the Hg maximum at two sites in the lake surface sediments, a tectonic origin of the mercury anomaly in the lake center cannot be excluded, even though the seismic survey did not yield any active faults in the respective lake area.

5 Conclusions

A multi-proxy approach combining sedimentological, geochemical and mineralogical analyses with statistical methods was performed on a set of 55 surface sediment samples from Lake El'gygytgyn/NE Russia. The results of this study provide a detailed understanding of the major physical and chemical processes controlling the modern sedimentation in this high Arctic crater lake.

1. The spatial distribution of mean grain-size, sand content and the concentration of group I elements (Ba, Sr, Al_2O_3, Na_2O, CaO, and K_2O) confirms the existence of

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a wind-induced two-cell current system triggering the surface-water circulation in the lake. Furthermore, mean grain-size strongly suggests transport of relatively coarse sediment from the southern shore towards the lake center as a result of the re-suspension of clay and silt-sized material during heavy storm events. High correlation of group I elements with the coarse fraction suggests that elements like sodium, calcium or strontium can be used as grain-size indicators in down-core samples of Lake El'gygytgyn.

2. Mafic-rock related elements, such as Cr, Cu, Zn, V, Ni, and Co, can be directly linked to basaltic volcanic rocks in the southeastern quadrant of the crater, implying a significant source-rock effect controlling the spatial distribution of these elements. The largely northward dispersion of the silt-sized basaltic weathering products confirms the suggestion of a two-cell surface current system with a dominating anti-clock wise circulation at the southeastern shore.

3. The distribution of MnO and heavy elements like Pb, Mo, As and Hg, but also P_2O_5 and SO_2, correlates with the organic matter content, which is generally enriched in the deepest parts of the lake basin. This correlation might be indicative of the sorption or co-precipitation of these elements with Fe and Mn hydroxides and oxides, or a fixation to organic matter in the oxic surface sediment layer.

4. Ongoing tectonic activity along a NW-SE striking fault zone in the lake catchment is indicated by variable mercury concentrations in the inlet stream deposits, being distinctly elevated in the southeastern corner of the lake catchment. A distinct Hg maximum in the lake center is not yet understood, but might point to ongoing neotectonic activity within the lake area as well.

These results are of essential importance for deciphering the climatic and environmental history of the area since 3.6 Ma from the composition of the sediments drilled on ICDP Site 5011-1 within the scope of the international El'gygytgyn Drilling Project.

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Table 1. Bulk mineralogy composition of surface sediments, inlet stream and bedrock samples of Lake El'gygytgyn. For creek numbering see Fig. 3a.

	Material	*n*	Quartz	Plagioclase	K-feldspar	Calcite	Mg-rich calcite	Dolomite	Ankerite	Siderite	Rhodocrosite	Smectites and montmor.	Mixed-layered clay minerals	Illites and micas	Kaolinite	Chlorite	Pyroxenes	Amphibols	Zeolites	Magnetite	Fe-oxides, -hydroxides	Barite
Surface sediments	Northern shelf	5	23.9	21.4	8.4	2.0	2.8	1.4	0.2	0.1	0.5	6.5	2.4	9.0	1.3	2.5	4.3	0.4	1.9	0.8	3.6	0.6
	Southern shelf	15	29.3	27.4	6.9	1.2	2.2	1.3	0.2	0.1	0.8	4.2	2.6	11.0	1.3	2.2	3.8	0.3	2.6	0.6	1.8	0.3
	Central basin	10	26.1	20.8	5.5	2.0	2.5	1.3	0.2	0.1	0.6	7.1	3.5	10.2	2.0	3.5	4.3	0.4	4.5	0.7	4.4	1.1
	South western shelf	6	28.0	24.2	6.0	1.0	2.1	1.0	0.2	0.1	0.7	5.7	3.0	12.8	3.0	3.8	3.7	0.1	4.7	0.6	1.3	0.6
Inlet streams	S and W (creeks 1–18)	11	30.3	26.7	7.0	1.8	2.6	1.6	0.4	0.1	0.6	1.9	3.0	10.6	0.6	1.7	3.7	0.5	1.7	0.7	3.6	0.4
	N (creeks 19–37)	12	28.9	26.0	7.2	2.2	2.5	2.1	0.4	0.1	0.7	2.1	2.0	6.3	0.5	1.4	4.2	0.3	5.7	0.9	5.3	0.5
	E and SE (creeks 39–50)	3	26.2	26.7	8.9	2.1	1.9	1.6	0.3	0.1	0.6	4.7	2.9	6.0	1.2	2.1	4.2	0.3	3.9	1.2	4.0	0.7
Bedrock samples	Pykarvaam Form.	5	18.5	26.1	5.2	1.6	3.2	1.2	0.3	0.1	0.7	2.8	1.9	21.7	0.6	1.1	3.4	0.2	2.7	0.7	3.1	0.5
	Koekvun Form.	1	2.9	41.9	8.7	5.8	1.2	4.2	0.1	0.3	0.4	1.7	2.7	3.4	0.3	2.5	0.3	0.1	1.9	5.2	6.6	1.1
	Ergyvaam Form.	1	26.9	26.0	10.4	1.0	2.6	2.0	0.0	0.2	0.1	1.5	1.9	5.4	4.1	9.9	4.5	0.4	8.6	0.7	0.3	0.5

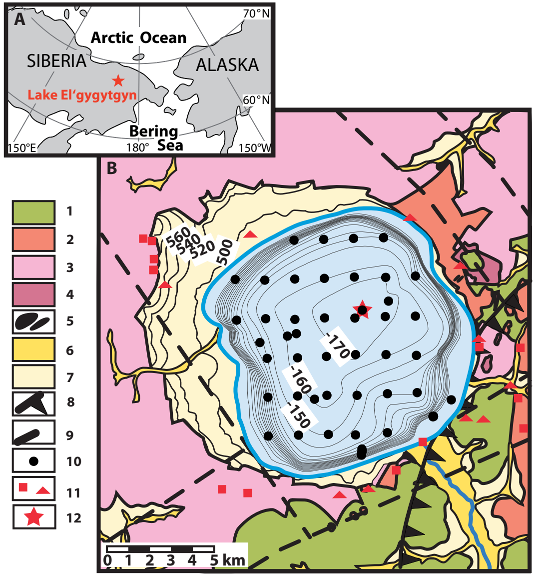

Fig. 1. (A) Map showing the location of Lake El'gygytgyn in the Western Berigian Arctic, **(B)** Geological map of the El'gygytgyn impact impact crater illustrating the major stratigraphic units (modified after Nowaczyk et al., 2002) and major fault systems (compiled after Belyi and Belaya, 1998; Belyi and Raikevich, 1994) in the lake catchment, the bathymetric contour lines in the lake (modified after Belyi, 2001), and the locations of lake floor and bedrock samples used in this study as well as of ICDP site 5011-1.; (1) Koekvun' Formation (basalt, andesite-basalt, tuff, tuff-breccia, sandstone, tuff-siltstone), (2) Ergyvaam Formation (ignimbrite, tuff), (3) Pykarvaam Formation (ignimbrite, tuff), (4) Voron'in Formation (ignimbrite, tuff), (5) Dykes, stocks, and sills of subvolcanic rocks, (6) Flood plain deposits, (7) Terrace deposits, (8) Boundary between the outer and inner OCVB zones, (9) major faults, (10) lake sediment surface samples, (11) bedrock samples (with squares refering to data from this study and triangels to data taken from Belyi and Belaya, 1998), (12) ICDP site 5011-1.

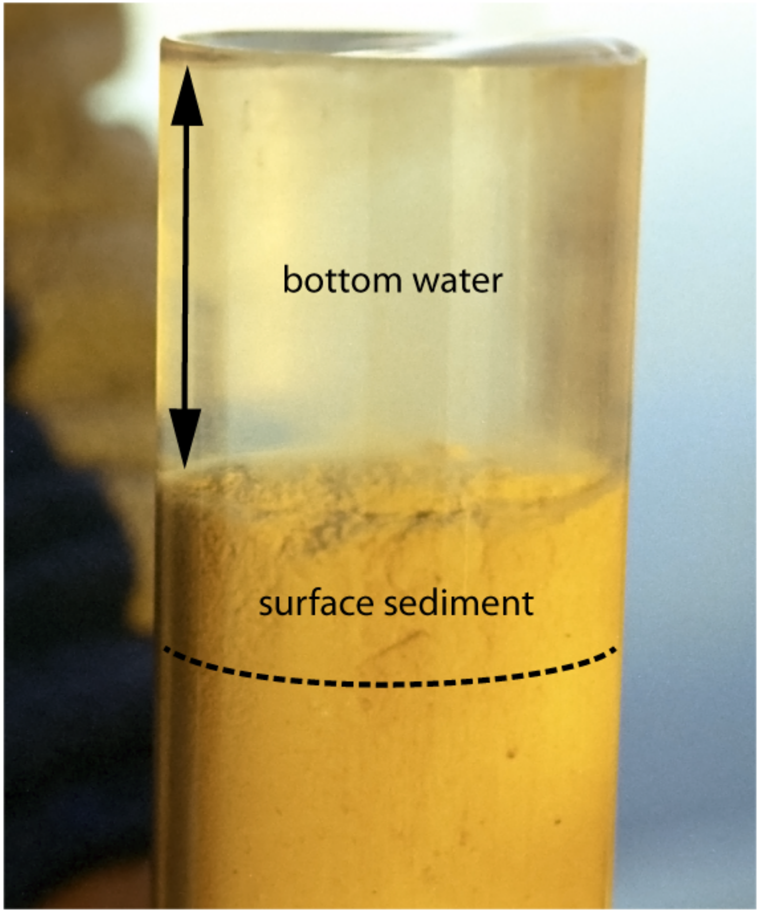

Fig. 2. Photograph of a gravity core taken near the northern shore of Lake El'gygytgyn from at water depth of 127.4 m. Surface samples comprise the uppermost 2 cm of the sediments (above the dotted line).

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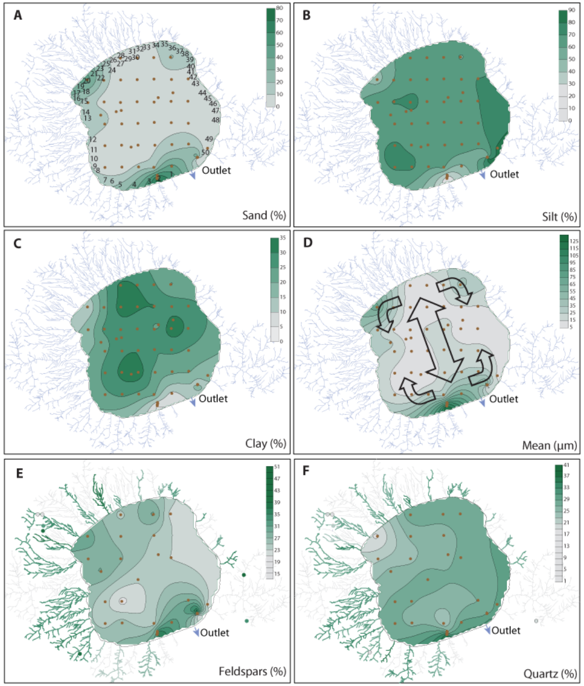

Fig. 3. Spatial distribution of volume percentages of **(A)** sand, **(B)** silt and **(C)** clay, **(D)** mean grain size, and proportions of **(E)** feldspars and **(F)** quartz in modern surface sediments (brown dots = sample location), inlet streams (coloured streams) and bedrock samples (coloured circles) of Lake El'gygytgyn. Numbers near the stream mouths in **(A)** refer to the creek numbering system of Nolan and Brigham-Grette (2007). Arrows in **(D)** indicate the near-surface circulation pattern, originated from prevailing northern and southern wind directions (modified after Nolan and Brigham-Grette, 2007). Note that data of inlet stream and bedrock samples are only available for **(E)** and **(F)**.

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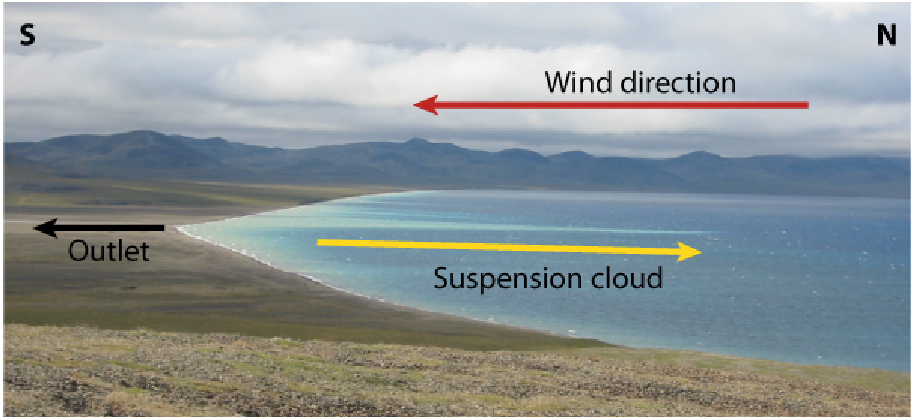

Fig. 4. Suspension cloud at the southern shelf of Lake El'gygytgyn, observed during a heavy storm with northerly winds in August 2003. View from the southeastern shore, also showing the Enmyvaam river outlet stream exiting the lake to the left (distance ca. 1.5 km).

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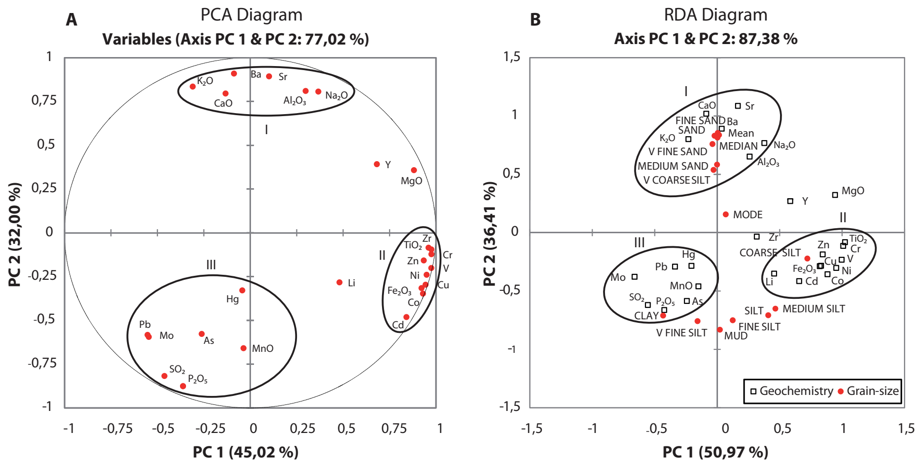

Fig. 5. Result of the **(A)** principal component analysis (PCA) of the inorganic geochemistry and **(B)** redundancy analysis (RDA) of the inorganic geochemistry and grain-size parameters (explanatory variables) in surface sediments of Lake El'gygytgyn.

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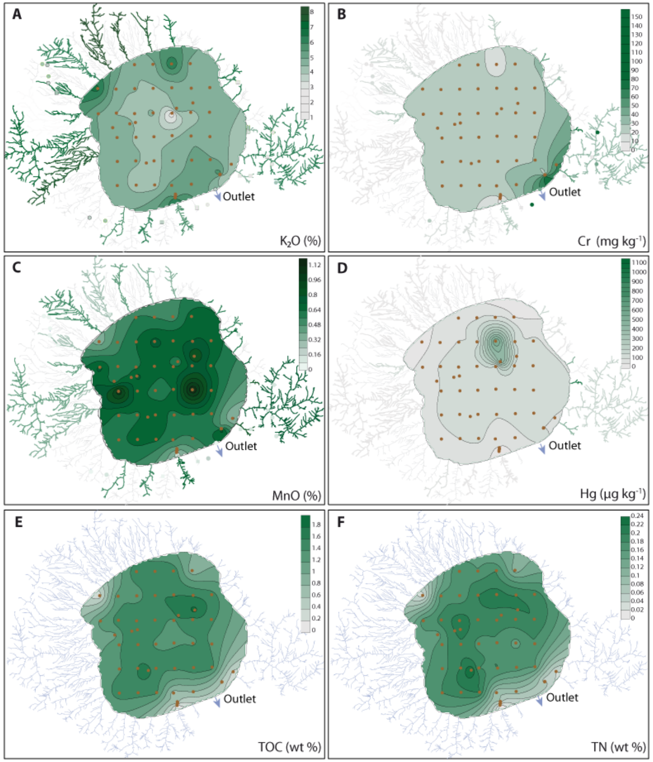

Fig. 6. Spatial distribution of concentrations of **(A)** K_2O [% wt/wt], **(B)** Cr [mg kg^{-1}], **(C)** MnO [% wt/wt], **(D)** Hg [µg kg^{-1}], **(E)** TOC [% wt/wt], and **(F)** TN [% wt/wt], in surface sediments (brown dots = sample location), inlet streams (coloured streams) and bedrock samples (coloured circles = this study; colored squares; taken from Belyi et al., 1998) of Lake El'gygytgyn. Note that no inlet stream and bedrock sample data are available for **(E)** and **(F)**.

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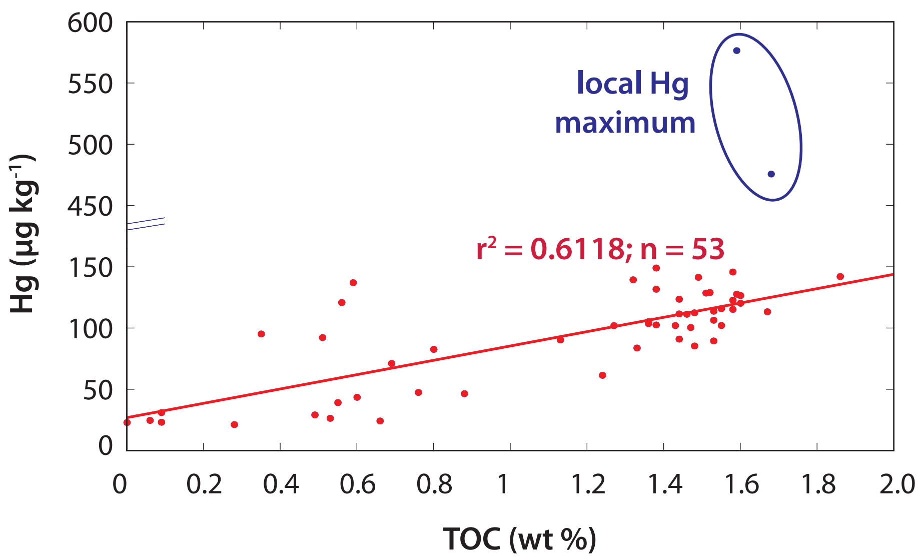

Fig. 7. Regression diagram of TOC [% wt/wt] vs. Hg [$\mu g\,kg^{-1}$] for surface sediment samples of Lake El'gygytgyn (n = 55). Linear regression line and coefficient of determination were calculated excluding the values of the local Hg maximum (> 450 $\mu g\,kg^{-1}$).