**Impact processes, permafrost dynamics, and climate and environmental variability in
the terrestrial Arctic as inferred from the unique 3.6 Myr record of Lake El'gygytgyn,
Far East Russia – a review**

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ABSTRACT

Lake El'gygytyn in Far East Russia is a 3.6 Myr old impact crater lake. Located in an area that has never been affected by Cenozoic glaciations nor dessication, the unique sediment record of the lake represents the longest continuous sediment archive of the terrestrial Arctic. The surrounding crater is the only impact structure on Earth developed in mostly acid volcanic rocks. Recent studies on the impactite, permafrost, and sediment sequences recovered within the framework of the ICDP "El'gygytyn Drilling Project" and multiple pre-site surveys yielded new insight into the bedrock origin and cratering processes as well as permafrost dynamics and the climate and environmental history of the terrestrial Arctic back to the mid-Pliocene.

Results from the impact rock section recovered during the deep drilling clearly confirm the impact genesis of the El'gygytyn crater, but indicate an only very reduced fallback impactite sequence without larger coherent melt bodies. Isotope and element data of impact melt samples indicate a F-type asteroid of mixed composition or an ordinary chondrite as the likely

1 impactor. The impact event caused a long-lasting hydrothermal activity in the crater that is
2 assumed to have persisted for c. 300 kyr.

3 Geochemical and microbial analyses of the permafrost core indicate a subaquatic formation of
4 the lower part during lake-level highstand, but a subaerial genesis of the upper part after a
5 lake-level drop after the Allerød. The isotope signal and ion compositions of ground ice is
6 overprinted by several thaw-freeze cycles due to variations in the talik underneath the lake.
7 Modelling results suggest a modern permafrost in the crater of c. 340 m, and further confirm a
8 pervasive character of the talik below Lake El'gygytgyn.

9 The lake sediment sequences shed new light into the Pliocene and Pleistocene climate and
10 environmental evolution of the Arctic. During the mid-Pliocene, significantly warmer and
11 wetter climatic conditions in western Beringia than today enabled dense boreal forests to
12 grow around Lake El'gygytgyn and, in combination with a higher nutrient flux into the lake,
13 promoted primary production. The exceptional warmth during the mid-Pliocene is in
14 accordance with other marine and terrestrial records from the Arctic and indicates a period of
15 enhanced "Arctic amplification". The favourable conditions during the mid-Pliocene were
16 repeatedly interrupted by climate deteriorations, e.g., during Marine Isotope Stage (MIS) M2,
17 when pollen data and sediment proxies indicate a major cooling and the onset of local
18 permafrost around the lake.

19 A gradual vegetation change after c. 3.0 Ma points to the onset of a long-term cooling trend
20 during the Late Pliocene that culminated in major temperature drops, first during MIS G6, and
21 later during MIS 104. These cold events coincide with the onset of an intensified Northern
22 Hemisphere (NH) glaciation and the largest extent of the Cordilleran Ice Sheet, respectively.

23 After the Pliocene/Pleistocene transition, local vegetation and primary production in Lake
24 El'gygytgyn experienced a major change from relatively uniform conditions to a high-
25 amplitude glacial-to-interglacial cyclicity that fluctuated on a dominant 41 kyr obliquity band,
26 but changed to a 100 kyr eccentricity dominance during the Middle Pleistocene transition

(MPT) at c. 1.2–0.6 Ma. Periods of exceptional warming in the Pleistocene record of Lake El'gygytyn with dense boreal forests around and peaks of primary production in the lake are assigned to so-called “super-interglacial” periods. The occurrence of these super-interglacials well corresponds to collapses of the West Antarctic Ice Sheet (WAIS) recorded in ice-free periods in the ANDRILL core, which suggests strong intrahemispheric teleconnections presumably driven by changes in the thermocline ocean circulation.

1. Introduction

Lake El'gygytyn (Fig. 1) is a crater lake in the Far East Russian Arctic that was formed by a meteorite impact 3.58 ± 0.04 Ma ago (Layer, 2000). The lake and its surrounding lack any signs of perturbation neither by Cenozoic glaciations nor by desiccation (Brigham-Grette et al., 2007; Brigham-Grette et al., 2013; Melles et al., 2012). Thus, the new record from Lake El'gygytyn and its catchment recovered within the framework of the International Continental Scientific Drilling Program (ICDP) in 2009 (Melles et al., 2011) marks a new benchmark in Arctic climate reconstruction, impact research, as well permafrost dynamics.

The El'gygytyn crater is the only impact structure currently known on Earth that was formed in mostly acid volcanic rocks (Koeberl et al., 2013). The impact origin of the crater was previously evidenced by shock metamorphic features identified in volcanic rocks from the crater rim (Gurov et al., 1978; Gurov et al., 1979a; Gurov et al., 1979b). Impact rocks in the crater have been almost completely removed by erosion. Therefore, the deep drilling at lake El'gygytyn provides the unique opportunity to study the impactites, their succession, and relations in the crater *in situ*. These results shall provide new insights into shock metamorphism in siliceous volcanic rocks (cf. Gurov et al., 2005) that can be applied, e.g., to craters on Mars. Furthermore, the El'gygytyn crater offers the planetary community information on the nature and composition of the crater-forming asteroid and the amount of energy of the impact event.

From the paleoclimate point of view, the Arctic is known to play a crucial, albeit not yet well understood, role within the global climate system (ACIA, 2004). Climate projections predict future global warming to be most pronounced in high northern latitudes (e.g., Christensen et al., 2007; Pithan and Mauritsen, 2014; Screen and Simmonds, 2010). This so-called “Arctic amplification” is traced back to an interplay of temperature, water vapour, cloud cover, Arctic Ocean sea-ice, and associated feedbacks (Miller et al., 2010; Pithan and Mauritsen, 2014; Screen and Simmonds, 2010) and is hypothesized to trigger mid-latitude climate variations (e.g., Cohen et al., 2014; Francis and Vavrus, 2012).

Nevertheless, insufficient understanding of the underlying natural variability and associated feedback mechanisms still hampers the reliability of climate projections for the Arctic (Christensen et al., 2007; Miller et al., 2010). A thorough understanding of the natural variability of past Arctic climate change on longer and shorter timescales thus forms a prerequisite for the improvement and validation of climate projections. The present knowledge of the Arctic climate and environmental evolution is widely limited to the last glacial/interglacial cycle that is well documented in the Greenland ice-cores (e.g., CAPE-Last Interglacial Project Members, 2006; NEEM community members, 2013; NGRIP members, 2004). Marine records from the Arctic basin, e.g., from the Lomonosov, Mendeleev, and Northwind Ridges (Backman and Moran, 2008, and references therein; Cronin et al., 2013; Polyak et al., 2013), may have a much longer time range, however, they often experience a limited age control or lack the required temporal resolution to investigate climate variability on glacial/interglacial or even millennial timescales. Terrestrial archives from the adjacent Arctic borderland, in contrast, are mostly limited to the postglacial due to repeated glaciations (Hubberten, 2004; Kaufman et al., 2004) or represent only short time-slices, and only a few records extend continuously beyond the last interglacial (e.g., Zech et al., 2013).

In this perspective, the sediment sequence of Lake El’gygytgyn represents the first time-continuous record of terrestrial Arctic climate change back to the time of the impact during

1 the mid-Pliocene, a period often regarded as a potential analogue for the conditions expected
2 for the end of the 21st century under persistent global warming (Brigham-Grette et al., 2013;
3 Naish et al., 2009). Due to the high susceptibility of the lacustrine sedimentation to orbitally
4 induced regional and global climate changes (e.g., Andreev et al., 2014; Brigham-Grette et al.,
5 2013; Francke et al., 2013; Melles et al., 2012; Meyer-Jacob et al., 2014; Wennrich et al.,
6 2014), this longest terrestrial archive of the Arctic provides a unique window into the
7 Pliocene/Pleistocene climatic evolution of Beringia on centennial to millennial time-scales.

8 Although earlier studies speculated the El'gygytgyn area to have been subject to permafrost
9 conditions since late Pliocene (e.g., Glushkova and Smirnov, 2007), only little is known about
10 the age of the onset and the continuity of the permafrost around the lake. Modern permafrost
11 thickness in Central Chukotka reaches about 500 m (Yershov, 1998). Permafrost dynamics,
12 slope processes, and fluvial activity are regarded as primary agents for erosion, transport, and
13 sedimentation in the lake catchment, and thus, play a crucial role for sediment delivery to the
14 lake (Schwamborn et al., 2012b). Drilling into permafrost-affected alluvial/lacustrine
15 sediments in the lake's vicinity shall shed light about the onset of the permafrost, its stability
16 and dynamics through time, as well as changes in the depth and extension of the unfrozen
17 talik underneath the lake, especially in the context of modern warming.

18 The objective of this article is to compile and review the present knowledge on the climatic
19 and environmental history of Lake El'gygytgyn and the permafrost in its surrounding as well
20 as its impact genesis. Therefore, existing information derived from pre-site surveys is merged
21 with data that more recently became available from the Lake El'gygytgyn Deep Drilling
22 Project and presented in light of other available marine and terrestrial records to draw a
23 comprehensive picture of the Arctic climate history back to the formation of the crater some
24 3.6 Ma ago.

2. Study site

Modern Lake El'gygytgyn is a 12-km wide and 170-m deep lake with a surface area of c. 110 km² (Nolan and Brigham-Grette, 2007) that fills the deepest part of the c. 18-km wide El'gygytgyn impact crater (Gurov et al., 2007). The lake is fed by a system of approximately 50 ephemeral creeks and streams that drain the 293 km² lake catchment (Nolan and Brigham-Grette, 2007) and deliver c. 0.11 km³ yr⁻¹ of water and 350 t yr⁻¹ of sediment to the lake, mainly during snowmelt (Fedorov et al., 2013). In the south, Lake El'gygytgyn discharges into its single outlet, the Enmyvaam River, which flows towards the south-east via the Anadyr River and into the Bering Sea (Nolan and Brigham-Grette, 2007). Water discharge of the Enmyvaam River is limited to the summer months and has been estimated to c. 0.05 km³ yr⁻¹ (Fedorov et al., 2013). Fluvial discharge is hypothesized to be complemented by substantial underground water runoff of c. 0.07 km³ yr⁻¹ from the lake into floodplain gravels at the southern shore (Fedorov et al., 2013). Water balance modeling yielded an estimated residence time of the lake water of c. 100 years (Fedorov et al., 2013).

Located in a region influenced by Siberian, Arctic, and North Pacific pressure systems and air-masses (Barr and Clark, 2011; Nolan et al., 2013; Mock et al., 1998; Yanase and Abe-Ouchi, 2007), the climate at Lake El'gygytgyn is assumed to be sensitive to regional and overregional atmospheric change. Generally, the local climate is cold and dry with a mean annual air temperature (MAAT) of -10.4°C and absolute winter and summer temperature extremes of -40°C and +26°C, respectively (Nolan, 2013; Nolan and Brigham-Grette, 2007). Both summer rain and winter snowfall almost equally contribute to the mean annual precipitation (PANN), with cumulative summer rainfall between 2002 and 2007 varying between 73 and 200 mm as well as 108 mm water equivalent snow determined for the winter 2001/2002 (Nolan, 2013; Nolan and Brigham-Grette, 2007).

The local atmospheric circulation is dominated by strong winds either from the north or south with hourly wind speeds that average 5.6 ms⁻¹ but can reach peak values of up to 21.0 ms⁻¹

(Nolan and Brigham-Grette, 2007). Comparative temperature data of a local weather station at the lake measured between 2002 and 2007 with NCEP/NCAR reanalysis data yielded a high correlation, and thus, confirm the local climate at the lake to well represent the regional weather patterns over western Beringia (Nolan, 2013). A synoptic climatology approach for the Lake El'gygytgyn region, applying a self-organized mapping technique, demonstrates a strong seasonality of the weather patterns at the lake resulting from changes in the strength and location of the dominant pressure cells, and thus, helps to explain potential teleconnections with surrounding areas over time (Nolan et al., 2013). During the winter season a strong Aleutian low and pressure highs over the Beaufort and Chukchi Seas are thought to bring cold Arctic air from the east and north to the lake, whereas summer weather is generally characterized by weaker low pressure systems to the north and broad high pressure systems to the south and east forcing warm Pacific air into the lake area (Nolan et al., 2013; Wilkie et al., 2013). This seasonal difference is further confirmed by a isotope study of modern water and plant samples from the El'gygytgyn basin, which points to seasonal variations in the source region of precipitation at the lake with an unaltered isotope signal from northern and eastern moisture sources during the winter and a partly recycled south-southwestern continental source signal during summer (Wilkie et al., 2013).

Lake El'gygytgyn is a typical cold-monomictic lake (Cremer and Wagner, 2003) with a seasonal ice cover from mid-October until early to mid-July (Nolan et al., 2002) resulting in a seasonal thermal stratification of the water column and partially oxygen-depleted bottom waters during the winter months (Cremer et al., 2005). Full mixing of the water body is achieved by lateral movement of warmer shore waters accompanied by strong winds after snowmelt and the initial ice break-up during summer (Nolan and Brigham-Grette, 2007). Because the lake is mainly fed by ion-depleted meltwaters, the circum-neutral to weakly acidic lake water exhibits low conductivity and cation and anion concentrations as well as a

high transparency indicating an oligotrophic or even ultra-oligotrophic character of the lake (Cremer et al., 2005; Cremer and Wagner, 2003).

The strong and persistent wind from north or south during the ice-free period is assumed to drive a two-cell circulation system in the lake (Nolan and Brigham-Grette, 2007). This assumption was approved by the composition of surface sediment samples from Lake El'gygytgyn, which reflect erosion of fine material at the SW and SE corners of the lake and transport of suspended coarse-grained material from the southern lake part to the lake centre (Nolan and Brigham-Grette, 2007; Wennrich et al., 2013).

3. Materials and methods

3.1. Pre-site surveys

In 2000 and 2003, two seismic site surveys, acquiring 3.5-kHz echo sounder data as well as single-channel and multi-channel airgun reflection seismic profiles, were carried out to investigate the architecture of the lacustrine sediment infill (Gebhardt et al., 2013; Niessen et al., 2007). The seismic survey yielded a well-stratified lake sediment succession intercalated with frequent mass movement deposits (MMD) in the proximal part (Gebhardt et al., 2013; Fig. 2). A complementary refraction seismic survey suggests a five-layer model of the lake sediments down to 320-330 m depth below lake floor (mblf) underlain by impact breccia and brecciated bedrock, with the latter exhibiting a central ring structure in analogy to other terrestrial and lunar impact structures (Gebhardt et al., 2006).

To evaluate the potential of the Lake El'gygytgyn sediments as a far-ranging climate archive, two 12.91 and 16.60 m long pilot cores, PG1351 and Lz1024, were recovered in 1998 and 2003, respectively. Coring was conducted in the central part of the lake at 175 m water depth (Figs. 1, 2) using a gravity and piston corer system (UWITEC Ltd., Austria) from the ice cover (Melles et al., 2005; Melles et al., 2007; Melles et al., 2011). The chronology of these sediment cores is based upon a combination of radiocarbon dating, infrared and optical

1 stimulated luminescence (IRSL, OSL), and a subsequent tuning to the NH summer insolation,
2 yielding basal ages of c. 300 ka (Nowaczyk et al., 2002) and 252 ka (Nowaczyk et al., 2007)
3 for PG1351 and c. 300 ka for Lz1024 (Juschus et al., 2007), which were recently corrected to
4 275 ka and 350 ka for PG1351 and Lz1024, respectively (Frank et al., 2013; Nowaczyk et al.,
5 2013).

6 3.2. The ICDP El'gygytgyn Drilling Project

7 Within the framework of the ICDP El'gygytgyn Drilling Project, two sites were drilled in
8 autumn 2008 and spring 2009 in the western lake catchment (5011-3) and in the lake center
9 (5011-1), respectively (Figs. 1, 2). Drilling at site 5011-3 was performed by a local drilling
10 company (Chaun Mining Corp., Pevek) using a Russian mining rotary drill rig (SIF-650M).
11 One borehole was drilled into the frozen alluvial and lacustrine deposits down to a depth of
12 141.5 m with 91% recovery (Melles et al., 2011; Schwamborn et al., 2012a). Afterwards the
13 borehole was instrumented with a ground temperature monitoring system to provide data for
14 the “Global Terrestrial Network for Permafrost” (GTN-P) of the International Permafrost
15 Association (Melles et al., 2011; Mottaghy et al., 2013).

16 At site 5011-1, the drilling operation was conducted by the U.S. consortium DOSECC
17 using a modified GLAD 800 drilling system (Russian GLAD 800) from the artificially
18 thickened lake-ice cover (Melles et al., 2011). Overlapping holes, 1A, 1B, and 1C, were
19 drilled to depths of 147, 112, and 517 mblf, respectively (Fig. 3), with hole 1C reaching the
20 base of the lacustrine sediments at 316 mblf and penetrating c. 200 m deep into the impact
21 breccia and the underlain brecciated bedrock (Brigham-Grette et al., 2013; Melles et al., 2011;
22 Melles et al., 2012). The core recovery of holes 1A and 1B was 92 and 98%, respectively. The
23 recovery in hole 1C was much lower, reaching only 52% in the lacustrine sediments and 78%
24 in the impact rocks (Melles et al., 2011).

25 A composite profile of the three holes 1A, 1B, and 1C of site 5011-1 (Fig. 3) was compiled
26 based on initial logging data and a layer-by-layer correlation of overlapping core sections

during the initial visual description of the sediments, which also comprised the occurrence of prominent MMD (Sauerbrey et al., 2013), tephra layers (van den Bogaard et al., 2014), and fossil redox layers (Wennrich et al., 2014). The upper 5.67 m of the composite profile not recovered by the ICDP drill cores at site 5011-1 were subsequently complemented with data of pilot core Lz1024 from the same location (Fig. 3). For the subsampling and data presentation of the pelagic sediment record of Lake El'gygytgyn event layers, such as volcanic ash layers and distinct MMD with thicknesses exceeding 5 cm were omitted.

4 Outcomes

4.1 Dating results

The age of the El'gygytgyn impact was previously dated by $^{40}\text{Ar}/^{39}\text{Ar}$ on impact-melted rocks derived from the crater rim to 3.58 ± 0.04 Ma ago (Layer, 2000). This age is confirmed by paleomagnetic data measured on impact breccia and bedrock material recovered from hole 5011-1C that yielded a predominantly normal polarity of the characteristic remanent magnetization (ChRM; Maharaj et al., 2013). This implies the impact happened after the Gauss/Gilbert reversal that is dated to 3.596 (Ogg and Smith, 2004) or 3.588 Ma (Lisiecki and Raymo, 2005; Nowaczyk et al., 2013).

The chronology of the lacustrine sediment records is primarily based on the magnetostratigraphy of sediment sequence of site 5011-1 (Brigham-Grette et al., 2013; Haltia and Nowaczyk, 2014; Melles et al., 2012; Nowaczyk et al., 2013). Paleomagnetic measurements on U-channels and discrete samples from holes 1A, 1B, and 1C yielded distinct down-core variations in inclination of the ChRM that could be addressed to three polarity chronos (Gauss, Matuyama, Brunhes), five subchrones (Jaramillo, Olduvai, Réunion, Kaena, Mamooth), as well as to the Cobb Mountain cryptochron and the Intra-Jaramillo and Olduvai precursor excursion (Haltia and Nowaczyk, 2014; Fig. 4A). Published ages of the geomagnetic reversals and the given age of the impact were used as first order tie points for

1 an initial age-depth model of the core composite of site 5011-1 (Haltia and Nowaczyk, 2014;
2 Nowaczyk et al., 2013; Fig. 4A).

3 An iterative tuning approach was subsequently applied to further refine the age-depth model
4 (Nowaczyk et al., 2013). In the first step, tuning of a combination of the XRF scanning
5 derived Si/Ti ratios and Ti contents, the colour hue angles, and the biogenic silica (BSi)
6 contents obtained from Fourier transform infrared spectroscopy (FTIRS) to the global marine
7 isotope stack LR04 (Lisiecki and Raymo, 2005) provided second order tie points. Third order
8 tie points were obtained from the correlation of variations in the total organic carbon (TOC)
9 contents and the magnetic susceptibility (MS) to the cumulative 65°N summer (May to
10 August) insolation (Laskar et al., 2004). The final age-depth model of the sediment record of
11 Lake El'gygytgyn is based on altogether more than 600 anchor points (Nowaczyk et al., 2013;
12 Fig. 4A).

13 In the upper part of the record, the age-depth model is basically confirmed by the results
14 of several IRSL and OSL studies (Forman et al., 2007; Juschus et al., 2007; Zander and
15 Hilgers, 2013; Fig. 4B). Earlier studies on the pilot cores PG1351 (Forman et al., 2007) and
16 Lz1024 (Juschus et al., 2007) using a multiple aliquot additive dose IRSL protocol and a
17 single aliquot regeneration dose (SAR)-IRSL protocol, respectively, on polymineral fine grain
18 samples have shown the potential of the Lake El'gygytgyn sediments for luminescence
19 dating. By applying multiple OSL and IRSL protocols (SAR-OSL, SAR TT-OSL, SAR-
20 IRSL₅₀, post-IR IRSL (pIRIR₂₉₀)) for quartz and polymineral fine grains (4-11 µm grain size
21 range) to sub-samples from the same depths, Zander and Hilgers (2013) conducted a
22 feasibility study to date sediments older than 200 ka by luminescence techniques. Their
23 results clearly indicate the pIRIR₂₉₀ protocol to be the only protocol yielding increasing ages
24 with depth down to the B/M boundary that matches the ages derived by the proxy-data based
25 age model (Fig. 4B). The other tested protocols, in contrast, failed or underestimated the time
26 frame.

1 A tephrochronological/tephrostratigraphic approach comprised the eight macroscopically
2 visible volcanic ash layers (T0-T7) that have been found in the last c. 2.2 Myr of the Lake
3 El'gygytgyn sediment record (Ponomareva et al., 2013; van den Bogaard et al., 2014). The
4 geochemistry of the tephra layers is highly variable with glass compositions varying from
5 basaltic andesitic to rhyolitic. Based on their major-, minor-, trace-element, and Pb isotope
6 composition, the ash horizons are attributed to a subduction-zone-related volcanism, with
7 volcanic centers on the Kamchatka Peninsula being the most likely sources for T0-T5 and T7,
8 but a likely Alaskan-Aleutian Arc source of T6 (van den Bogaard et al., 2014). Of the eight
9 tephra layers identified in the Lake El'gygytgyn sediment record, only ash layer T1 was over-
10 regionally correlated, and thus, could be used as tephrochronological tie point (van den
11 Bogaard et al., 2014; Fig. 4B). Based on the geochemical composition of glass shards, T1
12 corresponds to the ~177 ka old Raucha tephra found on the East Siberian Sea coast and in
13 marine sediments of the Bering Sea and the NW Pacific (Dullo et al., 2009; Ponomareva et
14 al., 2013). Its source is hypothesized to be the Karymsky volcanic center on the Kamchatka
15 Peninsula located >1600 km distant from Lake El'gygytgyn.

16 In contrast to the lake sediment sequence, the succession of the permafrost hole 5011-3
17 currently lacks reliable absolute datings, and thus, the chronology of the sequence is mainly
18 based on palynological results. The pollen spectra of the uppermost 9 m of core 5011-3
19 (Andreev et al., 2012) yielded a resemblance to the Allerød to late Holocene succession of
20 well-dated cores from the lake and its vicinity (Andreev et al., 2012; Lozhkin et al., 2007b;
21 Matrosova, 2009). Unfortunately, except for one horizon between 19.8 and 19.3 m, which has
22 been palynologically assigned to an interglacial with some similarities to the MIS 7
23 succession in the lake record (Lozhkin et al., 2007a; Matrosova, 2009), the pollen content of
24 the lower core section of hole 5011-3 is only sparse or barren in pollen (Andreev et al., 2012).

4.2 Origin of bedrock

Bedrock in the El'gygytgyn area consists of Late Cretaceous volcanic rocks of the Okhotsk-Chukchi Volcanic Belt (OCVB; Gurov et al., 2007). The suite of volcanic rocks comprises basalts, basaltic andesites, andesites, rhyodacitic and rhyolitic ignimbrites as well as andesitic-dacitic, basaltic-andesitic, and rhyodacitic tuffs associated to the Pykarvaam, Voron'in, Koekvun', and Ergyvaam Formations of the Chaun Group (Gurov et al., 2005; Pittarello et al., 2013; Raschke et al., 2014; Fig. 5). These volcanic rocks were formed during the Cretaceous and are dated to c. 80-90 Ma (Belyi and Raikevich, 1994; Kelley et al., 1999; Stone et al., 2009).

The volcanic suites surrounding the crater are characterized by a complex network of faults with a dominating system of short impact-related radial faults that occur up to 2.7 crater radii in distance (Gurov and Gurova, 1983), few concentric faults, and NW-SE and NE-SW striking extensional lineaments, partly of pre-impact origin (Gurov et al., 2007; Raschke et al., 2014). Minor faults in the lake sediment infill of the crater, revealed from the seismic survey (Gebhardt et al., 2013; Niessen et al., 2007), abnormally elevated mercury contents recorded in the soil air along the southeastern catchment lake shore (Fedorov and Kupolov, 2005), as well as mercury anomalies in inlet stream sediments (Wennrich et al., 2013) point to an ongoing tectonic activity in the lake area, presumably along a NW-SE striking major boundary within the OCVB and/or a fault system along the southern lake shore that is linked to the Malyi-Chaun graben zone.

The bedrock at the base of the hole 5011-1C that formed the target of the impact mainly consists of felsic volcanics, and thus, mirrors the composition of the upper c. 250 m bedrock in the lake vicinity (Gurov and Gurova, 1991; Raschke et al., 2015; Wittmann et al., 2013). The lower bedrock unit in the drill core (517.09-420.89 mblf) is a brittly deformed, rather homogeneous unit of greenish welded trachyrhyodacitic ignimbrite that partly can be considered a cataclasite (cf. Koeberl et al., 2013; Pittarello and Koeberl, 2013b; Raschke et

1 al., 2013a; Fig. 6). The ignimbrite is intersected by numerous veins filled with volcanic ash
2 that are interpreted as fracture injections in the paleo-surface (Raschke et al., 2013b). The
3 lower bedrock shows only minor evidences of shock metamorphism. The upper bedrock unit
4 from c. 420 to 390 mblf represents a sequence of different volcanic rocks with a rhyodacitic
5 composition in the lower part (420.27-391.79 mblf) overlain by a basaltic part (391.79-390.74
6 mblf).

7 This (parautochthonous) basement unit is only very weakly affected by the impact: only
8 one shocked quartz grain with two sets of planar deformation features (PDFs) was recorded at
9 391.33 mblf. Over the whole length of the impactite core, the abundance of shock features
10 rapidly increases to the top. Although numerical modelling experiments inferred the bedrock
11 at the drill site, which is located c. 2.3 km away from the impact centre, experienced peak
12 shock pressures of up to 16 GPa (Collins et al., 2008), the low abundance of shock features
13 rather implies the bedrock in the drill cores were originally located outside the 5-10 GPa
14 isobar and subsequently placed in the crater center during crater modification (Wittmann et
15 al., 2013).

16 The geochemical abundance patterns and isotopic (Nd and Hf) compositions of the target
17 rocks and the drill core samples from the El'gygytgyn crater reveal similarities to the
18 "Berlozhya magmatic assemblage" (BMA), arguing for similar source magmas (Pittarello et
19 al., 2013). The primitive upper mantle (PUM)-normalized trace element plot of rocks
20 investigated in the project confirms a subduction-related signature as previously proposed for
21 rocks from both OCVB and BMA (Pittarello et al., 2013). The major and trace element
22 abundances as well as Hf and Nd isotopic compositions of the drill core rocks are best
23 explained as a cogenetic volcanic suite, which fits into the overall Andean-type subduction-
24 related geodynamic setting proposed earlier (e.g., Tikhomirov et al., 2008). Furthermore, Hf
25 and Nd isotope data might support scenarios involving melting-assimilation-storage-
26 homogenization (MASH)-type processes at deep crustal levels, leading to the measured near-

1 chondritic and rather uniform ϵHf and ϵNd values of +3.0 to +4.8 and -0.2 to -1.2,
2 respectively, for rocks from the El'gygytgyn area (c.f. Pittarello et al., 2013) and from other
3 locations. Notably, drill core suevites and ignimbrites isotopically match the trend defined by
4 the BMA and felsic pyroclastic rocks outcropping in the eastern part of the central Chukotka
5 segment of the OCVB. The common geochemical and isotopic features of drill core and BMA
6 rocks might argue for similar source magmas.

7 8 4.3 Impact scenario 9

10 During the crater-forming impact event at c. 3.58 Ma (Layer, 2000) an impactor hit the
11 mainly Cretaceous target rocks. Although the projectile vaporized during the impact, slight
12 enrichments in the abundances of some siderophile elements, as well as chromium and
13 osmium isotopic ratios of impactite samples and glass spherules from the drill and the crater
14 rim, indicate a small meteoritic contribution in the impact melt rocks (Gurov and Koeberl,
15 2004; Goderis et al., 2013; Foriel et al., 2013; Pittarello et al., 2013; Raschke et al., 2015;
16 Wittmann et al., 2013). The Cr isotopic composition of an impact glass sample yielded a non-
17 terrestrial value within the range of ureilite values and, within analytical error, of eucrites and
18 ordinary chondrites (Foriel et al., 2013). Given the chemical signatures found in previous
19 analyses of El'gygytgyn impactites and the similarity of the Cr isotopic data to ureilites, the
20 results suggest that the impacting asteroid could have been a F-type asteroid of mixed
21 composition, similar to the recent Almahata Sitta fall in Sudan. This confirmed interpretations
22 of Valter et al. (1982) on the basis of siderophile elements of glassy melt bombs. However,
23 Os isotopic ratios and platinum group element (PGE) abundance patterns of spherule samples
24 on top of the impactite sequence, which presumably represents fallback material, rather point
25 to a chondritic impactor (Goderis et al., 2013).

26 The impact created a transient cavity of >4 km depth in the Cretaceous target rock that
27 subsequently collapsed within minutes to the estimated final crater depth of c. 900 m during

1 crater modification (Collins et al., 2008; Gurov et al., 2007). Reflection and refraction seismic
2 data indicate the presence of a central ring structure (Gebhardt et al., 2006) as a relict of an
3 initial central uplift structure with a peak height of c. 1 km, that subsequently collapsed
4 (Collins et al., 2008; Wittmann et al., 2013). The collapse of the ejecta plume, and
5 simultaneous vertical movements due to the crater modification, as well as the development
6 and collapse of the central uplift, are interpreted to have caused chaotic ground-surfing in the
7 young crater (Wittmann et al., 2013). Surge-related mixing and dilution of highly shocked
8 fallback material with unshocked lithic components is documented in a c. 75-m thick impact
9 breccia sequence (390.74-316.08 mblf) overlying the target rock in the hole 5011-1C (c.f.
10 Koeberl et al., 2013; Pittarello and Koeberl, 2013b; Raschke et al., 2013a; Figs. 3, 6). The
11 basal breccia unit (390.74-328.00 mblf) represents a polymict lithic impact breccia with
12 volcanic and impact melt clasts in a fine-grained matrix. Based on the occurrence of relatively
13 rare, mm- and sub-mm-sized impact melt particles that exhibit considerable evidence of shock
14 deformation, such as planar fractures and PDFs in included minerals (Pittarello et al., 2013;
15 Raschke et al., 2013b), this breccia was classified as suevite. The impact origin of the breccia
16 is furthermore indicated by the occurrence of three several cm-sized clasts with shatter cones
17 (Raschke et al., 2013a; Fig. 6).

18 In the absence of shock evidence, impact melt clasts are almost indistinguishable from
19 unshocked volcanic clasts that originates from the target rocks, and thus, the differentiation
20 required further analytical methods. A first approach successfully applied semi-automatic
21 image analysis techniques to reproducibly distinguish grains of unshocked target rock and
22 drill core samples from melt clasts by their abundance, size distribution, elongation, shape,
23 and preferred orientation (Pittarello and Koeberl, 2013a). Results of another approach using
24 cathodoluminescence (CL) indicate that CL might provide a useful tool for detecting impact
25 melt fragments in the suevite (Pittarello et al., 2015).

1 The upper breccia unit from (328.00-316.77 mblf) consists of a transitional zone of partly
2 reworked impact breccias and fine-grained, sandy lacustrine sediments with first mesoscopic
3 clasts of shocked target rocks (Koeberl et al., 2013; Pittarello and Koeberl, 2013b; Raschke et
4 al., 2013a; Figs. 6, 7). Volcanic clasts in this reworked suevite section show all stages of
5 shock metamorphism, up to melting. Within this transitional zone, only the uppermost 4 m
6 contain numerous glass spherules that have been interpreted to originate from reworking of
7 spherule-rich fallout deposits from the distal crater and/or central uplift (Raschke et al.,
8 2013a; Wittmann et al., 2013). The reduced thickness of the fallback impactite sequence may
9 be explained by the location of the drill core on an elevated part of the central uplift, whereas
10 thickness of the fallback succession is postulated to gradual increase towards the annular
11 moats (Gebhardt et al., 2006; Fig. 2). In contrast to the similarly sized Bosumtwi impact
12 crater, Ghana (Koeberl et al., 2007), larger coherent melt bodies are lacking in the impact
13 breccia of El'gygytgyn.

14 Post-impact hydrothermal activity in the cooling impact crater caused intensive bedrock
15 alteration (Raschke et al., 2013b; Raschke et al., 2014; Raschke et al., 2015). Although
16 surface rocks exhibit no significant traces of weathering and alteration (Gurov and Koeberl,
17 2004; Raschke et al., 2014), hydrothermal overprint is especially significant in the removal of
18 Na and an extreme enrichment of V, Cr, and Ni the upper bedrock and in mafic blocks in the
19 suevite (Raschke et al., 2013b; Raschke et al., 2014). Alteration features within the strongly
20 altered suevite section and brecciated volcanic bedrock include secondary calcite and zeolites
21 as vein fillings and a highly oxidized suevite matrix (Raschke et al., 2013a; Raschke et al.,
22 2013b). Calcite is a common mineral in impact-induced hydrothermal systems and usually
23 marks the late phase of the mineralization formed at temperatures <100°C in a liquid-
24 dominated fluid environment (Kirsimäe and Osinski, 2012; Naumov, 2005). Hydrothermal
25 batch alteration experiments of impact melt glass from core 5011-1 and volcanic glass yielded
26 the formation of various silica phases such as cristobalite, opal, and quartz, (Hellevang et al.,

2013). Zeolites that are predicted by numeric modelling experiments also occur, but might be masked by zeolites in the target rocks. The results of batch alteration and modelling experiments enabled to draw conclusions on closed-system alteration processes below the surface of Mars (Hellevang et al., 2013).

Long-lasting hydrothermal activity in the El'gygytgyn crater is indicated by calcite-cemented sediments and findings of zeoliths in the basal lake sediment, and might also explain exceptional high peaks of uranium and the total natural gamma radiation at c. 3.4 and 3.45 Ma (Gebhardt et al., 2013; Fig. 8). The latter is likely caused by hydrothermal remobilization of progenetic uranium deposits as known i.e. from the Ternovka (Ukraine), Carswell (Canada), and Vredefort (South Africa) impact structures (Pirajno, 2009). Elevated calcite contents visible in high Ca values until c. 3.25 Ma (Meyer-Jacobs et al., 2014; Wennrich et al., 2014; Fig. 8) would imply that the hydrothermal activity has sustained for more than 300 kyr. A similar long-lasting hydrothermal phase that has proceeded several 100 kyr after the impact was just recently postulated for the Ries impact crater, Germany, a crater of comparable size to the El'gygytgyn crater (Arp et al., 2013).

4.4 Lacustrine depositional environment

4.4.1 Pelagic sediment facies

The pelagic sediments of the Lake El'gygytgyn record are mainly clastic dominated and highly variable in composition, with the five different lithofacies (facies A through E, Figs. 8, 10, 11, 12) being assigned to specific depositional conditions. Whereas sediments of facies B and C are abundant throughout the entire record, the occurrences of facies A and D are exclusively restricted to the Pleistocene and Pliocene core sections, respectively (Brigham-Grette et al., 2013; Melles et al., 2007; Melles et al., 2012), and sediments of facies E are characteristic for the transition to the impact-altered bedrock (Gebhardt et al., 2013).

1 Laminated sediments of alternating dark grey to black silt and clay horizons (facies A) are
2 hypothesized to represent peak glacial periods during the Pleistocene, with anoxic bottom
3 water conditions due to multi-year lake-ice coverage that has prevented bioturbation (Melles
4 et al., 2007; Melles et al., 2012). Modeling experiments have estimated a mean annual air
5 temperature threshold of $3.3 \pm 0.9^\circ\text{C}$ and $5.5 \pm 1.0^\circ\text{C}$ lower than today for the formation of a
6 perennial ice-cover and for the complete elimination of oxygen exchange with the
7 atmosphere, respectively, but a temperature reduction of only $1\text{--}3^\circ\text{C}$ required to maintain
8 multi-year ice cover (Nolan, 2013). Anoxic bottom and pore-water conditions with only
9 limited decomposition of the mainly aquatic derived organic matter (Holland et al., 2013) are
10 indicated by pronounced minima in the E_h and pH dependent Mn/Fe ratio and MS as well as
11 elevated TOC contents (Melles et al., 2012; Minyuk et al., 2014; Nowaczyk et al., 2002;
12 Wennrich et al., 2014). Although the carbon-preference index based on *n*-alkanes gives some
13 indication for decreased organic matter biodegradation during peak glacials (D'Anjou et al.,
14 2013), no clear biogeochemical evidence for anoxic conditions has yet been found (Holland et
15 al., 2013). Under the postulated reducing conditions, the syn/post-depositional formation of
16 vivianite ($\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$) and to a lower extend siderite (FeCO_3) and rhodochrosite
17 (MnCO_3) is promoted in the Lake El'gygytgyn sediments (Minyuk et al., 2013; Murdock et
18 al., 2013; Nowaczyk et al., 2002). The formation of vivianite in glacial sediments is indicated
19 by elevated phosphorous concentrations and confirmed by electron-microprobe analyses by
20 single nodules (Minyuk et al., 2014). The perennial ice cover during peak glacials effectively
21 diminished the sediment influx into the lake, which was mainly restricted to seasonal moats
22 and vertical conduits through the ice, and the subsequent lake-internal sediment distribution
23 by currents (Francke et al., 2013; Nolan, 2013; Wennrich et al., 2014). Peak glacial sediments
24 are thus enriched in fine-grained, mainly clay-sized clastic material, as visible e.g., in maxima
25 of Ti and Fe in the record (Minyuk et al., 2011; Minyuk et al., 2014; Minyuk et al., 2007;

Wennrich et al., 2014) that are interpreted to display a higher contribution of Ti and Fe-bearing chlorite (Minyuk et al., 2013).

Based on variations in the chemical composition and the occurrence of sediment clasts, the laminated silt and clay of facies A can be further sub-divided into two subfacies (Gebhardt et al., 2013), which have been interpreted to represent cold and dry (subfacies A_d) and cold and moist conditions (subfacies A_m), respectively (Melles et al., 2007; Fig. 9). Whereas light penetration through the lake ice is thought to have enabled limited phytoplankton production during subfacies A_d, thick snow coverage on the lake ice during the later subfacies effectively hampered bioproduction in the lake (Melles et al., 2011).

The majority of the sediments in contrast, is mainly composed of olive-grey to brownish silt (facies B) exhibiting a massive to faintly banded texture (Melles et al., 2011; Figs. 8, 9, 11, 12). The silt of facies B accounts for from glacial to interstadial as well as interglacial periods with only seasonal ice coverage at the lake similar to the modern conditions (Melles et al., 2007). The massive homogenous texture is traced back to minor bioturbation that is enabled by a complete mixing of the water body, and thus elevated oxygen contents down to the lake floor due to a semi-permanent ice cover (Melles et al., 2007).

Although, very similar in visible sediment texture and colour, interglacial and interstadial/glacial sediments attributed to facies B exhibit remarkable differences in the geochemical composition and grain-size distribution. Interglacial periods are generally marked by an enhanced aquatic primary production visible in elevated BSi contents, Si/Ti ratios, and diatom concentrations (Cherapanova et al., 2007; Melles et al., 2012; Meyer-Jacob et al., 2014; Snyder et al., 2013; Figs. 8, 11, 12). Primary production is promoted by a higher light availability due to a longer open-water season, expanded diversity in habitats in the lake and its catchment, and a higher nutrient flux into the lake (Snyder et al., 2013; Vogel et al., 2013). The latter is primarily triggered by an accelerated weathering in the catchment as a result of a thicker active layer of the permafrost in the lake surroundings. Similar to modern

1 conditions, warming of shore waters due to seasonal ice break-up is assumed to have caused
2 full mixing of the water column down to the lake floor (Nolan and Brigham-Grette, 2007). As
3 a result, the majority of the organic matter produced in the photic zone is decayed (Melles et
4 al., 2007).

5 Enhanced cryogenic weathering due to repeated thaw-freeze cycles in the active layer are also
6 displayed in the higher feldspar to quartz ratio in the coarse fraction of interglacial sediments
7 at the lake centre (Schwamborn et al., 2012b; Schwamborn et al., *subm.*, this issue; Wennrich
8 et al., 2013). Expanded open-water conditions during summer enabled the initiation of a
9 wind-driven current system that is thought to bring a higher flux of coarser material from the
10 shallow shelf into the central lake basin via vertical currents or bottom flows (Francke et al.,
11 2013; Wennrich et al., 2013). Grain-size analyses of interglacial sediments indicate an
12 additional contribution of fine material that is dominated by smectite and illite as typical
13 weathering products in soils under warm and/or hydrolyzing conditions (Asikainen et al.,
14 2007; Francke et al., 2013).

15 During colder periods, i.e. glacials and stadials, in contrast, lacustrine bioproduction is
16 hampered by lower temperatures, a lack of nutrients in the lake water, and a prolonged ice-
17 cover on the lake, which resulted in a shorter growing season (Holland et al., 2013; Melles et
18 al., 2012). Reduced bioproduction as compared to interglacials is clearly indicated by lower
19 BSi contents and Si/Ti ratios, whereas low TOC contents are additionally biased by an almost
20 complete organic matter decomposition due to summer-time mixing of the water column
21 (Melles et al., 2007). The shorter duration of open-water conditions also limited the sediment
22 influx into the lake and caused a reduction in the activity of the wind-driven current system,
23 thus leading to an enrichment in fine-grained clastic material (Francke et al., 2013).

24 The reddish brown colour of the sediments of facies C and their elevated Mn/Fe ratios are
25 thought to imply a deposition under well-oxygenated bottom waters conditions. Nevertheless,
26 the fine-layered texture with distinct laminae <5 mm (Fig. 9) points to a limited bioturbation

1 of the sediment, presumably due to winter stratification (Melles et al., 2012). The occurrence
2 of the reddish-brown laminated silt often coincides with periods of high regional summer
3 insolation and low oxygen isotope values in the global stack (Figs. 8, 11, 12), suggesting
4 warmer than modern conditions during peak interglacial periods (Melles et al., 2012). Dark
5 organic-rich layers with elevated TOC values within the reddish-brown laminated silt indicate
6 the warmer conditions have promoted maximum primary production with an only incomplete
7 organic matter decay. This is obvious in extraordinary high BSi contents and accumulation
8 rates, Si/Ti ratios >0.8 , peaks in diatom concentration and diversity, and highest dinosterol
9 concentrations as a molecular biomarker for dinoflagellates (D'Anjou et al., 2013; Melles et
10 al., 2012; Meyer-Jacob et al., 2014; Snyder et al., 2013; Vogel et al., 2013; Figs. 8, 11, 12).
11 The boost in autochthonous influx significantly diluted the clastic signal in the lake sediments
12 causing distinct minima in MS and clastic-bound elements, like Ti or K (Minyuk et al., 2014;
13 Nowaczyk et al., 2013; Wennrich et al., 2014).

14 A cluster analysis approach of proxy data including magnetic susceptibility (MS), S-ratio,
15 BSi, TOC, TiO_2 and the element-based chemical index of alteration (CIA) measured on
16 sediments of the last 340 ka (Lz1024) generally confirmed and refined the lithological
17 discrimination of the three Pleistocene facies with two subfacies (Frank et al., 2013).
18 Furthermore, the results of this study indicate two additional transitional modes that were
19 assigned to the early stages of a cold phase and slightly colder conditions during a warm
20 phase. Sensitivity tests reveal the obvious changes in the sediment colour from more greenish
21 in the laminated silt and clay (facies A), to more reddish in the massive silt (facies B) and
22 laminated reddish-brown silt (facies C) to be mainly driven by variations in the organic matter
23 content and the enhanced iron oxide formation in the lake catchment during warmer and
24 wetter intervals (Wei et al., 2014).

25 In the Pliocene core section, laminated sediments of alternating grey to reddish-brown silt
26 to clay (facies D) are abundant (Brigham-Grette et al., 2013; Fig. 9). The preservation of the

laminated texture points to a lack of bioturbation or physical disturbance at the sediment surface due to bottom-water currents. In contrast to the alternating silt and clay horizons of facies A, the preservation of the primary fine-layered texture of the Pliocene laminites (facies D) is rather addressed to sediment pulses to the lake as a result of a variable fluvial input and stream competency than to a perennial lake ice-cover (Brigham-Grette et al., 2013). Elevated Ca and TIC contents in the Pliocene sediments point to the formation and deposition of calcite (CaCO_3) that was also confirmed by FTIRS (Meyer-Jacob et al., 2014; Wennrich et al., 2014; Fig. 8). Observations of calcite-cemented sediment lenses in the lower core section imply a formation of the calcite by post-depositional precipitation from the pore-water rather than biologically-induced precipitation in the upper water-column (Wennrich et al., 2014). Because modern Lake El'gygytgyn waters are typically undersaturated in most cations and anions (Cremer et al., 2005), the calcite formation point to a much higher flux of both Ca^{2+} and CO_3^{2-} ions in the early lake history. The higher ion flux, especially of Ca^{2+} , can presumably be traced back to intense chemical weathering in the catchment due to warmer and moister climate conditions and ongoing hydrothermal activity in the young crater (Brigham-Grette et al., 2013; Wennrich et al., 2014).

At the base of the lacustrine succession, alternating beds of grey to reddish-brown clay, silt, and fine sand with intermittent brecciated intervals are included in facies E (Brigham-Grette et al., 2013; Gebhardt et al., 2013; Fig. 9). Angular shaped clasts in the brecciated sections are interpreted to be formed by dewatering processes or point to brief intervals of desiccation. These sediments mark the transition to the underlying impact rocks, and thus, the onset of the lacustrine sedimentation in the young impact crater (Brigham-Grette et al., 2013).

Beyond the pelagic sediments, the Lake El'gygytgyn sediment record contains numerous MMD that account for 32.5 and 33.1% of the Pliocene and Pleistocene composite record, respectively (Juschus et al., 2009; Sauerbrey et al., 2013; Fig. 4A). Sauerbrey et al. (2013) differentiate five types of MMD - turbidites, grain-flow deposits, debrites, slumps, and slides

1 - of which turbidites are the most common in the lake center. All these MMD types are
2 interpreted to be co-generic deposits of transitional mass-flow processes initially induced by a
3 slope failure, which, in turn, are thought to have been triggered by tectonic activity, lake-level
4 changes, delta collapses, and/or sediment overloading at the slopes (Sauerbrey et al., 2013).

6 4.4.2 Shallow-water and near-shore facies

7 In contrast to the deep-water sediments from the central part of the lake basin, shallow-
8 water deposits recovered in the permafrost core at site 5011-3, several pilot cores from the
9 southern and western lake margin, and exposed lake terraces give a very heterogeneous nature
10 of the near-shore sedimentation. The sediments of the permafrost 141.5-m long core mainly
11 consist of matrix-supported sandy gravel intercalated with gravel and sand layers of variable
12 thickness (Schwamborn et al., 2012a; Figs. 10). Whereas the remaining sediments are almost
13 organic-free, elevated organic contents in the uppermost 2 m of the core are traced back to
14 reworked plant detritus incorporated into the sediments by slope and soil mixing in the
15 modern or ancient active layer (Schwamborn et al., 2012a). Few sand layers in the sediment
16 succession are interpreted to be formed during lake-level highstands when paleo-shoreline
17 spread beyond the coring site 5011-3. Based on their sedimentological characteristics, the
18 sediment succession at the western slope of the El'gygytgyn crater is interpreted as
19 prograding delta or alluvial fan deposits that extend into the lake (Schwamborn et al., 2012a),
20 thus explaining the frequent occurrence of MMD in the lake sediment record (Juschus et al.,
21 2009; Sauerbrey et al., 2013).

22 As evident in prominent exposed lake terraces and paleo-shorelines at 35-40 m, 9-11 m,
23 and 3-5 m above and 10 m below the modern lake level identified by geomorphological
24 studies, Lake El'gygytgyn has experienced several severe lake-level changes in its history
25 (Glushkova and Smirnov, 2007; Juschus et al., 2011; Schwamborn et al., 2008; Schwamborn
26 et al., 2006). Further lake terraces 60 and 80 m above the modern lake level have also been

1 hypothesized (Gurov et al., 2007; Nekrasov, 1963), but their lacustrine origin has not yet been
2 finally confirmed (Glushkova and Smirnov, 2005; Juschus et al., 2011).

3 The age of the highest terraces (35-40 m) is rather speculative but it is assumed to have been
4 formed during the mid-Pleistocene (Glushkova and Smirnov, 2007). The formation of the
5 terrace might be isochronous to deep-water sediments of unit IV at the base of a core
6 (Lz1028) from the -10 m terrace (Juschus et al., 2011). The deposition of these fine-grained
7 deep-water sediments suggests a much higher lake level than today that has been IRSL dated
8 to a minimum age of 185 ka BP (Juschus et al., 2011). Pollen assemblages in these deep-
9 water sediments assign this interval to a final phase of an interglacial prior to MIS 5
10 (Raschke, 2015, pers. comm.). The observation of *Cyclotella* as the dominant planktonic
11 diatom genus in this horizon further suggests an age less than 1.2 Myr by correlation to the
12 deep core.

13 The deep-water sediments are erosively overlain by a sediment unit radiocarbon dated to >40
14 cal kyrs BP indicating medium water depth, which is hypothesized to be formed during
15 another lake-level highstand after a significant low-level phase with intensive erosion
16 (Juschus et al., 2011). Juschus et al. (2011) suggested a possible correlation of the medium
17 water sediments to the formation of the 9-11 m terrace widespread on the south bank of Lake
18 El'gygytgyn. Based on comparative pollen data, Glushkova and Smirnov (2007) interpreted
19 the 9-11 m terrace to be formed from the second half of the Kargin interstadial until the
20 Sartan stadial (25–12.5 cal kyrs BP), corresponding to MIS 3 to 2. A recent reinterpretation of
21 the pollen results of the 9-11 m terrace combined with new pIRIR₂₉₀ data, however, rather
22 indicate a terrace formation during MIS 5 to 3.

23 Coarse-grained sediments just below and an intensive erosion at sites above the -10 m terrace
24 at the southern shelf, respectively, document a lake-level of approx. 10 m lower than the
25 modern with near-beach conditions at the modern shelf edge at about 14 cal kyrs BP,
26 presumably during the final stage of significant lake-level drop that partly eroded older

1 sediments (Juschus et al., 2011). The timing of this lake-level drop is still unclear, but might
2 be indicated by a changes in the periphyton diatom assemblage during MIS 2 between 30 and
3 20 ka (Snyder et al., 2013).

4 After the lake-level lowstand until 14 cal kyrs BP, ancient shoreline deposits up to 4 m above
5 the modern lake level that have been dated to <13 cal kyrs BP suggest a rapid lake-level rise
6 during the Late Pleistocene and Early Holocene (Schwamborn et al., 2008). Radiocarbon
7 dates of alluvial terraces in the Enmyvaam River and 2–3 m high shore bars at the southern
8 and southeastern shore indicate that the higher lake level has lasted until the early to mid
9 Holocene, but has experienced a gentle drop to the modern level after 5 cal kyrs BP
10 (Glushkova and Smirnov, 2007; Schwamborn et al., 2006).

12 4.5 Permafrost dynamics

13 The 141.5-m long permafrost record recovered at site 5011-3 shed light on the permafrost
14 history and dynamics of the El'gygytgyn region (Mottaghy et al., 2013; Schwamborn et al.,
15 2014). The complex permafrost history on the western slope of the El'gygytgyn crater was
16 reconstructed on the basis of isotope and hydrochemical data of the ground ice at site 5011-3
17 that appears as structureless pore ice, ground-ice crusts, ice inclusions, or ice veins
18 (Schwamborn et al., 2012a; Schwamborn et al., 2014; Fig. 10). Whereas the results of the
19 uppermost 9.1 m exhibit a clear paleo-precipitation signal, the ground-ice composition and
20 isotope signature of the older part of the record reveal a post-depositional overprinting by at
21 least three cycles of thawing and refreezing. Due to the proximity of the coring site to the
22 modern lake shore, Schwamborn et al. (2014) hypothesized these thaw-freeze cycles to be
23 controlled by a repeated shoreward expansion of the talik during lake-level highstands (e.g.,
24 during the Allerød, Figs. 10) and a basinward migration of the freezing front during lake-level
25 lowstands (e.g., during the Last Glacial Maximum, LGM). Microbial permafrost communities
26 extracted from the core yielded only a small microbial signal in the lower core section, but

1 high abundances of *Bacteria* and *Archaea* biomarkers starting after the late Allerød and
2 especially during the Holocene (Bischoff et al., 2014). This change is interpreted to confirm a
3 predominantly subaquatic deposition of the lower core section, but subaerial conditions after a
4 lake-level decrease after the late Allerød with subsequent pedogenesis and methane formation
5 at the coring site during the Holocene (Bischoff et al., 2014).

6 With a comprehensive numerical modeling approach of the thermal field in the El'gygytgyn
7 crater based on temperature monitoring data of the site 5011-3 (Figs. 10) and downhole
8 logging data of site 5011-1 in the lake center, Mottaghy et al. (2013) derived constraints on
9 the depth of the modern permafrost in the lake vicinity and of the talik underneath the lake
10 today and in the past. The results of transient simulation runs, which have been proven to best
11 reflect the modern temperature condition, suggest a modern permafrost depth at site 5011-3 of
12 c. 340 m. Variations in the measured temperature profile are likely triggered by past surface
13 temperature changes (Mottaghy et al., 2013). Simulations of the permafrost conditions during
14 the LGM and the early Holocene yielded much higher permafrost thicknesses of 475 and 415
15 m, respectively. Moreover, the modeling results confirm a pervasive character of the talik
16 below Lake El'gygytgyn (Mottaghy et al., 2013).

17 The permafrost onset in the lake vicinity is postulated to have taken place during the late
18 Pliocene (Glushkova and Smirnov, 2007). Unfortunately, the permafrost core 5011-3 does not
19 provide information on the early permafrost history. Nevertheless, palynological,
20 geochemical, and mineralogical data from the lacustrine sediment record of site 5011-1
21 indicate an initial permafrost formation in the region already at c. 3.4 to 3.3 Ma (Brigham-
22 Grette et al., 2013; Schwamborn et al., *subm.*, this issue; Wennrich et al., 2014). This implies
23 the permafrost onset to be linked to the most pronounced global cooling of the mid-Pliocene
24 during MIS M2.

5. Palaeoenvironmental development and palaeoclimatic relevance of Lake El'gygytgyn

Investigations of the sediments from the lake and the permafrost in the lake surrounding have shown that Lake El'gygytgyn contains a unique archive of the environmental and climatic history of the Arctic since mid-Pliocene time. We compile the available data of the different studies on the El'gygytgyn records to draw a comprehensive picture of local environmental changes from the Pliocene warmth into the pronounced glacial/interglacial cycles of the Pleistocene and try to link the results to published regional and global-scale changes.

5.1. Mid to Late Pliocene warmth

After the initial crater-forming impact at c. 3.58 Ma and the subsequent onset of lacustrine conditions in the crater, the early history of Lake El'gygytgyn is thought to be primarily characterized by a high flux of clastic material into the basin. This influx is indicated by elevated values of proxies for clastic input, like K_s , and a sedimentation rate during the first approx. 20 kyr that was ten-fold higher than afterwards (Nowaczyk et al., 2013; Wennrich et al., 2014; Fig. 8). Higher annual precipitation of c. 600 mm/yr and the assumed lack of permafrost during this interval (Brigham-Grette et al., 2013; Tarasov et al., 2013) are hypothesized to have amplified an intensive erosion of the steep slopes of the young crater. The lack of any pollen and diatom remains in these initial lake sediments illustrates a significant vegetation loss due to the impact, and implies rather extreme conditions in the lake, presumably due to an ongoing hydrothermal activity in the crater (Andreev et al., 2014; Brigham-Grette et al., 2013).

Pollen occur in the sediments deposited after c. 3.575 Ma. Their composition suggests that during the mid-Pliocene warmth (3.58- 3.35 Ma) the region was predominantly covered by spruce-larch-fir-hemlock forests with other boreal and temperate taxa indicating 7 to 8°C warmer temperatures of the warmest month (MTWM) and c. 400 mm higher PANN in the

1 Beringian Arctic (Andreev et al., 2014; Fig. 8; Brigham-Grette et al., 2013; Tarasov et al.,
2 2013). This observation confirms recent reports of mid-Pliocene warmth in the terrestrial
3 Arctic, e.g., from the Beaver Pond site in the Strathcona Fjord in Arctic Canada (Ballantyne et
4 al., 2010; Rybczynski et al., 2013), which assume MAAT values even 18 to 19 °C warmer
5 than today. Furthermore, boreal forests during this time are reported to have extended to the
6 coast of the Arctic Ocean (AO; Schweger et al., 2011), and North Atlantic sea-surface
7 temperatures (SST) were about 7°C warmer than today (Lawrence et al., 2009). This
8 exceptional mid-Pliocene warming of the Arctic (ΔT : $+12\pm 3^\circ\text{C}$) by far exceeds the global
9 average warming of $4\pm 2^\circ\text{C}$ during that time (Miller et al., 2010), thus clearly pointing to an
10 “Arctic amplification” (e.g., Miller et al., 2010; Pithan and Mauritsen, 2014; Screen and
11 Simmonds, 2010). According to modelling experiments, the mid-Pliocene warming in the
12 terrestrial Arctic was mainly amplified by a loss in sea ice on the AO and subsequent
13 intensified warming of the adjacent continental interiors by the advection of water vapor from
14 the sea surface (Ballantyne et al., 2013). Contemporaneously, significant warming probably
15 has also occurred in the Ross Sea Embayment, Antarctica, as deduced from proxies for
16 persistent open-water conditions (McKay et al., 2012). A reduced latitudinal temperature
17 gradient during the mid-Pliocene (e.g., Dowsett et al., 1996; Hill, 2015) suggests the warmth
18 especially involved the polar regions.

19 The favourable climate during the mid-Pliocene lead to intense weathering in the
20 catchment and thus to a high nutrient availability in the lake water. In combination with well-
21 oxygenated bottom-water conditions, as inferred from high Mn/Fe ratios, this environment
22 resulted in a high seasonal primary production, which is reflected by high BSi accumulation
23 rates (Fig. 8) and larger planktonic diatom frustules during the interval 3.58- 3.35 Ma
24 (Brigham-Grette et al., 2013; Meyer-Jacob et al., 2014; Wennrich et al., 2014).

25 As mentioned before, the hydrothermal activity in the lake vicinity that was generated by
26 the impact probably lasted more than 300 kyr after the impact event (Wennrich et al., 2014;

Fig. 8), as suggested by a persistently high degree of chemical weathering in the lake catchment that is reflected by higher calcite contents and Ca values in the sediments deposited prior to c. 3.25 Ma.

After c. 3.35 Ma dark coniferous forests with *Pinus* (pine), *Picea* (spruce), and *Abies* (fir) were gradually replaced by more open cold deciduous forests as a result of decreasing summer temperatures and precipitation (Andreev et al., 2014; Tarasov et al., 2013; Fig. 8). This long-term trend was overprinted by a harsh environmental change to colder conditions during the MIS M2 event (c. 3.31–3.28 Ma; Fig. 8), when treeless tundra- and steppe-like habitats dominated the lake area for the first time (Andreev et al., 2014). Findings of large amounts of coprophilous fungi in the Lake El'gygytgyn sediments indirectly point to the presence of large grazing animals, thus confirming widespread open habitats around the lake during MIS M2 (Andreev et al., 2014). Statistical analyses of the pollen results prior and after the M2 event indicate a change from relatively thermophilic (*Tsuga*, *Abies*, *Picea*) to more cold-adapted coniferous taxa (*Larix*) around Lake El'gygytgyn, which was traced back to the onset of permafrost conditions in the region (Brigham-Grette et al., 2013). The latter is supported by cryogenic weathering features on quartz grains in the Lake El'gygytgyn sediment record, which suggest permafrost-related freeze-thaw weathering at c. 3.4–3.3 Ma (Schwamborn et al., subm., this issue). Furthermore, a distinct decrease in calcite contents at c. 3.25 Ma, slightly postdating the M2 event (Wennrich et al., 2014; Fig. 8), may point to a substantial impact of the permafrost onset on lacustrine and/or post-depositional processes. However, the disappearance of calcite could also be due to the final cessation of hydrothermal activity in the crater, which may have had a severe and sustained impact on the weathering condition in the lake catchment, leading to a slow-down of chemical weathering processes (Wennrich et al., 2014). The simultaneous drop of clastic sediment flux into the lake, reflected in decreasing sedimentation rates (Fig. 8) as well as a reduced MMD frequency and turbidite

1 thickness after 3.3 Ma (Sauerbrey et al., 2013), points to a persistent stabilization of the
2 catchment area.

3 The M2 cold event marks the most pronounced cooling of the mid-Pliocene. Detrital Nd
4 isotope values, C_{37:4} alkenone data, and the first appearance of sea-ice indicating microfossils
5 in the sediments from the Bering Sea at c. 3.3 Ma suggest intense ice-sheet growth in Alaska
6 during the MIS M2, which has caused higher influx of meltwater that resulted in a freshening
7 and an intensive sea-ice expansion in the Bering Sea (Horikawa et al., 2015). The subsequent
8 inflow of low-salinity Bering-Sea water into the AO is speculated to have strengthened the
9 AO halocline and pertubated the fresh-water balance in the North Atlantic, and thus, could
10 have caused a substantial subarctic cooling through ice-albedo feedbacks (Horikawa et al.,
11 2015). The global character of the M2 cooling is strongly indicated by its identification in
12 both Northern and Southern Hemisphere marine and terrestrial records, e.g., from the North
13 Atlantic, Lake Baikal, and the Ross Sea (De Schepper et al., 2009; Demske et al., 2002;
14 Lawrence et al., 2009; Naish et al., 2009).

15 After the M2 cooling, a vegetation change to dominant larch-pine forests suggests an
16 overall climate amelioration during the late mid-Pliocene (Andreev et al., 2014), with
17 temperature reconstructions yielding at least 8°C higher mean temperatures of the warmest
18 month (MTWM) than today (Brigham-Grette et al., 2013; Fig. 8). The protracted warm and
19 moist climate promoted a high bioproduction in Lake El'gygytgyn until after 3.0 Ma, as
20 suggested by high Si/Ti ratios and BSi accumulation rates (Fig. 8), accompanied by elevated
21 TOC values (Brigham-Grette et al., 2013; Meyer-Jacob et al., 2014; Wennrich et al., 2014).

22 Even higher July temperature anomalies of +10° to +11°C compared to today are inferred
23 from plant fossils and beetle remains at Meighen Island, Canada, dated to 3.0 Ma (Elias and
24 Matthews Jr, 2002). Boreal forests are known to have stretched from 60° to 80°N (Matthews
25 and Telka, 1997), thus indicating persistent Pliocene warmth over the Arctic. Climate-
26 vegetation-ice sheet simulations of the interval 3.26 to 3.02 Ma were performed within the

PRISM project (Dowsett et al., 2010). Assuming 300 and 400 ppm atmospheric CO₂, they show the Greenland Ice Sheet (GIS) to be diminished to smaller ice caps on high elevations during both cold and warm boreal summer orbits (Brigham-Grette et al., 2013; Koenig et al., 2011).

In the following, pollen data suggest the late Pliocene warmth to have repeatedly been interrupted by colder and drier intervals, when open landscapes expanded around Lake El'gygytgyn, presumably as a consequence of a drop in winter temperatures after 3.25 Ma (Brigham-Grette et al., 2013; Tarasov et al., 2013). These climate deteriorations also hampered the primary production in the lake as indicated by a gradual decrease in Si/Ti (Fig. 8) and an increase in clastic elements after MIS KM2 (3.150-3.119 Ma; Lisiecki and Raymo, 2005). Since 3.02 Ma, pollen-based temperature reconstructions indicate summer temperatures commenced a stepwise cool trend (Brigham-Grette et al., 2013; Fig. 8).

5.2. Transition to icehouse world

The interval between 2.8 and 1.5 Ma is marked by significant changes in the regional climate system and vegetation around Lake El'gygytgyn linked to the onset and intensification of NH glaciation. From c. 2.735 Ma onwards the boreal forest composition around the lake tend to change gradually, first with the loss of temperate and later boreal evergreen conifers (Andreev et al., 2014; Brigham-Grette et al., 2013; Tarasov et al., 2013). The progressive trend culminated in the absence of *Pinus* and *Picea* between 2.71 and 2.695 Ma, corresponding to MIS G6 (Andreev et al., subm., this issue; Fig. 8). Climate reconstructions yielded a significant drop in precipitation and winter temperatures around Lake El'gygytgyn at c. 2.73 Ma, whereas summer temperatures remained at a rather constant level of 1 to 3°C warmer than today even during pronounced glacial periods (Brigham-Grette et al., 2013; Tarasov et al., 2013; Fig. 8). This winter cooling coincided with an intensification of NH glaciation since MIS G6 (e.g., De Schepper et al., 2014, and references therein; Duk-

Rodkin and Barendregt, 2011; Flesche Kleiven et al., 2002; Matthiessen et al., 2009, and references therein) that is hypothesized to have been triggered by a winter SST cooling and the onset of subarctic stratification in the Northern Pacific (Haug et al., 2005). Persistent high summer temperatures that even extended into autumn, as also suggested for the Subarctic Pacific, are thought to have provided the moisture, mainly as snow, required to initiate the major glaciation in North America (Haug et al., 2005). The asynchronous trend in winter and summer temperatures in Beringia and the Northern Pacific also illustrate the stepwise rather than abrupt character of the NH cooling during the late Pliocene and early Pleistocene (Brierley and Fedorov, 2010; Herbert et al., 2010; Lawrence et al., 2009).

The Pliocene/Pleistocene transition, which is effectively synchronous to the Gauss/Matuyama magnetic Chron boundary at 2.588 Ma (Cohen and Gibbard, 2011; Fig. 8), is manifested in the Lake El'gygytgyn record in a major cooling during the transition from MIS 104 to 103. This cooling is deduced from an expansion of treeless and shrubby environments and the first occurrence of cold steppe habitats around the lake at the end of MIS 104 (Andreev et al., *subm.*, this issue). The synchronous first occurrence of finely laminated dark silt and clay (facies A) in the Lake El'gygytgyn record during MIS 104 (Fig. 8) further points to a substantial cooling, since it requests the formation of a multi-year ice cover on the lake (Melles et al., 2007; Melles et al., 2012; Nolan, 2013).

Substantial cooling at c. 2.6 Ma, combined with the onset of aridity, is also inferred from the pollen record of Lake Baikal (Demske et al., 2002). Furthermore, numerous records indicate a major ice-sheet expansion especially over North America (e.g., Bailey et al., 2013), for instance glaciofluvial gravels from the Klondike region, NW Canada, which got dated by cosmogenic nuclides to $2.64^{+0.20}_{-0.18}$ Ma (Hidy et al., 2013). Marine records from the North Atlantic imply that the NH cooling at the Pliocene/Pleistocene transitions was mainly associated with a drop in early spring SST and a resulting increase in seasonality that culminated during MIS 104 (Hennissen et al., 2015). All this indicates that the Lake

1 El'gygytyn cooling during MIS 104 is no regional climatic phenomenon but of overregional
2 to hemispheric nature.

3 During the Pliocene/Pleistocene transition, steppe- and tundra-like habitats with shrubs and
4 herbs became more widespread in the Lake El'gygytyn region and replaced forested habitats
5 as a result of a stepwise cooling at 2.6, 2.56, and 2.53 Ma (Andreev et al., 2014; Brigham-
6 Grette et al., 2013; Figs. 8). Contemporaneous dryer conditions in the early Pleistocene are
7 derived from an increasing number of peaks in green algae colonies (*Botryococcus*), which
8 are indicative of expansions of shallow-water environments in the lake catchment due to lake-
9 level drops (Andreev et al., subm., this issue; Andreev et al., 2014; Zhao et al., 2015).
10 Simultaneously, most geochemical proxies for clastic influx, redox-conditions, or primary
11 production in the Lake El'gygytyn record, like Ti, Mn/Fe, TOC, and Si/Ti, exhibit a shift to
12 high-amplitude variations since the earliest Pleistocene (Figs. 8, 11, 12). This variability
13 suggests that internal lake and catchment processes have experienced a major transition from
14 relatively uniform conditions during the Pliocene to a pronounced glacial-to-interglacial
15 cyclicity during the early Pleistocene (Wennrich et al., 2014).

16 After c. 2.3 Ma, the Lake El'gygytyn record is characterized by the progressive
17 appearance of dark laminated silt and clay (facies A), while the redox-dependent Mn/Fe ratio
18 and MS show a gradual baseline-level drop and TOC experiences more abundant maxima
19 (Figs. 11, 12). These trends point to an increase in the frequency and intensity of pervasive
20 peak glacial episodes, which are characterized by reduced bottom-water conditions in the lake
21 (Melles et al., 2012; Wennrich et al., 2014). At c. 1.8 Ma, knickpoints in the Mn/Fe and MS
22 records (Fig. 11) suggest the establishment of full glacial/interglacial frequencies (Melles et
23 al., 2012). Contemporaneously, a widespread glaciation with accelerated glacial erosion is
24 recorded in the coastal mountains of British Columbia, Canada (Shuster et al., 2005). Major
25 changes also took place in the paleoceanography of the Pacific Ocean. For instance, in
26 sediments from the central Bering Sea, a drop in the opal accumulation and an increase in MS

recorded at c. 1.8 Ma are hypothesized to have been caused by a shift in the water mass exchange with the North Pacific (Kim et al., in press; März et al., 2013), while results of diatom studies at the Bering slope point to a synchronous major cooling and a sea-ice expansion (Teraishi et al., in press). A similar SST cooling of 4-5°C in the subarctic North Pacific, which lasted until c. 1.2 Ma, was linked to the onset of the Equatorial Pacific cold tongue (Martínez-García et al., 2010).

5.3 Super-interglacials

The overall pattern of glacial/interglacial cycles during the Pleistocene is interrupted by the exceptional warm interglacials MIS 93, 91, 77, 55, 31, and 11c at c. 2.38, 2.34, 2.03, 1.60, 1.07 Ma, and 420 ka, respectively. During these periods the dominance of coniferous taxa (Figs. 11, 12) with higher abundances of *Picea* and *Pinus* (probably originating from tree pine species) and *Larix* points to an extensive cover of dark boreal evergreen conifer in the lake region (Andreev et al., 2014; Lozhkin and Anderson, 2013; Melles et al., 2012; Tarasov et al., 2013). Pollen-based climate reconstructions yielded much higher summer temperatures and annual precipitation during these so-called “super-interglacials”. For two of these super-interglacials, MIS 31 and 11c, the warmest and wettest conditions in the entire Pleistocene record of Lake El’gygytyn have been inferred, reaching 4 to 5°C higher MTWM and c. 300 mm higher PANN compared to the Holocene thermal maximum (Melles et al., 2012; Tarasov et al., 2013; Fig 13). These data are confirmed by the results of recent high-resolution biomarker-based temperature reconstructions of MIS 31 sediments from Lake El’gygytyn (de Wet et al., 2016). Furthermore, the biomarker data indicate that exceptional warmth prevailed in the Beringian Arctic for c. 50 kyr and covers the entire period between MIS 33 and 31 (c. 1.114-1.062 Ma), with MIS 32 having the character of a stadial rather than a glacial.

1 The exceptional warmth during the super-interglacials had a significant impact on the
2 lacustrine sedimentation in Lake El'gygytgyn. Dense forest cover in the catchment
3 presumably caused a more intense chemical weathering and/or soil formation in the lake
4 catchment, and thus, enhanced nutrient flux into the lake as suggested by the occurrence of
5 specific planktonic taxa in the diatom record (Snyder et al., 2013; Vogel et al., 2013). As
6 already mentioned, the combination of a longer growing season due to a shorter seasonal
7 lake-ice cover and higher nutrient flux strongly amplified the lacustrine productivity, as seen
8 e.g., in BSi, Si/Ti and dinosterol maxima (D'Anjou et al., 2013; Melles et al., 2012; Meyer-
9 Jacob et al., 2014; Snyder et al., 2013; Vogel et al., 2013; Figs. 11, 12).

10 Other records of super-interglacials in the Arctic, especially during the early Pleistocene, are
11 sparse and/or poorly dated. One or more of the early Pleistocene super-interglacials recorded
12 at Lake El'gygytgyn might be correlative to the c. 2.4 Ma old Kap København Formation,
13 Northern Greenland. These deposits document a strong sea-ice reduction and a shift of the
14 treeline c. 1000 km northward than today to the coast of the AO (Funder et al., 2001). The
15 Fishcreekian transgression of the Plio/Pleistocene Gubik Formation, northern Alaska
16 (Goodfriend et al., 1996) and terrestrial deposits at Fosheim Dome on Ellesmere Island dated
17 to c. 1.1 Ma (Elias and Matthews Jr, 2002) are assumed to correlate to MIS 31. For the latter,
18 beetle-based temperature reconstructions imply summer and winter temperature anomalies of
19 8° and 13°C above modern values.

20 More is known about the latest super-interglacial MIS 11c. Recent studies on sediment cores
21 from the Mendeleev and Northwind Ridges clearly show an extreme warming during MIS 11
22 also in the central AO, with summer SST 8 to 10°C higher than today and significantly
23 reduced sea-ice (Cronin et al., 2013; Polyak et al., 2013). Isotope-based provenance and
24 pollen investigations on marine sediments of the Eirik Drift (de Vernal and Hillaire-Marcel,
25 2008; Reyes et al., 2014) and DNA analyses of basal ice of the Dye 3 ice core (Willerslev et
26 al., 2007) suggest an almost complete deglaciation of South Greenland and the spread of

1 boreal forests during MIS 11. Modeling studies estimated a complete loss of the GIS during
2 MIS 11 equivalent to a sea-level rise of 4.5 to 6 m (Reyes et al., 2014). Findings of
3 exceptional warm conditions in the records of Lake Baikal, South Siberia (Prokopenko et al.,
4 2010) and Lake Biwa, Japan (Tarasov et al., 2011) suggest that the MIS 11 warming was of
5 global rather than of regional importance.

6 The extreme Arctic warmth at Lake El'gygytyn during several of these super-interglacials
7 coincides remarkably with phases of ice-free conditions in the Ross Embayment, Antarctica
8 as deduced from diatomite layers in the ANDRILL 1B record, which are interpreted to
9 display major retreats or even collapses of the WAIS (McKay et al., 2009; McKay et al.,
10 2012; Naish et al., 2009; Fig. 13).

11 The driving mechanisms for these exceptional warm conditions during the super-interglacials
12 are not yet fully understood. For some of these periods, like MIS 31, the exceptional warming
13 can potentially be explained by elevated greenhouse-gas levels (e.g., DeConto et al., 2012).
14 For others, e.g., MIS 11c, in contrast, orbital and greenhouse-gas forcing have been shown to
15 only contribute in a minor way (Melles et al., 2012). Nevertheless, the synchrony of extreme
16 Arctic warming documented in the Lake El'gygytyn record and WAIS retreats points to
17 strong intra-hemispheric teleconnections, and thus, imply changes in the paleoceanographic
18 configuration and its influence on the thermocline circulation. A postulated potential
19 perturbation of the thermocline circulation due to a diminished Antarctic Bottom Water
20 (AABW) formation and injection into the South Pacific (Foldvik et al., 2004; Hall et al.,
21 2001) could have caused a reduced upwelling, and thus, a warming in the northern North
22 Pacific (Galbraith et al., 2007). A similar mechanism has been reported for the super-
23 interglacials MIS 31 and 11c (Haug et al., 1995; Jaccard et al., 2005; Melles et al., 2012).
24 Strong climate ocean-land teleconnections (Nolan et al., 2013) might have subsequently
25 transferred the North Pacific heat to the Beringian landmass. Alternatively, a higher global
26 sea-level, e.g., of c. 6 to 13 m above modern as estimated for late MIS 11 (Raymo and

Mitrovica, 2012), due to the postulated collapse and/or retreat of the WAIS and GIS, could have resulted in an increased warm-water influx into the AO via the Bering Strait. Such an increased inflow of warmer Pacific waters into the AO via the Bering Strait with a severe sea-ice reduction has also been interpreted from exceptional ostracod and foraminifera assemblages in the central AO during MIS 11 (Cronin et al., 2013; Polyak et al., 2013). Comparable to the postulated mid-Pliocene conditions, warmer water masses and reduced sea-ice in the AO could have even amplified the warming through subsequent feedbacks, thus leading to an exceptional warming of the adjacent landmasses (e.g., Serreze et al., 2009; Woodgate et al., 2010). This indicates the super-interglacials during the Pleistocene can be taken as perfect examples of ancient “Arctic amplification“. However, modeling results indicate that even an extreme increase in Bering Strait throughflow of +3 Sv (equivalent to a additional 8 Wm^{-2} of ocean heat convergence under sea ice) would only partly explain the exceptional warm temperatures of the adjacent Arctic landmasses during the super-interglacials (Coletti et al., 2015; Melles et al., 2012).

5.4. Mid and Late Pleistocene glacial-interglacial variability

The Mid and Late Pleistocene sediment record of Lake El’gygytyn is characterized by a pronounced cyclicity on a glacial/interglacial scale, which is visible, for instance, in most parameters for lake-internal bioproduction (Si/Ti, BSi, total diatom concentration), clastic influx from the catchment (e.g., Ti, Fe), and post-depositional processes (e.g., TOC preservation, vivianite formation). Variations in most of these processes are primarily controlled by changes in the persistence of a seasonal or perennial ice cover on the lake that can be biased by secondary driving factors, like nutrient supply, thickness of the active layer during summer, or seasonal wind strength (Francke et al., 2013; Melles et al., 2007).

Pollen analyses of the past c. 1.5 Ma yielded glacial/interglacial variations to have also influenced the regional vegetation in the lake surrounding varying from cold steppe

1 vegetation during glacial periods (e.g., MIS 2; MIS 6) to tundra with tree-sized shrubs and
2 cold deciduous birch forests during normal (e.g., MIS 1) and warm interglacials (e.g., MIS 5e;
3 MIS 9), respectively (Lozhkin and Anderson, 2006; Lozhkin and Anderson, 2013; Lozhkin et
4 al., 2007a; Lozhkin et al., 2007b; Tarasov et al., 2013; Figs. 11, 12). Pollen-based temperature
5 reconstructions yielded maximum glacial-interglacial MTWM amplitude variations of c. 9°C
6 (Melles et al., 2012; Tarasov et al., 2013), which corresponds well to MAAT estimates
7 derived from diatom oxygen isotope ratios of the past 23 and 250 ka (Chapligin et al., 2012;
8 Swann et al., 2010) and biomarker-derived MBT/CBT paleo-temperatures of the periods MIS
9 12 to 8 and MIS 4 to 1 (D'Anjou et al., 2013; Holland et al., 2013).

10 The glacial/interglacial cycles in the Lake El'gygytgyn record show a high agreement in
11 frequency and amplitude to variations in the marine oxygen isotope stack LR04 (Lisiecki and
12 Raymo, 2005), thus indicating a high susceptibility of the lake and its catchment to orbitally-
13 driven global climate change. Frequency analyses show dominant variations, for instance, in
14 the Si/Ti ratio, the hue angle of sediment colour, and especially the mean grain size and grain-
15 size dependent Rb/Sr ratio on the 100 kyr eccentricity and the 41 kyr obliquity bands
16 (Francke et al., 2013; Nowaczyk et al., 2013; Wennrich et al., 2014). A shift in the frequency
17 of the grain size and Rb/Sr signals from a 41 to a 100 kyr dominance between c. 1.2 and 0.6
18 Ma is interpreted to indicate the MPT (Francke et al., 2013; Wennrich et al., 2014), a globally
19 observed change in the glacial/interglacial frequency (e.g., Clark et al., 2006). Beyond these
20 lower-frequent fluctuations, especially the anoxia and thus almost exclusively parameters
21 dependent on ice cover, like MS and TOC, but also the $\delta^{18}\text{O}$ of diatoms exhibit higher
22 frequency variations that correspond to changes in the NH insolation on the 23 kyr precession
23 band (Chapligin et al., 2012; Nowaczyk et al., 2013; Nowaczyk et al., 2007; Fig. 12). The
24 divergence in the dominant frequency suggests different threshold levels in the reaction of the
25 processes within the lake system to orbital forcing.

1 High-resolution geochemical data of interglacials MIS 11.3, 9, and 5.5 imply that the
2 overall warmer interglacial conditions at Lake El'gygytgyn have been repeatedly interrupted
3 by short-term deteriorations, like a 'Younger Dryas'-like cold reversal during Termination II
4 (Cunningham et al., 2013a; Cunningham et al., 2013b; Vogel et al., 2013). A high frequency
5 climatic variability during these interglacials suggests that the orbitally-driven climatic and
6 environmental changes are further superimposed by cycles on sub-Milankovitch scale.
7 Driving mechanisms of these sub-Milankovitch cycles and their impact on the lake and its
8 catchment need to be investigated more in detail in the future, and requires further high-
9 resolution proxy datasets and refinements of the age model.

10 Beyond the regular glacial/interglacial and sub- Milankovitch variability, TOC and TN
11 exhibit a gradual increasing trend after c. 1.5 Ma, which is synchronous with the more
12 abundant occurrence of dark laminated silt and clay (facies A; Figs. 11, 12). The increase in
13 TOC and TN is interpreted to be caused by intensified ice coverage during glacials that might
14 be triggered by larger variations in glacial/interglacial temperature amplitudes (Wennrich et
15 al., 2014). A similar conclusion is drawn from the concentration of biomarker proxies for sea-
16 ice in sediment cores taken in the Fram Strait/Yermak Plateau implying a gradually rising sea-
17 ice cover over the past 1.2 Myr (Stein and Fahl, 2013). Polyak et al. (2013) furthermore
18 postulated a shortening of the ice-free season in the AO between 1.5 to 0.8 Ma and a
19 subsequent shift from mostly seasonal to mostly perennial sea ice based on foraminiferal
20 fauna diversities. The authors discussed a link to a progressive global sea-level lowering
21 between 1.5 and 0.9 Ma (Miller et al., 2005; Figs. 13) that is hypothesized to have diminished
22 the warm-water inflow into the Arctic Ocean through the shallow Bering Strait.

23 24 6. Conclusions 25

26 Lake El'gygytgyn in the Russian high Arctic is a unique site because (1) it is located
27 within the only known impact structure on Earth known that is formed in acid volcanic rocks,

(2) it's region is assumed to be influenced by permafrost conditions since the Pliocene, and (3) it comprises an undisturbed 3.58 Ma record of climate and environmental evolution, and thus, marks the longest time-continuous sediment record of the terrestrial Arctic. Recent studies on the impactite, permafrost, and sediment sequences recovered within the framework of the ICDP "El'gygytgyn Drilling Project" and multiple pre-site surveys yielded new insight into the bedrock origin and cratering processes as well as permafrost dynamics and the climate and environmental history of the terrestrial Arctic on longer and shorter time-scales back to the mid-Pliocene.

1. Lithological studies on the bedrock section underneath the lake sediments in hole 5011-1C yielded a weakly impact-affected bedrock of variable composition that could be geochemically linked to the subduction-related volcanism of the OCVB.
2. Shock deformation features, shatter cones, and remains of fallout deposits within the only 75-m thin suevite and uppermost transitional zone of the impactite section clearly confirm the impact genesis of the El'gygytgyn crater. Cr and Os isotope as well as PGE data of different impact melt samples from the ICDP core and the crater give contradictory evidences for a F-type asteroid of mixed composition or an ordinary chondrite as presumable projectile. Surprisingly, the impactite sequence of core 5011-1C contains only a very reduced fallback sequence compared to other craters without any larger coherent melt bodies. Elevated calcite values at the base of the lake sediments and peaks in uranium indicate the impact-induced hydrothermal activity in the crater persisted for more than 300 kyr after the impact.
3. Although absolute dating of the permafrost record is difficult, isotope and hydrochemical as well as microbial data imply a subaquatic genesis of the lower section that is overprinted by several thaw-freeze cycles due to lake-level changes at least since MIS 7. The Holocene section, instead, has an obvious subaerial origin, with ground ice exhibiting a paleo-precipitation signal. Modelling results suggest a modern

1 permafrost in the crater of c. 340 m, and further confirm a pervasive character of the
2 talik below Lake El'gygytyn. Geochemical, palynological, and mineralogical data
3 from the lake sediment core imply an initial permafrost onset already at c. 3.3 Ma that
4 is consistent with the first mid-Pliocene cooling during MIS M2.

5 4. Multi-proxy data from the lower part of the 318-m long lake sediment sequence display
6 a warmer and moister climate during the mid-Pliocene optimum as documented by a
7 dense forest cover around and maxima in the primary production in the lake. In
8 accordance with other Arctic records, the exceptional warmth at Lake El'gygytyn
9 point to a strong "Arctic amplification" during the mid-Pliocene. Severe changes in the
10 pollen assemblage and sediment composition after c. 3.3 Ma clearly indicate a first
11 major cooling during MIS M2 with a sudden spread of tundra- and steppe-like habitats
12 around the lake. Changes in the vegetation and diatom production after c. 3.0 Ma
13 indicate a gradual cooling during the late Pliocene.

14 5. The Pliocene/Pleistocene transition in the Lake El'gygytyn record is marked first by a
15 major drop in precipitation and winter temperatures at c. 2.73 Ma that coincides with
16 the onset of an intense NH glaciation during MIS G6. A second cooling after MIS 104
17 as suggested from the first occurrence of perennial ice-cover on the lake and cold
18 steppe habitats in the local vegetation illustrates the stepwise rather than abrupt
19 character of the transition.

20 6. Extreme peaks in the lacustrine productivity and changes in the local vegetation from
21 steppe tundra to evergreen conifer and broadleaf forests reflect periods of exceptional
22 warming in the Arctic during Pleistocene super-interglacials. The synchronicity of some
23 of these super-interglacials at Lake El'gygytyn to collapses of the WAIS and GIS
24 points to strong intrahemispheric teleconnections, presumably as a result of a
25 perturbation of the ocean thermocline circulation.

7. After 2.58 Ma and especially during the mid and late Pleistocene, most geochemical, biological, and sedimentological proxies the Lake El'gygytgyn record exhibits a shift to a pronounced glacial-to-interglacial cyclicity. Reconstructed variations in lacustrine bioproduction, clastic influx, and post-depositional processes as well as in the local vegetation exhibit a high congruence to variations in the orbital parameters on the eccentricity, obliquity, and precession bands. This indicates processes in the lake and its catchment to be highly susceptible to orbitally-driven changes, e.g., in NH insolation. A frequency shift from the dominant 41 kyr obliquity band to a 100 kyr eccentricity dominance during the MPT at c. 1.2–0.6 Ma is especially obvious in several grain-size parameters. High-resolution studies indicate higher frequent environmental and climatic changes on sub-Milankovitch cycles, but these have to be investigated more in detail in the future.

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Figure captions:

Figure 1. Aerial image of the El'gygytgyn impact crater with the bathymetry of Lake El'gygytgyn and the location of ICDP drill site 5011-1 and 5011-3 as well as the pilot cores Lz1024 and PG1351 superimposed. The white line indicated the position of the crater rim, the insert map the location of Lake El'gygytgyn in the western Beringian Arctic.

Figure 2: (A) Schematic NW-SE oriented cross-section of the El'gygytgyn basin stratigraphy with location and recovery of ICDP sites 5011-1 and 5011-3 (modified after Melles et al., 2011). At site 5011-1, three holes (1A, 1B, and 1C) were drilled to replicate the Pleistocene and uppermost Pliocene sections. Lz1024 is a 16-m-long percussion piston core taken in 2003 that fills the stratigraphic gap between the lake sediment surface and the top of drill cores 1A and 1B. (B) Sediment echosounder profile AWI-20038540 (3.5 kHz) in a WSW–ENE direction crossing the coring site and showing multiple MMD as acoustically transparent units on the western slope and lake floor (modified after Sauerbrey et al., 2013).

Figure 3. Core composite profile of the lacustrine basin infill of Lake El'gygytgyn illustrating the used intervals from holes 1A, 1B, 1C, and pilot core Lz1024 (modified after Wennrich et al., 2014). Hatched sections illustrate gaps in the composite profile.

Figure 4. (A) Age/depth model with resulting sedimentation rates for the ICDP 5011-1 core composite (modified after Melles et al., 2012). Initial first-order tie points based on paleomagnetic polarity changes (Haltia and Nowaczyk, 2014) are indicated by black diamonds; second- and third-order tie points, based on matching sediment proxy data to the LR04 marine isotope stack (Lisiecki and Raymo, 2005) and regional spring and

summer insolation (Laskar et al., 2004) are denoted by the blue curve. The red star marks the time of the impact at 3.58 ± 0.04 Ma inferred from $^{40}\text{Ar}/^{39}\text{Ar}$ dating (Layer, 2000). Black and white bars along the age and depth axes denote normal and reversed polarity, respectively. MMD and core gaps thicker than 50 cm are indicated on the depth axis by grey and blue colors, respectively. (B) Age/depth model of the uppermost 35 m for the ICDP 5011-1 core composite with luminescence ages determined by different luminescence dating protocols on the fine-grained quartz and the polymineral fraction (Zander and Hilgers, 2013). Ages of tephra T1 (van den Bogaard et al., 2014; red triangle) and the Brunhes/Matuyama polarity change (Haltia and Nowaczyk, 2014; black diamond) are also indicated. The extended triangle in the lower right corner correlates with the sample from the B/M boundary and illustrates an pIRIR₂₉₀ age of >700 ka.

Figure 5: Geological map of the El'gygytgyn impact crater (modified after Raschke et al., 2014). The red dashed line marks the position of the crater rim.

Figure 6. General stratigraphy of the impactite and bedrock section recovered from hole 5011-1C (modified after Pittarello et al., 2013). The red rectangle marks the position of the core segment in figure 7.

Figure 7. Core segment from the El'gygytgyn impact crater, showing suevitic impact breccia, from c. 319 mblf, just below the transition from the post-impact lake sediments.

Figure 8. Inclination of the characteristic remanent magnetisation (ChRM), with magnetic polarity (Haltia and Nowaczyk, 2014), pollen-derived mean temperature of the warmest month (MTWM) and annual precipitation (PANN; from Brigham-Grette et al., 2013; Melles et al., 2012; Tarasov et al., 2013), XRF core scanning-derived Si/Ti ratio, biogenic

silica (BSi) contents and BSi accumulation rate, both obtained from Fourier transform infrared spectroscopy, trees and shrubs pollen sum, pollen percentages of spruce (*Picea*) and sum of dark coniferous taxa (*Pinus+Picea+Abies*), uranium (U) concentration determined by downhole logging, sedimentation rate (modified after Sauerbrey et al., 2013), XRF core scanning-derived Ca counts, magnetic susceptibility, and the occurrence of sediment facies A through C in the interval 3.58-2.4 Ma of the sediment record from Lake El'gygytgyn vs. age compared along with the LR04 global marine isotope stack (Lisiecki and Raymo, 2005) and 65° N summer (May to August: MJJA) insolation (after Laskar et al., 2004). Pliocene cooling events M2 and G6 are highlighted with blue bars. XRF data are plotted as 101 point weighted running average. Grey bars indicate gaps in the record. Please note the logarithmic scales of the Ca, Si/Ti and MS curves.

Figure 9. Images of the primary lithofacies identified in the lacustrine sequence from Lake El'gygytgyn (modified after Brigham-Grette et al., 2013; Melles et al., 2011). Facies A is limited to the Pleistocene interval of the core whereas facies D and E are found only in the Pliocene section; Facies B and C are found throughout the record.

Figure 10. Lithology, pollen and hydrochemical zonation (HZ), oxygen and hydrogen isotopic composition, pH values, and ion concentrations of ground ice along with sediment and hydrochemical interpretations, and temperature profile of the permafrost hole 5011-3 (modified after Andreev et al., 2012; Mottaghy et al., 2013; Schwamborn et al., 2012a; Schwamborn et al., 2014). Red diamonds in the temperature profile indicate average temperature values. Please note the inverse scale of the cation concentrations.

Figure 11. Inclination of the characteristic remanent magnetisation (ChRM), with magnetic polarity (Haltia and Nowaczyk, 2014), pollen-derived mean temperature of the warmest

month (MTWM) and annual precipitation (PANN; from Melles et al., 2012; Tarasov et al., 2013), XRF core scanning-derived Si/Ti ratio and Ti counts, biogenic silica (BSi) contents obtained from Fourier transform infrared spectroscopy, trees and shrubs pollen sum, pollen percentages of spruce (*Picea*) and sum of dark coniferous taxa (*Pinus+Picea+Abies*), XRF core scanning-derived Mn/Fe ratio, total organic carbon (TOC) content, magnetic susceptibility, and the occurrence of sediment facies A through C in the interval 2.4-1.2 Ma of the sediment record from Lake El'gygytyn vs. age compared along with the LR04 global marine isotope stack (Lisiecki and Raymo, 2005) and 65° N MJJA insolation (after Laskar et al., 2004). XRF data are plotted as 101 point weighted running average. "Super-interglacials" at Lake El'gygytyn are highlighted with red bars. Grey bars indicate gaps in the record. Please note the logarithmic scales of the Si/Ti, TOC, and MS curves. Vertical arrows in the Mn/Fe record mark values beyond 0.4 that were cropped for displaying reasons, whereas red arrows under the Mn/Fe and Ms records illustrate the base-line level drop between 2.3 and 1.8 Ma.

Figure 12. Inclination of the characteristic remanent magnetisation (ChRM), with magnetic polarity (Haltia and Nowaczyk, 2014), pollen-derived mean temperature of the warmest month (MTWM) and annual precipitation (PANN; from Melles et al., 2012; Tarasov et al., 2013), XRF core scanning-derived Si/Ti ratio, biogenic silica (BSi) contents obtained from Fourier transform infrared spectroscopy (light blue) along with dinosterol concentration (after D'Anjou et al., 2013; red), diatom concentration, trees and shrubs pollen sum (orange) along with arborinol concentrations (after D'Anjou et al., 2013; dark blue), pollen percentages of spruce (*Picea*) and sum of dark coniferous taxa (*Pinus+Picea+Abies*), XRF core scanning-derived Mn/Fe ratio, total organic carbon (TOC) content, magnetic susceptibility, and the occurrence of sediment facies A through C in the interval 1.2 Ma to modern times of the sediment record from Lake El'gygytyn vs. age compared along with

the LR04 global marine isotope stack (Lisiecki and Raymo, 2005), 65° N MJJA insolation (after Laskar et al., 2004), and the $\delta^{18}\text{O}_{\text{diatom}}$ record of pilot core Lz1024 (Chapligin et al., 2012). XRF data are plotted as raw data (blue dots) and 101 point weighted running average (coloured lines). “Super-interglacials” MIS 31 and 11.3 at Lake El’gygytgyn are highlighted with red bars. Gaps in the record are shaded with grey bars. Please note the logarithmic scales of the Si/Ti, TOC, and MS curves. The black arrow at the base of the LR04 stack illustrates a sea-level lowering and glacial built-up proposed by Polyak et al. (2013).

Figure 13. Correlation of super-interglacials at Lake El’gygytgyn with diatomites in the ANDRILL 1B record (modified after Melles et al., 2012). (A) Facies succession of the El’gygytgyn record during the past 2.8 Ma. Peak glacial conditions are indicated by facies A (blue bars), intermediate glacial to interglacial conditions by facies B (brown bars), and super interglacials by facies C (red bars). (B) LR04 global marine isotope stack with selected numbers of isotope stages (Lisiecki and Raymo, 2005). (C) Lithology of the uppermost 215 m of core ANDRILL 1B (modified after McKay et al., 2009; McKay et al., 2012). Lines indicate possible correlations to the LR04 stack according to Naish et al. (2009).

Figure 1_1col

Figure 1

Figure 2_1.5col

Figure 2

Figure 3_1col

Figure 3

Figure 4_1.5col

Figure 5_2col

Figure 5

Figure 6_1col

Figure 6

Figure 7

Figure 8_2col

Figure 8

Figure 9

Figure 10

Figure 11_2col

Figure 11

Figure 12_2col

Figure 12

Figure 13_2col

Figure 13