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Arctic Glacial and Interglacial Variability throughout the Quaternary: Evidence from Lake El'gygytgyn, northeastern Russia

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Abstract: Lake El'gygytgyn in the north-eastern Russian Arctic became the target of extensive international site surveys in the late 1990s, with complex geoscientific fieldwork conducted in 1998, 2000, and 2003. The surveys strongly supported the hypothesis that the lake hosts a nearly continuous sediment record, which is highly sensitive to climatic and environmental changes and covers the time since the lake formation by a meteorite impact some 3.6 Ma ago. These promising findings led to deep drilling operations within the scope of the International Continental Scientific Drilling Program (ICDP) in 2008 and 2009, during which 141 m of permafrost deposits in the catchment, the 318 m thick lake sediment succession in the lake centre, and about 200 m of impact rocks underneath were drilled. Palaeoenvironmental and palaeoclimatological research on the Quaternary part of the lake sediment record revealed that full glacial conditions, with mean annual air temperatures at least 3.3 ±0.9 °C lower than today, first commenced at the Pliocene/Pleistocene boundary 2.6 Ma ago. They gradually increased in frequency from ca. 2.3 to 1.8 Ma, eventually concurring with all global glacials and several stadials. The interglacials at Lake El'gygytgyn significantly differ in intensity. So-called super interglacials irregularly occurred throughout the Quaternary, including Marine Isotope Stages 11.3 and 31, when mean temperatures of the warmest month and annual precipitation were up to 4-5 °C and ~300 mm higher than today, respectively. According to climate modelling these climatic settings cannot in all cases be traced back to orbital forcing or greenhouse gas concentrations. They are, at least partly, the result of other processes and feedbacks in the climate system. A remarkable coincidence of the super interglacials with diatomite layers in the Antarctic ANDRILL 1B record suggests that they were associated with considerable retreats of the West Antarctic Ice Sheet. The ice decay may have caused reductions in Antarctic Bottom Water formation, its transport to the Pacific Ocean, and its upwelling in the north-western Pacific, and potentially increased warm-water intrusions through the Bering Strait into the Arctic Ocean.

Zusammenfassung: Der Elgygytgynsee in der nordöstlichen russischen Arktis wurde in den späten 1990er Jahren Ziel von umfangreichen internationalen Vorstudien, einschließlich komplexer geowissenschaftlicher Feldarbeiten in den Jahren 1998, 2000 und 2003. Die dabei erzielten Ergebnisse stützten die Hypothese, dass der See eine weitgehend kontinuierliche Sedimentabfolge enthält, welche die Klima- und Umweltveränderungen mit hoher Sensitivität widerspiegelt und die Zeit seit der Seebildung durch einen Meteoriteneinschlag vor etwa 3,6 Ma abdeckt. Diese viel versprechenden Erkenntnisse führten dazu, dass in den Jahren 2008 und 2009 Tiefbohrungen im Rahmen des Internationalen Kontinentalen Tiefbohrprogramms (ICDP) abgeteuft wurden, mit denen die Permafrostablagerungen im Einzugsgebiet bis 141 m Tiefe und eine 318 m mächtige Seesedimentabfolge mit etwa 200 m unterlagernden Impaktgesteinen im Seezentrum erbohrt wurden. Entsprechend den Paläoumwelt- und Paläoklimaforschungen an den Seesedimenten, die in den letzten 2,8 Ma abgelagert wurden, traten glaziale Klimabedingungen mit Jahresmitteltemperaturen zumindest 3,3 ±0,9 °C kälter als Heute erstmals an der Pliozän/Pleistozän-Grenze vor 2,6 Ma auf. Diese kaltzeitlichen Klimabedingungen nahmen zwischen ca. 2,3 bis 1,8 Ma in ihrer Häufigkeit zu und treten seitdem zeitgleich mit allen globalen Glazialen und einigen Stadialen auf. Die Interglaziale am Elgygytgynsee zeigen deutliche Unterschiede in ihrer Intensität. Dabei traten sogenannte Super-Interglaziale unregelmäßig im Quartär auf, einschließlich der Marinen Isotopenstadien 11.3 und 31, in denen die mittleren Temperaturen des wärmsten Monats bis zu 4-5 °C und die Jahresniederschläge etwa 300 mm höher waren als Heute. Diese Klimabedingungen können nach Klimamodellierungen nicht in allen Fällen auf die orbitalen Randbedingungen oder die Konzentrationen von Treibhausgasen zurückgeführt werden. Sie sind zumindest teilweise die Folge von anderen Prozessen und Rückkopplungen im Klimasystem. Eine auffallende zeitliche Übereinstimmung der Super-Interglaziale mit Diatomit-Lagen im antarktischen Bohrkern ANDRILL 1B deutet an, dass sie im Zusammenhang mit erheblichen Massenverlusten des Westantarktischen Eisschildes stehen. Der Eisabbau könnte Reduktionen der Bildung des Antarktischen Bodenwassers, seines Transports in den Pazifischen Ozean und seines Auftriebs im nordwestlichen Pazifik bedingt haben, und möglicherweise ursächlich für einen erhöhten Warmwasserstrom durch die Beringstraße in den Arktischen Ozean gewesen sein.

Keywords: Lake El'gygytgyn, paleoclimate, paleolimnology, ICDP, super interglacials

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INTRODUCTION

The effects of global warming are documented and predicted to be most pronounced in the Arctic, which plays a crucial, albeit not yet well-understood role within the global climate system (e.g., ACIA 2004, Christensen et al. 2007, Pithan & Mauritsen 2014). 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. 2010a, Screen & Simmonds 2010), and is hypothesised to trigger mid-latitude climate variations (e.g., Francis & Vavrus 2012, Cohen et al. 2014). The reliability of climate projections for high northern latitudes is, however, hampered by the complexity of the underlying natural variability and associated feedback mechanisms (Christensen et al. 2007, Miller et al. 2010a). A prerequisite for the improvement and validation of climate projections is a more thorough understanding of the natural variability of past Arctic climate change on a range of geological timescales, when external forcings and boundary conditions may have been different.

The present knowledge of the Arctic climatic and environmental evolution is widely limited to the last glacial/interglacial cycle that is well documented in ice cores penetrating the entire Greenland Ice Sheet (e.g., NGRIP Members 2004, CAPE-Last Interglacial Project Members 2006, NEEM Community Members 2013). Marine records from the Arctic Ocean, for instance from the Lomonosov, Mendeleev, and Northwind Ridges (Backman & Moran 2008 and references therein, Cronin et al. 2013, Polyak et al. 2013), may have a much longer time range, but they often experience a limited age control or insufficient temporal resolution to investigate climate variability on millennial or even orbital timescales. On the other hand, terrestrial archives from the adjacent Arctic borderland, in areas covered by Pleistocene glaciations, often are limited to histories after the last glacial period (Hubberten et al. 2004, Kaufman et al. 2004), with the consequence that only a few records extend continuously beyond the last interglacial (e.g., Berger & Anderson 2000, Melles et al. 2007, Zech et al. 2013).

The first record from the Arctic that spans the entire Quaternary continuously has become available in 2009, when a drilling campaign of the "International Continental Scientific Drilling Program" (ICDP) drilled the entire, 318 m thick lacustrine sediment sequence from the bottom of Lake El'gygytgyn on Chukotka, Russian Arctic (Melles et al. 2011; Fig. 1). Since then, this unique record has been thoroughly investigated by an international team of geoscientists, providing new important insights into the Pliocene and Pleistocene climatic and environmental history of the Arctic and its feedbacks with lower latitudes (e.g., Melles et al. 2012, Brigham-Grette et al. 2013).

Here, we outline the major findings of the site survey that was conducted for the El'gygytgyn Drilling Project, describe the challenging drilling operations in the remote Arctic, and provide a review of the information derived from the drill cores thus far concerning the climate variability of glacials and interglacials throughout the Quaternary.

STUDY SITE

Lake El'gygytgyn is located 100 km to the north of the Arctic Circle in Chukotka, north-eastern Russia (67°30' N, 172°05' E; Fig. 1). The lake lies within a meteorite impact crater measuring 18 km in diameter (Gurov et al. 1978, 2007) that was created 3.6 million years ago in volcanic target rocks of Cretaceous age (Layer 2000). The bedrock in the vicinity of the lake predominantly consists of ignimbrites, tuffs and andesite-basalts (Belyi & Raikevich 1994, Nowaczyk et al. 2002).

Today, the study area belongs to the zone of continuous permafrost, experiencing a mean annual ground temperature of -10 °C at 12.5 m below the

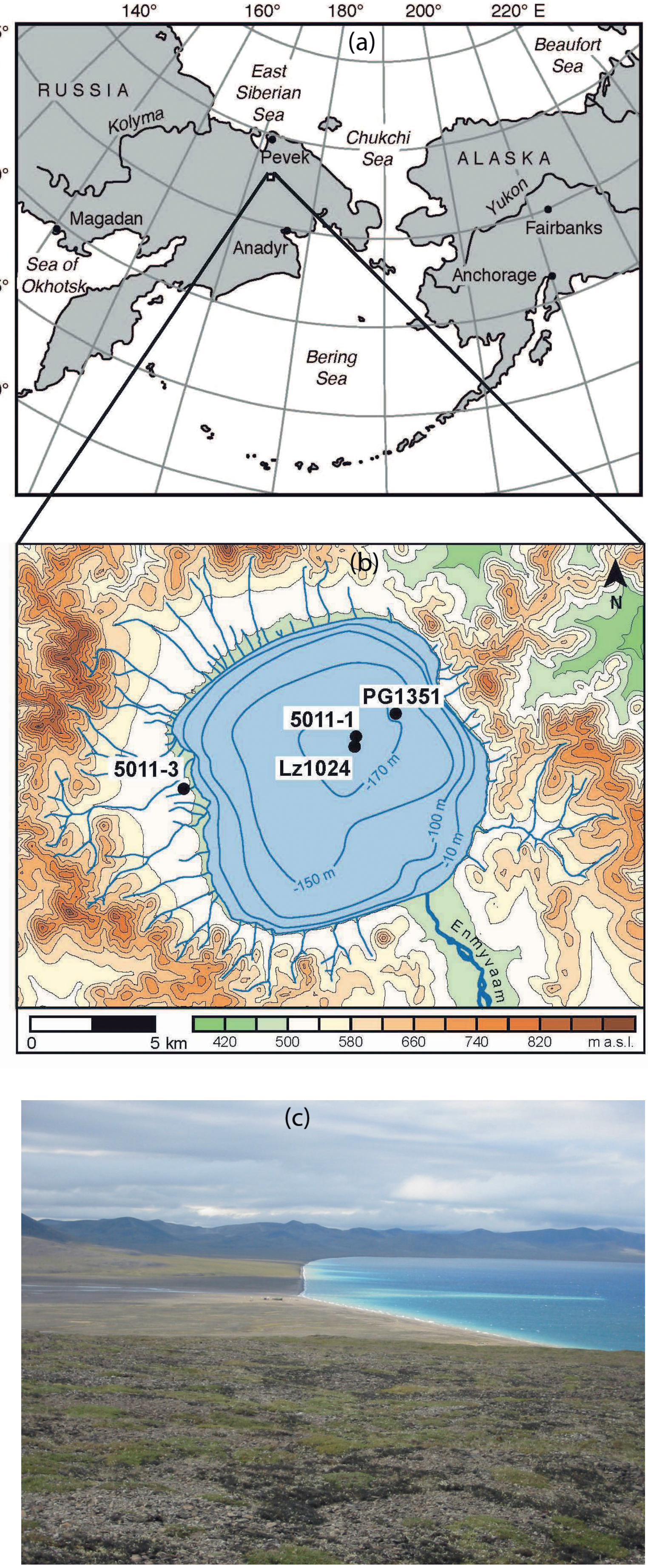

Fig. 1(a): Overview map showing the location of Lake El'gygytgyn in Chukotka, north-eastern Russian Arctic; (b) map of the El'gygytgyn Crater with the piston coring sites PG1351 and Lz1024 along with the ICDP drill sites 5011-1 and 5011-3 in the central lake and in its western catchment; (c) photo of the southern shore of Lake El'gygytgyn in summer 2003 (view from the east), showing the Enmyvaam outflow plain to the left, and suspension-loaded lake waters close to the shore due to wave and current erosion and transport under strong northerly winds (cf. Wennrich et al. 2013).

Abb. 1(a): Übersichtskarte mit der Lage des Elgygytgynsees in Tschukotka, nordöstliche russische Arktis. (b): Karte des Elgygytgyn-Kraters mit den Positionen der Kolbenlotkerne PG1351 und Lz1024 sowie den Bohrkernen des ICDP 5011-1 und 5011-3 im zentralen Seebereich und im westlichen Einzugsgebiet. (c): Foto vom Südufer des Elgygytgynsees im Sommer 2003 (Blick aus Osten) mit der Ebene des Enmyvaam-Ausflusses in der linken Bildhälfte und mit Suspension beladenem Seewasser nahe des Ufers als Folge von Wellen- und Strömungserosion und -transport bei starken nördlichen Winden (vgl. Wennrich et al. 2013).

ground surface (SCHWAMBORN et al. 2008). It is part of the subzone of southern shrub and typical tundra (ANDREEV et al. 2016). The modern treeline for larch and shrub stone pine is positioned roughly 100 km to the south and west of the lake. Only dwarf birches and willow grow in the lake vicinity. Although the northern boundary of shrub alder is reported to be located further to the north of the lake, the only few shrub-alder stands grow approximately 10 km from the lake, in more protected river valley habitats (ANDREEV et al. 2013, LOZHKIN & ANDERSON 2013). For a more detailed description of the local vegetation see BELIKOVICH & GALANIN (1994) and ANDREEV et al. (2014) and references therein.

The climate at Lake El'gygytgyn is assumed to be sensitive to regional and overregional atmospheric change, being controlled by Siberian, Arctic, and North Pacific pressure systems and airmasses (MOCK et al. 1998, YANASE & ABE-OUCHI 2007, BARR & CLARK 2011, NOLAN et al. 2013). 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 & BRIGHAM-GRETTE 2007, NOLAN 2013). Summer rainfall and winter snowfall almost equally contribute to the mean annual precipitation, with cumulative summer rainfall from 2002 to 2007 varying between 73 and 200 mm a^{-1} and the water equivalent of snowfall determined for the winter 2001/2002 amounting to 108 mm.

The local atmospheric circulation is dominated by strong winds either from the north or from the south, with hourly wind speeds that average 5.6 m s^{-1} but can reach peak values of up to 21.0 m s^{-1} (NOLAN & BRIGHAM-GRETTE 2007). Comparative temperature data of a local weather station at the lake, measured between 2002 and 2007, yielded a high correlation with NCEP/NCAR (US National Centers for Environmental Protection/National Center for Atmospheric Research) reanalysis data, thus confirming that the local climate at the lake well represents the regional weather patterns over western Beringia (NOLAN et al. 2013). During the winter season, a strong Aleutian low and pressure highs over the Beaufort and Chukchi Seas transport cold Arctic air from the east and north to the lake, whereas the 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).

Lake El'gygytgyn today is 175 m deep and has a roughly circular shape with a diameter of 12 km and a bowl-shaped morphology, leading to a lake volume of 14.1 km^3. The crater rim at up to 935 m a.s.l. (above sea level) forms a watershed of 293 km^2, which is less than three times the lake's surface area of 110 km^2 at 492 m a.s.l. (NOLAN & BRIGHAM-GRETTE 2007). The lake is fed by a system of approximately 50 ephemeral creeks and streams that deliver ca. 0.11 km^3 yr^{-1} of water and 350 t yr^{-1} of sediment, mainly during snowmelt (FEDOROV et al. 2013). Drainage of the lake takes place at the south-eastern shore via the Enmyvaam River, which flows towards the southeast into the Anadyr River and further into the Bering Sea.

Ice formation on Lake El'gygytgyn usually starts in October (NOLAN et al. 2003, 2013, NOLAN & BRIGHAM-GRETTE 2007). The blanketing snow cover on the lake ice melts in May/June. The lake ice, measuring 1.5 to 2 m in thickness, starts disintegrating by forming moats at the shore in June/July and is absent from July/August onwards, thus giving a maximum of three months duration to the open-water season. Lake El'gygytgyn is a cold monomictic lake (NOLAN & BRIGHAM-GRETTE 2007). The ice cover results in a thermal stratification of the water column and partial oxygen-depletion of bottom waters during the winter months. Full mixing of the water body, with oxygen-supply of the hypolimnion, is achieved after snowmelt and ice break-up during summer, when warming of shore waters towards +4 °C enables their descend to the deepest parts of the lake. The strong and persistent wind from north or south during the ice-free period drives a two-cell circulation system in the lake surface waters (NOLAN & BRIGHAM-GRETTE 2007, WENNRICH et al. 2013). 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 that indicates an oligotrophic or even ultra-oligotrophic character of the lake (CREMER et al. 2005, CREMER & WAGNER 2003). Primary production predominantly occurs during the ice-free period but phytoplankton growth also takes place in wintertime beneath the ice cover (CREMER et al. 2005).

PRE-SITE SURVEYS

A first international expedition was carried out on Lake El'gygytgyn as early as spring 1998. Using the lake ice as a platform, initial shallow coring down to a sediment depth of 12.9 m below lake floor (mblf) was carried out in the deepest part of the lake (PG1351; Fig. 1). Transportation of equipment and personnel to and from the lake was via Anchorage and Magadan. From Magadan, both the equipment and the participants were shipped to the settlement Pevek at the coast of the Arctic Ocean by chartered plane, from where the lake was reached by helicopters. Using similar logistics, a first seismic survey of the lake sediment infill was carried out in summer 2000, accompanied by first investigations of the modern hydrology and sediment formation. A much larger, more complex expedition, separated into a spring and a summer campaign with individual parties, was conducted in 2003, with the logistics organised via St. Petersburg and charter flights to/from Pevek (MELLES et al. 2005). On this expedition, the seismic survey was completed, additional lake sediment cores down to 16.6 mblf (Lz1024; Fig. 1) were retrieved, the regional geology, permafrost deposits, and geomorphology were mapped and sampled, and the modern weather, hydrology, and sediment formation were investigated.

These surveys conducted in preparation for the later drilling provided in-depth understanding of the modern weather conditions at Lake El'gygytgyn and their relation to the regional climate (NOLAN & BRIGHAM-GRETTE 2007, NOLAN et al. 2013). The results were put into context with the modern environmental settings existing and the processes operating in the lake area. This includes the vegetation (MINYUK 2005, LOZHKIN et al. 2007a), the permafrost behaviour (SCHWAMBORN et al. 2008a, MOTTAGHY et al. 2013), and the geology (LAYER 2000, GUROV & KOEBERL 2004) in the catchment, as well as the seasonal ice cover (NOLAN et al. 2003, NOLAN 2013) and hydrology (NOLAN & BRIGHAM-GRETTE 2007, WILKIE et al. 2013) of the lake. Investigations of the modern processes of sediment formation cover the allochthonous sediment supply, the autochthonous biogenic production, the water and sediment balance, and the surface sediment distribution in Lake El'gygytgyn (Cremer & Wagner 2003, Cremer et al. 2005, Cremer & van de Vijver 2006, Fedorov et al. 2013, Wennrich et al. 2013).

The initially collected sediment cores PG1351 and Lz1024 from central Lake El'gygytgyn (Fig. 1), with lengths of 12.9 and 16.6 m, yielded basal ages of ca. 275 and 350 kyr BP, respectively, and evidenced very low and relatively constant sedimentation rates during both interglacial and glacial times (Nowaczyk et al. 2002, 2007, 2013, Forman et al. 2007, Juschus et al. 2007, Frank et al. 2013). The continuous deposition confirmed the expectation that Lake El'gygytgyn was neither inundated by continental ice masses nor became desiccated, at least during the last three glacial/interglacial cycles. The highly variable characteristics of the sediment underlined the sensitivity of this lacustrine environment to regional climatic and environmental change (Lozhkin & Anderson 2006, Asikainen et al. 2007, Brigham-Grette et al. 2007, Cherepanova et al. 2007, Lozhkin et al. 2007a, b, Melles et al. 2007, Minyuk et al. 2007, Stachura-Suchoples et al. 2008, Vogel et al. 2008, Matrosova 2009, Rosén et al. 2010, 2011, Swann et al. 2010, Juschus et al. 2011, Chapligin et al. 2013, Cunningham et al. 2013, Frank et al. 2013, Holland et al. 2013, Murdock et al. 2013). Additional shallow cores retrieved subrecent mass movement deposits (MMDs), first identified in seismic profiles as originating from the steep (up to 30°) lake slopes (Niessen et al. 2007). This case study demonstrated that debris and density flows can be associated with significant erosion on the slopes of the lake rim, but the flows usually do not reach the lake centre, where suspension clouds produced by these mass movements are subsequently deposited as non-erosive turbidites (Juschus et al. 2009).

Complementary information concerning Mid to Late Quarternary lake-level fluctuations, cryogenic weathering, vegetation change, and slope processes was obtained by ground-penetrating radar surveys and investigations of sediment stratigraphic sections exposed in subaerial outcrops in the catchment of Lake El'gygytgyn (Schwamborn et al. 2006, 2008a, b, 2013a, Glushkova et al. 2009, Andreev et al. 2013). Sediment sections exposed at the shore of the Enmyvaam River, some 20-30 km to the south of Lake El'gygytgyn, provided first information concerning the regional environmental settings at the time of the meteorite impact ca. 3.6 Ma ago, and on the presumable existence of a lake in the crater already during Pliocene and Early Pleistocene times (Glushkova & Smirnov 2007).

During the seismic pre-site surveys conducted in the summers of 2000 and 2003, a 3.5 kHz sediment echosounder with high spatial resolution (up to 40 m penetration) was combined with single-channel and multi-channel airgun seismic systems, in order to provide the clearest information possible of the deeper lacustrine sediments and the structure of the impact crater underneath (Niessen et al. 2005). Both systems were

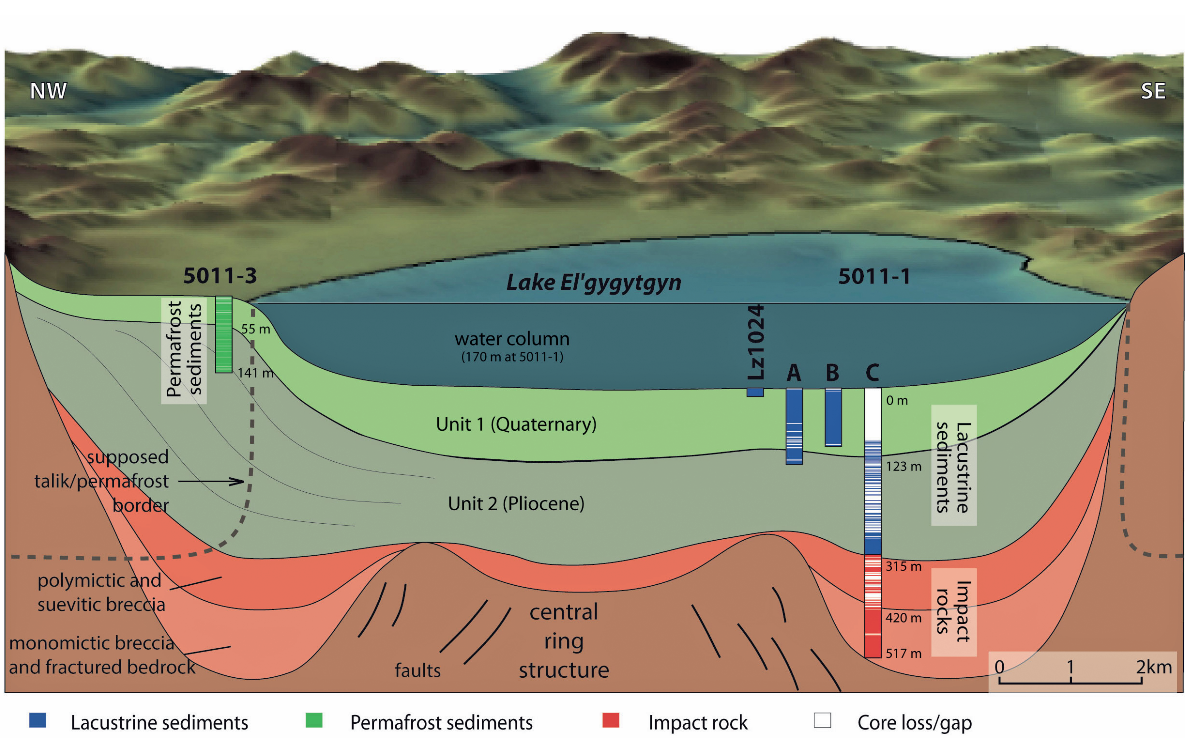

Fig. 2: Schematic cross-section of the El'gygytgyn basin stratigraphy showing the locations and recoveries of ICDP Sites 5011-1 and 5011-3 (modified after Melles et al. 2011). At Site 5011-1, three holes (1A, 1B, and 1C) were drilled to replicate the Pleistocene and upper Pliocene sections. Hole 1C further penetrated through the remaining lacustrine sequence down to its base at 318 mblf and then another ca 200 m into the impact rock sequence underneath. Lz1024 is a 16.6 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.

Abb. 2: Schematischer Querschnitt durch die Schichtenfolge im Elgygytgyn-Becken, mit der Lage und den Kerngewinnen der ICDP-Lokationen 5011-1 und 5011-3 (modifiziert nach Melles et al. 2011). An Lokation 5011-1 wurden drei Löcher (1A, 1B und 1C) gebohrt, um die Sedimente des Pleistozäns und obersten Pliozäns zu replizieren. Das Loch 1C durchteuft die verbliebenen Seesedimente bis zu deren Basis in 318 m Tiefe unter dem Seeboden, und dringt dann weitere ca. 200 m in die unterlagernde Abfolge der Impaktgesteine vor. Lz1024 ist ein 2003 gewonnener, 16,6 m langer Kolbenlot-Kern, der die stratigraphische Lücke zwischen dem Seeboden und dem Beginn der Tiefbohrkerne 1A und 1B schließt.

run simultaneously for efficiency from a small open platform resting on four inflatable pontoons. Sonobuoy refraction data from the lake centre formed the basis of a five-layer velocity-depth model. The results showed that the El'gygytgyn Crater has an uplifted central ring structure with its crest at about 330 mblf, which consists of impact breccia and is buried under alluvial deposits in the northwestern part of the basin (GEBHARDT et al. 2006, 2013, NIESSEN et al. 2007; Fig. 2). Above this structure, two lake sediment units were identified based on seismic characteristics. According to the airgun reflection data, the upper unit down to 170 mblf appears to be well stratified, whilst the lower unit appears to be only crudely stratified. Draping of the uplift structure is observed in the lower part of the upper unit. Both units were shown to be intercalated with thick MMDs, largely confined to marginal areas.

Extrapolating the sedimentation rates determined on pilot cores PG1351 and Lz1024 down to the top of the impact rocks, thereby taking into account the lack of seismic discontinuities indicative of glacial overriding or lake desiccation, it was considered highly likely that the lacustrine sediment record at the bottom of Lake El'gygytgyn is nearly continuous and spans the time from today back to the meteorite impact ca. 3.6 Ma ago.

ICDP DRILLING CAMPAIGN

The pre-site survey had confirmed the high potential that drilling operations in the El'gygytgyn Crater have to address important questions of three different geoscientific disciplines, namely: (i) palaeoclimate research, (ii) impact research, and (iii) permafrost research. Consequently, funding to conduct the drilling and subsequent investigations of the drill cores successively became available from 2005 onwards. However, due to cost increases, the drilling operations, which extended to two summer seasons, did not commence before 2008.

In summer 2008, the majority of the technical equipment and field supplies were transported in fifteen shipping containers from Salt Lake City, USA, to Pevek, Russia, by way of Vladivostok and the Bering Strait (MELLES et al. 2011). Additional freight from Germany (two containers) joined the cargo in Vladivostok via the Trans-Siberian Railway. In Pevek, the combined cargo was loaded onto trucks driven with bulldozer assistance more than 350 km over winter roads and cross-country to Lake El'gygytgyn. There, the operation was supported by a temporary winter camp that was designed for up to thirty-six people and set up on the western lakeshore (Fig. 3a). The camp included a laboratory container for whole-

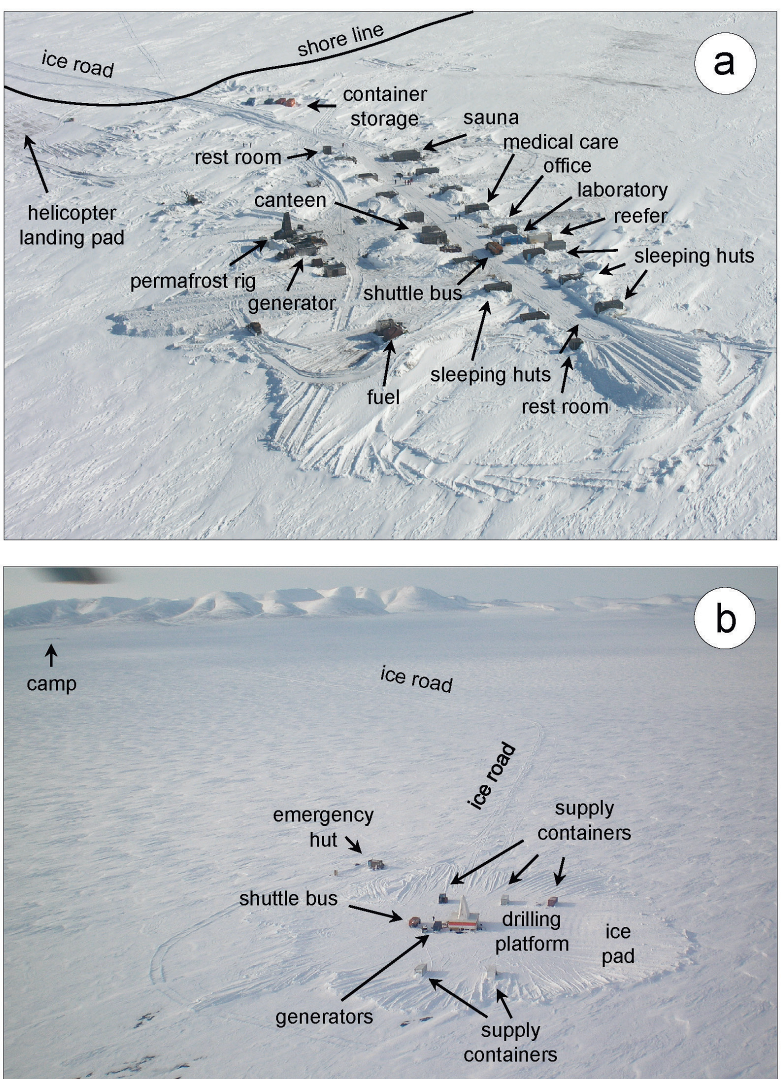

Fig. 3: Aerial views (a) from the west to the field camp on the western shore of Lake El'gygytgyn and (b) from northeast to the drilling platform on the ice pad at ICDP Site 5011-1. The camp was designed for up to 36 people with facilities for maintaining two 12-hour shifts. The ice pad was first cleared of snow and then artificially flooded with lake water to thicken and strengthen the ice to roughly 2 meters. Crew changes along the 7 km long ice road to the camp, which was flagged every 25 m for safe travel during whiteouts, were accomplished by shuttle bus and tracked vehicles.

Abb. 3: Luftaufnahmen (a) vom Westen zum Feldlager am Westufer des Elgygytgynsees und (b) vom Nordosten zur Bohrplattform auf der Eisplatte an der ICDP Bohrlokation 5011-1. Das Feldlager war für 36 Personen ausgelegt und hatte Infrastruktur zur Versorgung von zwei 12-Stunden-Schichten. Die Eisplatte wurde zunächst von Schnee befreit und dann mittels künstlicher Flutung mit gefrierendem Seewasser bis zu etwa 2 m Dicke verstärkt. Schichtwechsel erfolgten mittels Shuttlebus oder Kettenfahrzeugen entlang einer 7 km langen Eisstraße zum Feldlager, die für eine sichere Orientierung bei Schneedrift alle 25 m mit Flaggen versehen wurde.

core measurements of magnetic susceptibility and a reefer in which the lake sediment cores were kept from freezing.

The project completed one borehole into permafrost deposits in the western lake catchment (ICDP Site 5011-3) and three holes at 170 m water depth in the centre of the lake (Site 5011-1; Figs. 1 and 2). Permafrost drilling at Site 5011-3 was conducted in November and December 2008. Using a mining rig (SIF-650M) employed by a local drilling company (Chaun Mining Corp., Pevek), the crew reached a depth of 141.5 m with 91 % recovery. After drilling, the borehole was permanently instrumented with a thermistor chain for future ground temperature monitoring as part of the "Global Terrestrial Network for Permafrost" (GTN-P) initiative of the International Permafrost Association (IPA), thus contributing to our understanding of future permafrost behaviour in light of contemporary rapid change (Mottaghy et al. 2013). The drill core likely reflects the bottom-set to top-set sequence of an alluvial fan, which has prograded into Lake El'gygytgyn (Schwamborn et al. 2013). A very limited age control on this record, which solely is based on discontinuous pollen data, as yet excludes its correlation with the lake sediment record (Andreev et al. 2012).

In January/February 2009 an ice road was established between the camp and Site 5011-1 on Lake El'gygytgyn (Fig. 3b). Subsequently, an ice pad of 100 m diameter at the drill site was artificially thickened to ca. 2 m to allow for lake drilling operations from the 100-ton drilling platform. The Russian GLAD 800 drill system was developed for extreme cold and operated by the US consortium DOSECC (Drilling, Observation and Sampling of the Earth's Continental Crust). It consisted of a modified Christensen CS-14 diamond coring rig positioned on a mobile platform that was weather-protected by insulated walls and a tent on top of the 20 m high derrick.

Drilling at Site 5011-1 was conducted from February to April 2009. The drill plan included the use of casing anchored into the lakebed to allow drilling to start at a field depth of 2.9 mblf. Holes 1A and 1B had to be abandoned after twist-offs at 147 mblf and 112 mblf, respectively. In Hole 1A the Hydraulic Piston Corer (HPC) system was used down to 110 mblf, followed by the Extended Nose Corer (EXC) below. The recovery achieved with these tools was 92 %. Similarly, drilling with HPC down to 100 mblf and with EXC below provided 98 % recovery in Hole 1B. Hole 1C was first drilled by HPC from 42 mblf to 51 mblf, in order to fill gaps still existing in the core composite from Holes 1A and 1B, and was then continued from 100 mblf. Due to the loss of tools during the twist-offs, further drilling had to be performed with the Alien Bit Corer (ALN). The employment of this tool may at least partly explain a much lower recovery of the lake sediments in Hole 1C (total 52 %). This assumption is supported by the fact that the recovery jumped up to almost 100 % again at a depth of 265 m, when the tool was changed to a Hardrock Bit Corer (HBC), which has a smaller diameter as the tools employed before. The boundary between lake sediments and impact rocks was encountered at 318 mblf. Further drilling into the impact breccia and brecciated bedrock down to 517 mblf by HBC took place with 76 % recovery.

On-site processing of the cores recovered at Site 5011-1 involved magnetic susceptibility measurements with a Multi-Sensor Core Logger (MSCL, Geotek Ltd.) down to a depth of 380 mblf. Initial core descriptions were conducted based on macroscopic and microscopic investigations of the material contained in core catchers and cuttings (lake sediments) and on the cleaned core segments not cored with liners (impact rocks). Additionally, downhole logging was carried out in the upper 394 m of Hole 1C by the ICDP Operational Support Group (OSG), employing a variety of slim-hole wireline logging probes. Despite disturbance of the electrical and magnetic measurements in the upper part of the hole, due to the presence of metal after the twist-offs at Holes 1A and 1B, and to some technical problems, these data provided important information on the *in situ* conditions in the hole (e.g., temperature, natural gamma ray for determining U, K, and Th contents) and permitted sub-bottom depth correction of the individual core segments.

LABORATORY ANALYSES

The composite profile from ICDP Site 5011-1 (given in corrected depths below lake floor) was constructed from the best-preserved sediment intervals in overlapping core sequences based upon initial logging data and a layer-by-layer correlation of overlapping core sections (Melles et al. 2012, Wennrich et al. 2016). The layers comprised prominent MMDs (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 record were taken from pilot core Lz1024. Below 5.67 m, to a depth of 104.8 m, alternating sediment intervals from parallel cores 5011-1A and -1B were spliced together. Between 104.8 m and 145.7 m, cores 1A, 1B and 1C contributed to the composite. Below 145.7 m down to the interface between lacustrine sediment and impact breccia at 318 m composite depth, the record relies solely on core 5011-1C. For the subsampling and data presentation of the pelagic sediment record of Lake El'gygytgyn event layers, such as volcanic ash layers and distinct MMDs, with thicknesses exceeding 5 cm were omitted.

For the purpose of this paper, the core composite was investigated for lithology as well as selected physical, chemical and biological proxies using high-resolution logging and scanning technologies on half-cores along with standard techniques employed on discrete subsamples (Melles et al. 2012, Wennrich et al. 2014, 2016). Magnetic (volume) susceptibility (MS) (10^{-6} SI) was measured in 1 mm steps on half cores using an automated split-core logger. Data from core Lz1024 were acquired with a Bartington MS2E spot-reading sensor in combination with an MS2 control unit. MS on the ICDP 5011-1 cores was measured using a Bartington MS2E sensor first attached to an MS2 control unit, which was later replaced by a technically improved MS3 control unit. During data acquisition, blank readings against air were obtained after every 10 measurements in order to correct the data for subtle shifts in the sensor's background due to temperature drift.

Acquisition of magnetostratigraphic data (inclination and declination) was mainly performed on sediments sampled in U-channels (2×2 cm in cross-section) at 2 cm intervals. Below 145.7 m, the sediments were too stiff for extracting U-channels, so that sampling was accomplished with discrete samples every 10 cm, using 2×2×1.5 cm plastic boxes. From the lowermost core sections, irregularly shaped but consolidated pieces of core were directly placed into the magnetometer's sample holder. In all cases, magnetic polarity was determined from the results of stepwise alternating field demagnetization of the natural remanent magnetization in ten steps (5, 10, 15, 20, 30, 40, 50, 65, 80 and 100 mT) and subsequently applied principle component analysis according to KIRSCHVINK (1980).

The manganese/iron (Mn/Fe) and the silicon/titanium (Si/Ti) ratios in the sediments of Lake El'gygytgyn are sensitive proxies for the redox conditions and for the diatom primary production, respectively (MELLES et al. 2012, WENNRICH et al. 2014). These proxies were determined on half cores and U-channels using an X-ray fluorescence (XRF) core scanner (ITRAX, Cox Ltd., Sweden), equipped with a Mo-tube, which was set to 30 kV and 30 mA. XRF scanning was performed at 2 mm resolution using an integration time of 10 s per measurement. Since the element intensities derived from wet sediments, especially those of light elements such as Si, might be influenced by effects of the sediment matrix (LÖWEMARK et al. 2011), matrix-corrected Si counts were calculated from the raw Si integrals as described in MELLES et al. (2012).

The content of total organic carbon (TOC) in the 5011-1 composite record was determined at 2 cm step size by subtracting total inorganic carbon from total carbon measured with a DIMATOC carbon analyser (Dimatec Corp.) in aqueous suspension. TOC of percussion piston core Lz1024 was measured with a METALYT CS 1000S analyser (ELTRA Corp.) at 1 cm spacing, following sediment pre-treatment with 10 % HCl in order to remove calcium carbonate.

Palynological investigations of the ICDP 5011-1 composite record are restricted to selected intervals, yet. These include core intervals encompassing the Marine Isotope Stages MIS 1 (0-20 ka BP), MIS 5.5 (110-140 ka BP) MIS 11.3 (383-428 ka BP), and MIS 31 (1058-1088 ka BP) (MELLES et al. 2012). Pollen sample processing followed standard techniques used for organic-poor sediments (PALE STEERING COMMITTEE 1994). Water-free glycerol was used in sample storage and preparation of the microscopic slides. Pollen and spores as well as a number of non-pollen palynomorphs were identified and counted at magnifications of 400x and 1000x, with the aid of published pollen keys and atlases. Tablets containing *Lycopodium* marker spores were added to the samples to allow for calculation of pollen concentrations (DAVIS 1966). If available, at least 250 pollen grains were counted in each sample.

The best modern analogue (BMA) climate reconstruction, also known as modern analogue approach (e.g., OVERPECK et al. 1985, GUIOT 1990), assumes that pollen assemblages with a similar composition of taxa are produced by compositionally and structurally similar vegetation communities, which grow under similar climatic conditions. This assumption allows to identify the closest modern analogues for each analysed fossil sample by comparison with modern pollen samples included in the reference dataset. The modern climate parameters affiliated with the sites of modern pollen samples serve as the closest analogues and these values are then assigned to the analysed fossil samples and considered as reconstructed values of the past climate. A more detailed description of the method is provided by TARASOV et al. (2013).

The development of the age/depth model for the composite core ICDP 5011-1 followed a 3-step approach (MELLES et al. 2012, NOWACZYK et al. 2013). First-order tie points are provided by the magnetostratigraphic results, which show 16 polarity reversals for chrons, subchrons, and cryptochrons (HALTIA & NOWACZYK 2014; black diamonds in Fig. 4). Fourteen of these reversals are well defined in the El'gygytgyn lake sediment record. Only the top of the Kaena and the base of the Mammoth, both within the Gauss Chron, are somewhat ambiguous, when only palaeomagnetic information is considered. Another first-order tie point is provided for the base of the lacustrine sediment by the impact event, which is dated to 3.58 ±0.04 Ma (LAYER 2000), assuming that limnic sedimentation started shortly after. The age/depth record based on these first-order tie points then allowed to correlate fluctuations in palaeoenvironmental proxies with known climate events (blue dots in Fig. 4). This concerns correlations of the Si/Ti ratio and of the tree and shrub pollen concentrations with the LR04 oxygen isotope stack measured on benthic foraminifera from deep-sea sediments (LISIECKI & RAYMO 2005) as second-order tie points. These correlations assume that all glacial and interglacial MIS are present, as can be expected from the complete composite record, and are inherently associated with at least the uncertainties in the age model of the LR04 stack, which are estimated to be 6 ka for the time interval 3 to 1 Ma and 4 ka in the younger sediments (LISIECKI & RAYMO 2005). Fluctuations of MS and TOC were then correlated with the regional (67.5° N) cumulative spring/summer insolation (LASKAR et al. 2004) providing third-order tie points. These tie points take advantage of the observed environmental changes and coincident Northern Hemisphere summer insolation, which shows a stronger variability then the LR04 isotope stack. For the last ca. 700 ka, the age/depth model is confirmed by the results of infrared-stimulated luminescence (IRSL) dating (ZANDER & HILGERS 2013).

QUATERNARY SEDIMENTATION AND CLIMATE VARIABILITY

The upper 135 m of the sediment record at ICDP Site 5011-1 continuously represent the environmental history of the past 2.8 Ma (Fig. 4), with the Pliocene/Pleistocene boundary at 2.58 Ma occurring at 125.2 mblf. Disregarding volcanic ash layers and MMDs, the resultant pelagic sediments in this part of the record were formed by rather low and constant sedimentation rates of usually 4-5 cm kyr^{-1} and consist of three dominant lithofacies that reflect different climate modes (MELLES et al. 2012).

Glacial settings and variability

Facies A is characterized by dark grey to black, finely laminated (<5 mm) silt and clay (Fig. 5a). This facies was deposited during times of heavy global marine isotopic values and low regional July insolation (Fig. 6). It represents peak glacial conditions, when perennial lake ice persisted (MELLES et al. 2007), which according to numerical lake-ice modelling requires MAATs at least 3.3 ±0.9 °C lower than today (NOLAN 2013). The perennial lake ice cover resulted in a stagnant water column with oxygen-depleted bottom waters. This is reflected by low Mn/Fe ratios and minima in MS (Fig. 6),

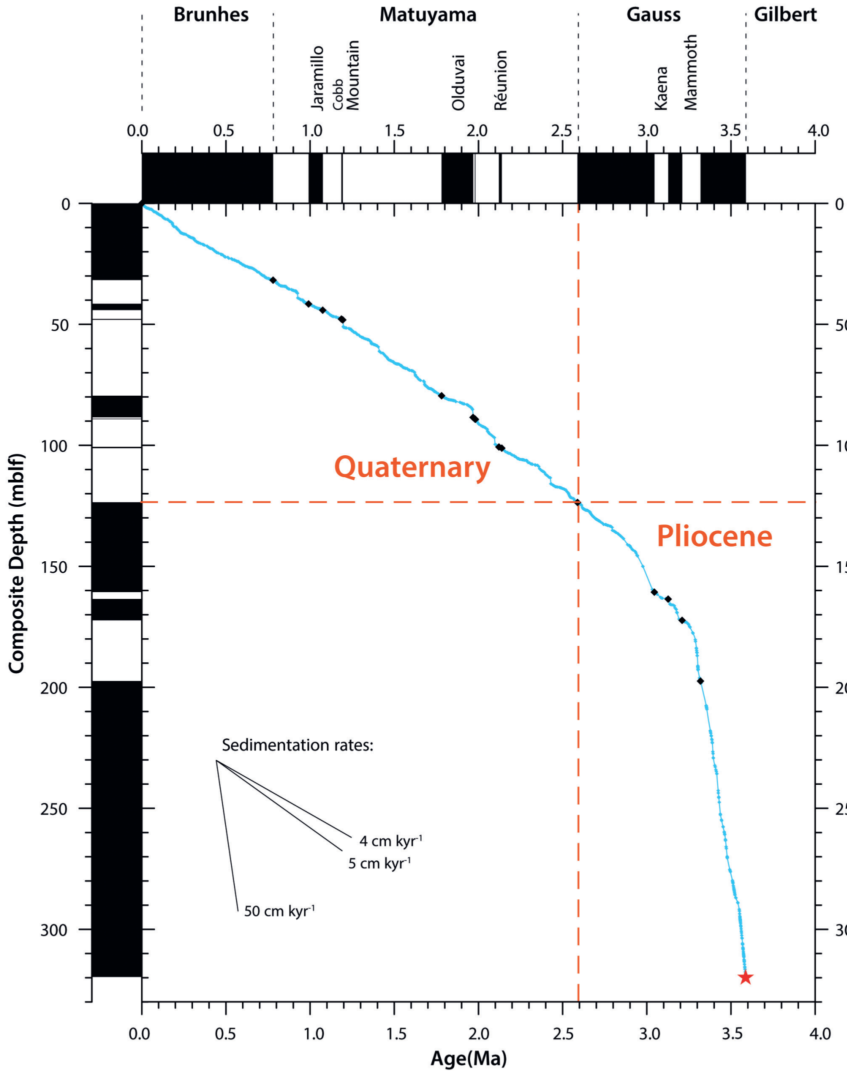

Fig. 4: Age/depth model with resulting sedimentation rates for the ICDP 5011-1 core composite after Melles et al. (2012). The age model is based on magnetostratigraphy (black diamonds) and correlation of sediment proxy data with a marine isotope stack (Lisiecki & Raymo 2005) and regional spring and summer insolation (Laskar et al. 2004; blue dots). The red asterisk marks the time of the impact according to Layer (2000).

Abb. 4: Alters/Tiefen-Modell und daraus resultierende Sedimentationsraten für das ICDP 5011-1 Kernkomposit nach Melles et al. (2012). Das Modell basiert auf magnetostratigraphischen Daten (schwarze Rauten) und Korrelationen von Stellvertreter-Daten (Proxies) mit gestapelten marinen Isotopendaten (Lisiecki & Raymo 2005) und der regionalen Frühjahrs- und Sommer-Sonneneinstrahlung (Laskar et al. 2004; blaue Punkte). Der rote Stern markiert die Zeit des Meteoriteneinschlags entsprechend Layer (2000).

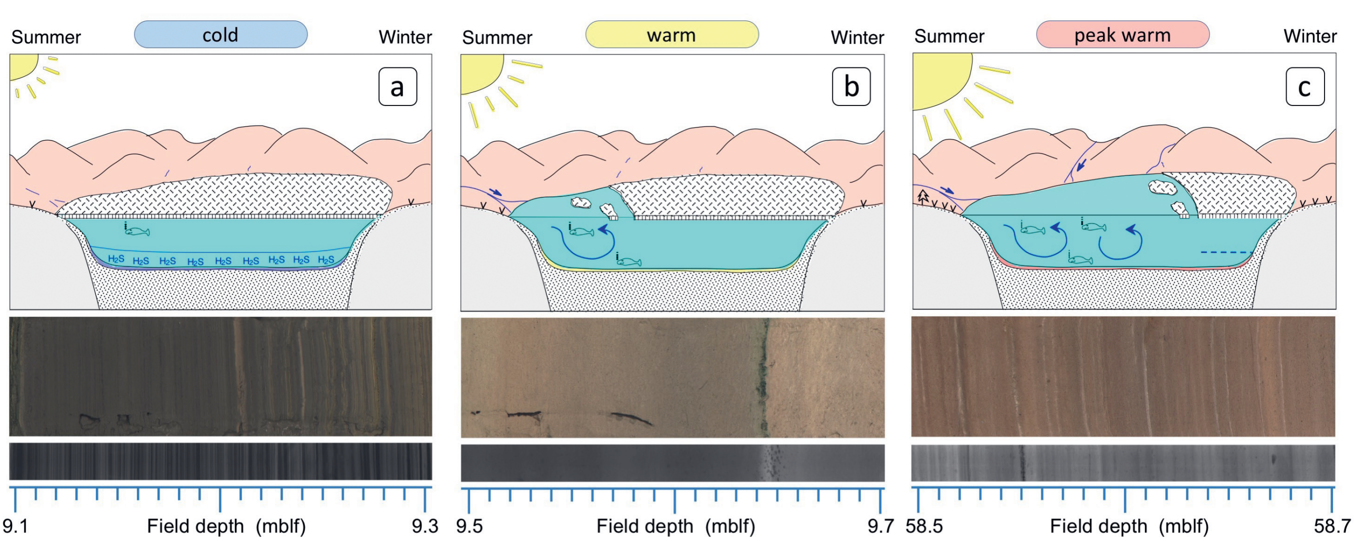

Fig. 5: Sketches of the environmental conditions from summer (left) to winter (right) at Lake El'gygytgyn during (a) cold, (b) warm, and (c) peak warm climate modes (after Melles et al. 2007, 2012), with the degree of vegetation and fluvial activity in the catchment, the duration of lake-ice coverage (illustrated by the extent of the ice), and the mixing, stratification, and biogenic production the water column. The line-scan pictures and X-radiographs below illustrate the characteristic structures of the corresponding sedimentary facies A, B, and C, respectively.

Abb. 5: Skizzen der Umweltbedingungen vom Sommer (links) bis zum Winter (rechts) am Elgygytgynsee während (a) kalter, (b) warmer und (c) sehr warmer Klimabedingungen (nach Melles et al. 2007, 2012), mit dem Grad der Vegetation und der fluvialen Aktivität im Einzugsgebiet, der Dauer der Seeeisbedeckung (über die Ausdehnung illustriert) und der Durchmischung, Stratifizierung und biogenen Produktion in der Wassersäule. Die Linescan-Fotos und Röntgenaufnahmen im unteren Bereich zeigen die charakteristischen Sedimentstrukturen der zugehörigen Sedimentfazies A, B und C.

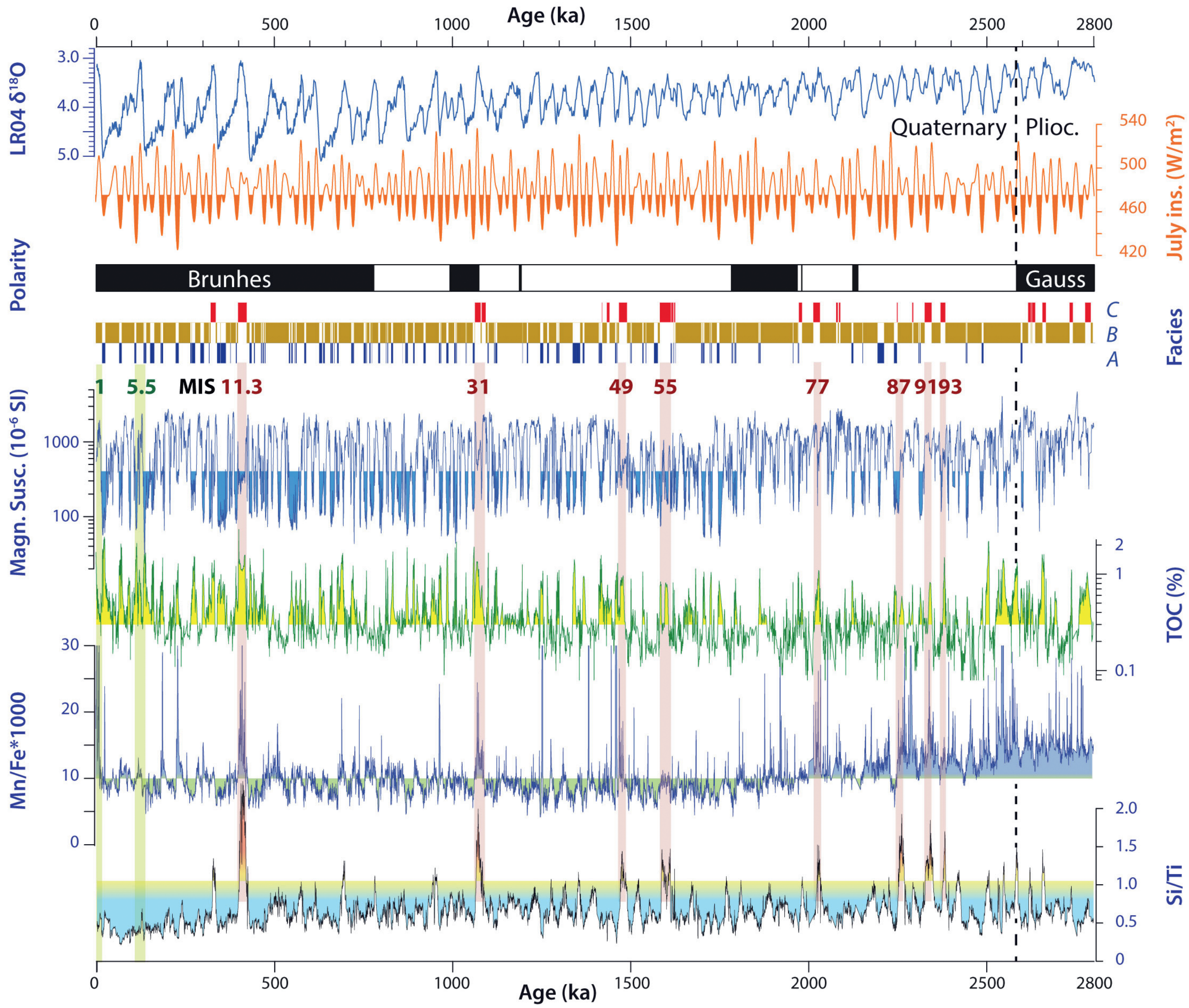

Fig. 6: From top to bottom: LR04 oxygen isotope stack analysed on benthic foraminifera from deep-sea sediments (Lisiecki & Raymo 2005) and mean July insolation for 67.5°N (Laskar et al. 2004) for the past 2.8 Ma compared to magnetostratigraphy, facies, magnetic susceptibilities, TOC contents, Mn/Fe ratios, and Si/Ti ratios in the sediment record from Lake El'gygytgyn (MS and XRF data are smoothed using a 500-year weighted running mean in order to improve the signal-to-noise ratio). Super interglacials at Lake El'gygytgyn are highlighted with red bars, the regular interglacials MIS 5.5 and MIS 1 with green bars.

Abb. 6: Von oben nach unten: Gestapelte Sauerstoff-Isotopendaten von benthischen Froraminiferen aus Tiefsee-Sedimenten (LR04; Lisiecki & Raymo 2005) und mittlere Sonneneinstrahlung im Juli bei 67,5°N (Laskar et al. 2004) für die vergangenen 2,8 Ma, verglichen mit der Magnetostratigraphie, den Fazies, der magnetischen Suszeptibilität, den TOC-Gehalten und den Mn/Fe- sowie Si/Ti-Verhältnissen in der Sedimentabfolge des Elgygytgynsees (die MS- und Verhältnis-Daten wurden mit einem laufenden gewichteten 500-Jahres-Mittelwert geglättet, um das Verhältnis Signal zu Rauschen zu verbessern). Die roten Balken kennzeichnen die Superinterglaziale am Elgygytgynsee, die grünen Balken die normalen Interglaziale MIS 5.5 und MIS 1.

which indicate reducing conditions with dissolution of the mineral magnetite and formation of the mineral vivianite, as confirmed by rock magnetic and mineralogical analyses (Nowaczyk et al. 2002, 2007, Koinig et al. 2003, Minyuk et al. 2013, 2014, Murdock et al. 2013). Dark laminations along with maxima in the content of TOC (Fig. 6) reflect the absence of bioturbation and enhanced preservation of organic matter. Reduced organic matter biodegradation is also indicated by the carbon-preference index based on *n*-alkanes in a case study on sediments assigned to MIS 8, MIS 10, and MIS 12 (D'Anjou et al. 2013). On the other hand, low Si/Ti ratios (Fig. 6) and a robust correlation between Si/Ti ratios and biogenic silica (BSi) contents (Melles et al. 2012, Meyer-Jacob et al. 2014) suggest relatively low primary production. Good sorting and small grain sizes of the clastic sediment components indicate that the perennial ice cover did not exclude fluvial sediment input into the lake, which probably took place via seasonal moats at the shore. However, higher contents of the fine fraction in the lake centre, compared to the modern sedimentation pattern, suggest that the intensity of lake currents was significantly reduced (Francke et al. 2013, Nolan 2013, Wennrich et al. 2014).

Based on differences in sediment composition, Facies A may reflect different degrees of humidy (Melles et al. 2007, Gebhardt et al. 2013, Frank et al. 2013). Particularly dry climate is indicated by Facies A sediments with relatively high TOC, total nitrogen, BSi, and diatom concentrations, as well as increased diatom diversity (Snyder et al. 2013), thus indicating somewhat enhanced bioproduction. This can best be explained by the absence of blanketing snow on the ice cover, which has a stronger impact on the limitation of light penetration into the water column then the consistency and thickness of the ice cover itself (Gore 1997). A largely bare lake-ice cover during the formation of this Facies A is also suggested by the common occurrence of elongated sediment clasts, which usually have a diameter of 1 to 2 mm and differ from the surrounding sediments by a grey colour and larger mean grain size. The clasts could have evolved by agglomeration of wind-blown particles during their transport through the ice along vertical conduits formed in late summer, similar to what is observed today on a perennially ice-covered lake without blanketing snow in the Dry Valleys, Antarctica (Squyres et al. 1991). In the course of the last three glacial/interglacial cycles, Facies A with the characteristics indicative for a particular dry climate occurred at Lake El'gygytgyn during MIS 8.4, MIS 8.2, MIS 7.4, MIS 6.6 and MIS 4, whereas more moist glacials and stadials, with reduced bioproduction and absence of sediment clasts presumably due to blanketing snow, are indicated for MIS 6.4, MIS 6.2, MIS 5.4, MIS 5.2, and MIS 2.

Facies A first appears 2,602-2,598 ka ago, during MIS 104 (Fig. 6), corresponding with pollen assemblages that indicate a significant cooling and the first occurrence of cold steppe habitats at the Pliocene/Pleistocene boundary (Andreev et al. 2014, 2016). This cooling coincided with distinct climatic deterioration at Lake Baikal (Demske et al. 2002), and may have been associated with the poorly dated Okanaanean Glaciation in eastern Chukotka at the beginning of the Pleistocene (Fradkina et al. 2005). It also seems to be synchronous with a major ice-sheet expansion in North America (Hidy et al. 2013, Bailey et al. 2013), and a drop in early spring sea-surface temperature in the North Atlantic (Hennissen et al. 2015). On the other hand, the first occurrence of Facies A at Lake El'gygytgyn clearly postdates the onset of stratification across the western subarctic Pacific Ocean at 2.73 Ma, an event believed to have triggered the intensification of Northern Hemispheric glaciation (Haug et al. 2005). Hence, the onset of full glacial cycles in central Chukotka cannot directly be linked to changes in the thermohaline circulation in the Pacific, but is rather the consequence of over-regional to hemispheric effects.

The long-term record of the occurrence of Facies A and the Mn/Fe ratios (Fig. 6) shows that pervasive glacial episodes at Lake El'gygytgyn gradually increased in frequency from ca. 2.3 to 1.8 Ma, eventually concurring with all glacials and several stadials reflected globally in stacked oxygen isotope records (e.g., Lisiecki & Raymo 2005). The full establishment of glacial/interglacial cycles by ca. 1.8 Ma at Lake El'gygytgyn coincides well with a major cooling and sea-ice expansion at the continental slope of the southern Bering Sea (Teraishi et al. 2016) and a shift in water-mass exchange between the Bering Sea and the North Pacific (März et al. 2013, Kim et al. 2016). It is also synchronous with enhanced glacial erosion in British Columbia (Shuster et al. 2005) and the onset of subpolar cooling in both hemispheres with an average bipolar temperature drop of 4 to 5 °C due to the emergence of the tropical Pacific cold tongue (Martinez-Garcia et al. 2010). On the other hand, this event clearly predates and thus is independent from the Mid-Pleistocene Transition (MPT) between 1.25 and 0.7 Ma ago, when the dominance of 41 ka obliquity was globally replaced by the 100 ka eccentricity cycle (Clark et al. 2006). The MPT at Lake El'gygytgyn seems to be reflected not by the frequency of full glacial conditions but by their duration. This is indicated in the MS record, which shows longer periods with low MS values in particular since 900 ka (Fig. 6), when an abrubt increase in Antarctic ice volume is believed to have initiated the MPT (Elderfield et al. 2012).

Interglacial settings and variability

The majority of the Quaternary sediments in Lake El'gygytgyn, including modern sedimentation, is composed of Facies B (Fig. 6). This facies is characterized by massive to faintly banded silt of olive grey to brownish colours (Fig. 5b). It reflects a wide range of stadial to interglacial settings, which have an only seasonal ice coverage in common (Melles et al. 2007, 2012, Frank et al. 2013, Gebhardt et al. 2013). Ice-free conditions during summer times allow wind and density-driven mixing of the water column. This leads to oxygenated bottom waters, as suggested by the sediment colours (Fig. 5b), low TOC contents due to enhanced degradation of organic matter, peaks of high MS resulting from high magnetite contents, and high Mn/Fe ratios (Fig. 6). Additional indication for oxic bottom waters comes from the occurrence of bioturbation, leading to the scarcity of stratification. Furthermore, oxic conditions are evident from layers rich in iron and manganese oxides, which are formed today in sediment depths of 20 to 30 cm, and whose fossil remnants form characteristic greenish bands (Fig. 5b). These bands may occur in the upper parts of Facies A, too, since there is a significant time lag between the age of the sediments the oxides are formed in and the formation age of the oxides. The only seasonal ice-cover on the lake during formation of Facies B, together with enhanced nutrient supply due to increased biological activity and chemical and cryogenic weathering in the catchment (Lozhkin & Anderson 2006, 2013, Asikainen et al. 2007, Schwamborn et al. 2012), promotes higher diatom productivity, which is indicated by high Si/Ti ratios (Fig. 6), high BSi contents (Meyer-Jacob et al. 2014), as well as high diatom concentrations and diversities (Cherepanova et al. 2007, Snyder et al. 2013).

Compared to Facies A and B, Facies C occurs only occasionally in the record, coinciding with some of the periods of light oxygen isotope values in the LR04 stack and high regional July insolation (Fig. 6). This facies consists of reddish-brown, silt-sized sediment with distinct fine laminations (<5 mm; Fig. 5c). The characteristics of Facies C suggest that it represents particularly warm interglacials. Exceptionally high Si/Ti ratios (Fig. 6), BSi contents (Vogel et al. 2013, Meyer-Jacob et al. 2014), dinosterol contents (D'Anjou et al. 2013), and diatom concentrations and diversities (Snyder et al. 2013) indicate very high primary production, presumably caused by a longer ice-free season and enhanced nutrient supply from the catchment relative to other interglacials. The reddish-brown sediment colours along with high Mn/Fe ratios (Fig. 6) imply well-oxygenated bottom waters. The lamination, on the other hand, evidences the wide absence of bioturbation. This cannot be due to quick burial, since the sedimentation rates during Facies C, despite the enriched BSi accumulation, are rather low (Nowaczyk et al. 2013), possibly due to a dense vegetation cover that significantly restricts clastic sediment supply from the catchment. The absence of bioturbation is believed to reflect winter stratification under a seasonal ice cover, in consequence of a particularly high primary production in spring and summer, that leads to a high organic matter flux and anoxic bottom water conditions during winter times (MELLES et al. 2012). This scenario could be in agreement with high TOC contents (Fig. 6), reflecting not only high primary production but possibly also incomplete decomposition compared to Facies B, as well as variable MS values (Fig. 6), presumably reflecting partial dissolution of magnetite in anoxic bottom waters.

The described characteristics of Facies C are most pronounced for MIS 11.3, MIS 31, MIS 49, MIS 55, MIS 77, MIS 87, MIS 91, and MIS 93 (red bars in Fig. 6), leading MELLES et al. (2012) to conclude that these interglacials represent unusual "super interglacials" in the Arctic throughout the Quaternary.

The exceptional character of the super interglacials becomes evident based upon a comparison of MIS 1 and MIS 5.5 (Facies B) with MIS 11.3 and MIS 31 (Facies C), using additional biological proxies and pollen-based climate reconstructions (Fig. 7).

Sediments formed in Lake El'gygytgyn during MIS 1 and 5.5 have Si/Ti ratios only slightly higher than those formed during glacial and stadial conditions of the adjacent MIS 2, MIS 5d, and MIS 6 (Fig. 7). Pollen data show distinct increases in tree and shrub pollen and suggest that notably birch and alder shrubs dominated the vegetation (LOZHKIN et al. 2007a,b). Our BMA climate reconstructions suggest that the mean temperature of the warmest month (MTWM; i.e., July) and the annual precipitation (PANN) during the peaks of MIS 1 and MIS 5.5 were only ~1-2 °C and, with a few exceptions, ca. 50 mm higher than today, respectively (MELLES et al. 2012, TARASOV et al. 2013).

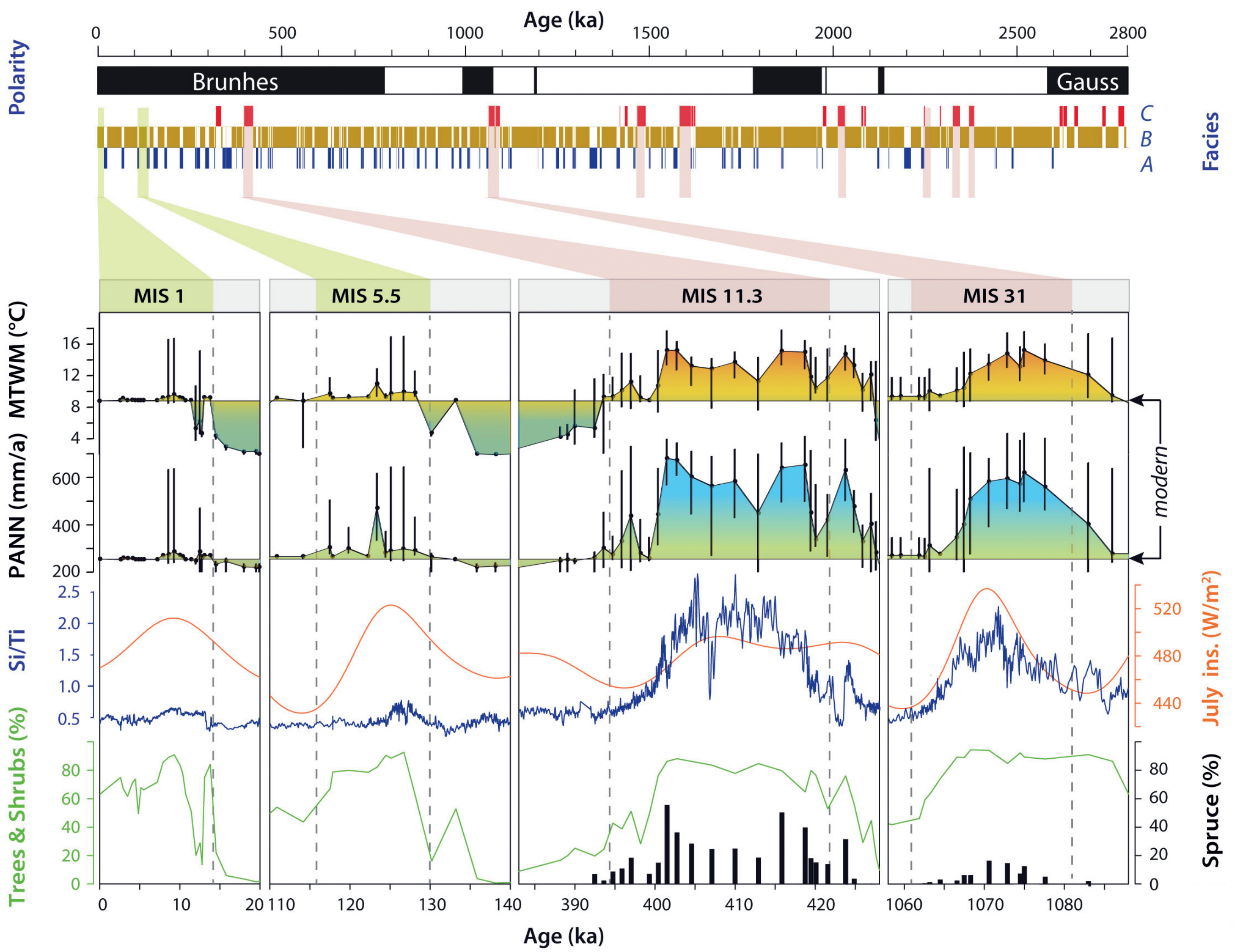

Fig. 7: From top to bottom: Magnetostratigraphy and facies at Lake El'gygytgyn for the past 2.8 Ma, with expanded views into the interglacials MIS 1, 5.5, 11.3, and 31 and neighbouring glacials/stadials, showing reconstructed mean temperatures of the warmest month (MTWM) and reconstructed annual precipitation (PANN) based on the pollen spectra and best modern analogue approach (with error bars; modern values from NEW et al. 2002), mean July insolation for 67.5°N (LASKAR et al. 2004) compared to El'gygytgyn Si/Ti ratios (smoothed by 5-point weighted running mean), and tree and shrub pollen percentages compared to spruce pollen content.

Abb. 7: Von oben nach unten: Magnetostratigraphie und Fazies am Elgygytgynsee für die vergangenen 2,8 Ma, mit Herausvergrößerungen der Interglaziale MIS 1, 5.5, 11.3 und 31 einschließlich benachbarter Glaziale/Stadiale. Die Vergrößerungen zeigen Rekonstruktionen der mittleren Temperatur des wärmsten Monats (MTWM) und des jährlichen Niederschlages (PANN) basierend auf den Pollenspektren und dem Ansatz der besten modernen Analoge (mit Fehlerbalken; rezente Werte aus NEW et al. 2002), die mittlere Sonneneinstrahlung im Juli bei 67.5°N (LASKAR et al. 2004) im Vergleich zum Si/Ti-Verhältnis im Elgygytgynsee-Kern (mit einem laufenden gewichteten 5-Punkt-Mittelwert geglättet), und die Prozente von Baum- und Strauchpollen im Vergleich zu den Prozenten von Fichtenpollen.

This is consistent with temperature reconstructions for the Holocene thermal maximum, which indicate +1.6 (±0.8) °C warming in the western Arctic (Kaufman & Brigham-Grette 1993) and +1.7 (±0.8) °C across the entire Arctic (Miller et al. 2010a,b) relative to modern. In contrast, published temperature reconstructions for the MIS 5.5 thermal maximum are more variable, indicating +5 (±1) °C across the entire Arctic, even though smaller anomalies were reconstructed for the Pacific sector (Miller et al. 2010a,b). The presumed warmer climate across the Arctic during MIS 5.5 compared to MIS 1 is thought to have caused a size reduction of the Greenland Ice Sheet (GIS) equivalent to 1.6-2.2 m in global sea-level rise (Colville et al. 2011, cf. NEEM Community Members 2013). Two more recent studies come to conflicting conclusions in this respect: while Schaefer et al. (2016) found indications that Greenland was nearly ice-free for extended periods under Pleistocene climate forcing, including MIS 5.5, data of Biermann et al. (2016) suggest that the GIS, although being dynamic, persisted for most of the last 7.5 Ma. The El'gygytgyn temperature reconstructions for MIS 5.5 support the latter study, if they record regional rather than just local climate, as suggested by modern data (Nolan 2013) and by the comparison of the temperature reconstructions for the Holocene with published data presented here.

During the super interglacials MIS 11.3 and MIS 31, the strongly enhanced primary productivity compared to MIS 1 and MIS 5.5 is associated with comparable maxima in tree and shrub pollen (Fig. 7), but marked by distinct differences in pollen composition (Lozhkin & Anderson 2013). For instance, substantial spruce pollen is present during MIS 11.3 and MIS 31, but is missing during shrub-dominated MIS 1 and MIS 5.5 interglacials. According to the BMA climate reconstruction, maximum MTWM and PANN were up to 4-5 °C and ~300 mm higher than those of MIS 1 and MIS 5.5, respectively (Fig. 7). The extreme temperatures are confirmed by recent high-resolution biomarker-based temperature reconstructions on MIS 31 sediments from Lake El'gygytgyn (de Wet et al. 2016).

Other records of super interglacials in the Arctic are sparse and/or poorly dated. One of the early Pleistocene super interglacials recorded at Lake El'gygytgyn (Fig. 6) might be correlative to Member B of the Kap København Formation, northern Greenland, which was initially dated to about 2.0 Ma by Repenning et al. (1987) and Matthews & Ovenden (1990), but according to Funder et al. (2001) could be as old as about 2.4 Ma. These deposits imply temperatures nearly 6 °C above present, as well as an ice-free Greenland, a strong sea-ice reduction, and a shift of the treeline ca. 1000 km further north than today, i.e. to the coast of the Arctic Ocean. Rather similar climatic and environmental setting were deduced from the Store Koldewey formation in northeast Greenland, which was deposited 1.9 - 1.7 Ma ago (Bennike et al. 2010). Another candidate for super interglacials is the balmy Bigbendian Transgression of the Gubik Formation in northern Alaska, which was dated to about 2.6 Ma (Brigham-Grette & Carter 1992). The Gubik Formation includes at least five sea-level highstands associated with episodes of warm climate and reduced sea ice. One of those, the Fishcreekian transgression, is now thought to be ca. 1.2 Ma old (Goodfriend et al. 1996) and thus may be correlative with MIS 31. This also holds true for a site at Fosheim Dome on Ellesmere Island, where terrestrial deposits were dated to about 1.1 Ma, which enclose fossil beetle (Coleoptera) assemblages suggesting temperatures 8 to 14 °C above modern values (Elias & Matthews 2002).

More is known about the latest super-interglacial MIS 11.3. Recent studies on sediment cores from the Mendeleev and Northwind Ridges clearly show that an extreme warming during MIS 11 also took place in the central Arctic Ocean, with summer sea-surface temperatures (SST) 8 to 10 °C higher than today and significantly reduced sea-ice coverage (Cronin et al. 2013, Polyak et al. 2013). Unusually warm, high sea-level conditions during MIS 11 were also deduced from the diatom assemblages of the Cape Blossom and Hotham Inlet formations on Baldwin Peninsula, NW Alaska (Pushkar et al. 1999), however, the age assignment for these deposits is regarded questionable (Hillenbrand et al. 2009). In any case, isotope-based provenance and pollen investigations on marine sediments of the Eirik Drift (de Vernal & Hillaire-Marcel 2008, Reyes et al. 2014), and DNA analyses of basal ice of the Dye 3 ice core (Willerslev et al. 2007), suggest an almost complete deglaciation of South Greenland and the spread of boreal forests during MIS 11. An even complete loss of the GIS during MIS 11, equivalent to a sea-level rise of 4.5 to 6 m, was assumed from modelling studies (Reyes et al. 2014). Findings of exceptional warm conditions in the records of Lake Baikal, southern Siberia (Prokopenko et al. 2010), and Lake Biwa, Japan (Tarasov et al. 2011), as well as in the mid-latitude Atlantic Ocean (Stein et al. 2009) and in the Belize Reef (Gischler et al. 2010), suggest that the MIS 11 warming was not restricted to the Arctic.

Interglacial forcing mechanisms and feedbacks

In order to investigate potential reasons for the super interglacials at Lake El'gygytgyn, the response of a Global Climate Model (GCM) to the orbital and greenhouse gas (GHG) forcings during the insolation maxima in MIS 1, MIS 5.5, MIS 11.3, and MIS 31 was tested. The modelling results revealed that much of the extraordinary warmth of MIS 31 could be due to elevated GHG levels (DeConto et al. 2012). The equally elevated MTWM and PANN during MIS 11.3, in contrast, can neither be explained by the GHG concentration, nor to orbital forcing or feedbacks in the climate system associated with boreal forest expansion, decay of the GIS, or meltwater impacts on oceanic overturning (Melles et al. 2012). This suggests that other processes and feedbacks contributed to the extraordinary climate at least during MIS 11.

The super interglacials at Lake El'gygytgyn coincide remarkably with diatomite layers in the Antarctic ANDRILL 1B record (Fig. 8). This is most obvious for MIS 31, which is well dated in both records, due to its coincidence with the onset of the palaeomagnetic Jaramillo Subchron (Fig. 7). Deeper in time, the super interglacial MIS 55 at Lake El'gygytgyn may coincide with a diatomite deposited in the Ross Sea from MIS 54 to MIS 58, and MIS 77, MIS 87, MIS 91, and MIS 92 in the lake record may coincide with four diatomites deposited between MIS 74 and MIS 104 at the ANDRILL 1B site. Super interglacials MIS 11.3 and MIS 49 appear not to be correlative with diatomites in the Ross Sea. However, this could be caused by unconformities in the ANDRILL 1B record (McKay et al. 2009, 2012).

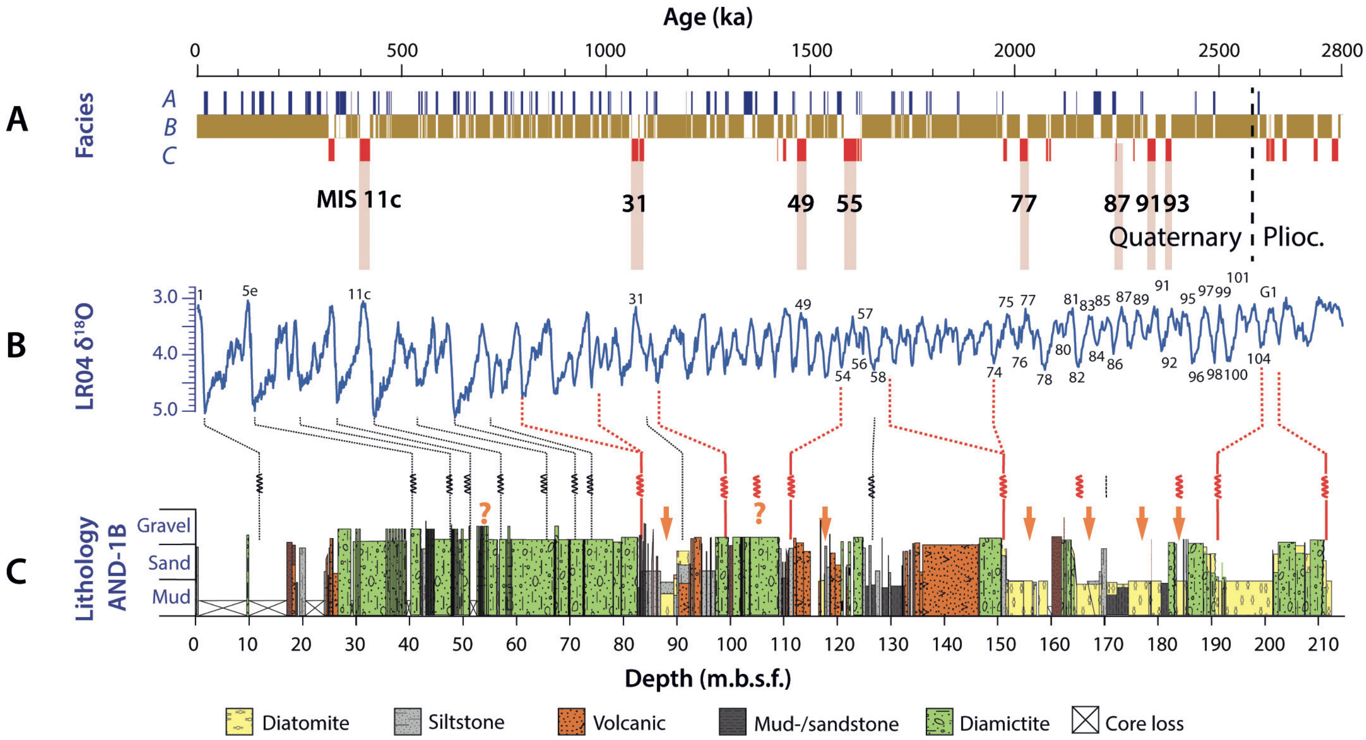

Fig. 8: Stratigraphic correlation of the super interglacials at Lake El'gygytgyn with diatomites in the ANDRILL 1B record from the Ross Sea, Antarctica (after Melles et al. 2012), which are interpreted to mark major retreats of the Antarctic ice sheets. The facies succession in the El'gygytgyn record throughout the past 2.8 Ma is indicated in the upper part of the figure. The middle part displays the LR04 global marine isotope stack (Lisiecki & Raymo 2005), with selected marine isotope stages indicated by numbers. The lower part indicates the lithology of the uppermost 215 m of the ANDRILL 1B record (m.b.s.f.: metres below seafloor), modified from McKay et al. (2009, 2012) and correlated to the LR04 stack (dashed and solid lines) according to Naish et al. (2009). There, Quaternary diatomites are highlighted with orange arrows, and saw-toothed lines indicate larger (red) and smaller (black) unconformities.

Abb. 8: Stratigraphische Korrelation der Superinterglaziale am Elgygytgynsee mit den Diatomitlagen im Kern ANDRILL 1B aus dem Rossmeer, Antarktis (nach Melles et al. 2012), die großflächige Rückzüge der antarktischen Eisschilde anzeigen sollen. Der obere Teil der Abbildung zeigt die Faziesabfolgen im Elgygytgynsee im Verlauf der vergangenen 2,8 Ma. Im mittleren Teil sind die gestapelten globalen marinen Isotopendaten LR04 (Lisiecki & Raymo 2005) mit ausgewählten marinen Isotopenstadien (Nummern) dargestellt. Der untere Teil zeigt die Lithologie in den obersten 215 m im Kern ANDRILL 1B (m.b.s.f.: Meter unter dem Meeresboden), modifiziert nach McKay et al. (2009, 2012) und korreliert mit dem LR04 (gestrichelte und durchgezogene Linien) entsprechend Naish et al. (2009). Die quartären Diatomite sind darin durch orange Pfeile hervorgehoben und die gezackten Linien deuten größere (rot) und kleinere (schwarz) Diskordanzen an.

The diatomites in the Ross Sea were interpreted to reflect periods of open water in the Ross Embayment due to a collapsed Ross Ice Shelf, which according to ice-sheet modelling would have led to collapses of the West Antarctic Ice Sheet (WAIS; Naish et al. 2009, Pollard & DeConto 2009). However, provenance studies by Talarico et al. (2012) evidenced that the ANDRILL site throughout the entire Quarternary was affected exclusively by ice draining the East Antarctic Ice Sheet (EAIS). Indeed, at least during MIS 31 significant changes took place not only in the WAIS but also around Antarctica, including a southward shift of the subtropical front and warmer waters in the Southern Ocean (Scherer et al. 2008, Maiorano et al. 2009, Villa et al. 2012).

The likely synchronicity of the super interglacials at Lake El'gygytgyn with retreats of the Antarctic ice sheets points to strong intra-hemispheric climate coupling that could be related to reductions in Antarctic Bottom Water (AABW) formation (Foldvik et al. 2004) during times of ice sheet and ice shelf retreat and elevated fresh water input into the Southern Ocean. This suggestion is supported by distinct minima in AABW inflows into the southwest Pacific during MIS 11 and MIS 31 (Hall et al. 2001). As a consequence, changes in thermohaline circulation during these periods might have reduced upwelling in the north-western Pacific Ocean (Galbraith et al. 2007), as indicated by distinctly lower BSi accumulation rates compared to other interglacials at ODP Site 882 (Haug et al. 1995, Jaccard et al. 2005). A stratified water column during the super interglacials would have resulted in higher sea surface temperatures in the north-western Pacific, with the potential to raise air temperatures and precipitation rates over adjacent land masses via effects on the dominant pressure patterns (Nolan et al. 2013).

An alternative or additional mechanism linking Lake El'gygytgyn with Antarctica could be related to a higher eustatic sea level due to the combined retreats of the Antarctic ice sheets (e.g., Naish et al. 2009) and the GIS (e.g., Willerslev et al. 2007, Schäfer et al. 2016), which for MIS 11 may have been in the order of 6 to 13 m above modern (Raymo & Mitrovica 2012, Dutton et al. 2015). Such sea-level rises may have resulted in enhanced warm-water intrusions into the Arctic Ocean. Potential gateways affected by intrusions from the Atlantic Ocean may have been the Denmark Strait and the Barents Sea, while the Bering Strait may have been affected by intrusions from the Pacific Ocean. In the north-eastern Atlantic, however, other than in the north-western Pacific, SSTs at least during MIS 11 were lower than during MIS 9, MIS 5.5 and MIS 1 (Helmke & Bauch 2003). In the Bering Strait, sea-level rises might have particularly strong impacts, since its through-flow today is restricted by water depths of less than ca. 50 m, resulting in an average northward transport of ~0.8 Sv (1 Sv = 10^6 m^3 s^{-1}; WOODGATE et al. 2010). Evidence for an increased inundation of warmer Pacific waters into the Arctic Ocean via the Bering Strait, associated with severe sea-ice reduction, has been provided for MIS 11 by specific ostracod and foraminifera assemblages in the central Arctic Ocean (CRONIN et al. 2013, POLYAK et al. 2013). Comparable to postulated mid-Pliocene conditions, warmer water masses and reduced sea-ice in the Arctic Ocean could have amplified the warming through subsequent feedbacks, thus leading to an exceptional temperature rise on the adjacent landmasses (SERREZE et al. 2009, WOODGATE et al. 2010). This scenario, however, could not be confirmed by GCM modelling of an increased through-flow by 3 Sv, being equivalent to an additional 8 Wm^{-2} of ocean heat flux convergence under sea ice, which results in substantial reductions in seasonal sea ice and warmer Arctic SSTs, but contributes little additional warming (<7 °C) in the Beringian interior (MELLES et al. 2012, COLETTI et al. 2015).

CONCLUSIONS

The El'gygytgyn Drilling Project in the Russian Arctic was a huge logistical undertaking that required pre-site surveys over several years, fundraising from a variety of national and international sources, and complex preparations and technical developments. It took almost 20 years from the first international expedition in 1998 via the challenging drilling operations in 2008/2009, towards extensive laboratory analyses, data interpretation, and publication of major findings.

The investigations of the lake sediment record from the El'gygytgyn crater, although still in progress, have already set a benchmark for palaeoclimatic research. They have opened the first almost continuous window towards the history of the terrestrial Arctic back to 3.6 Ma, 30 times deeper in time than the longest ice cores from Greenland. Amongst the results obtained are new findings concerning the variability of glacials and interglacials over the past 2.8 Ma, and the reasons for differences in their intensities. It was found that both, the first occurrence and the full orbital frequency, of full glacial conditions at Lake El'gygytgyn were triggered by overregional and hemispheric processes rather than changes in the thermohaline circulation of the northern Pacific Ocean. In contrast, the intensities of the interglacials were, at least partly, driven by reductions of the upwelling in the adjacent northern Pacific. Alternatively, or in addition, they may be controlled by the intensity of warm-water intrusions from the Pacific Ocean into the Arctic Ocean. Both the upwelling and the Bering Strait through-flow seem to be dependent on repeated deglaciation events in Antarctica and their impacts on global oceanic circulation and eustatic sea level.

Despite the important contributions the El'gygytgyn Drilling Project has already made to palaeoclimatological research, in particular on Arctic Amplification and teleconnections between both polar regions, substantial work still needs to be done to answer open or newly arising questions.

First, additional analytical work has to be conducted on the lake sediment record. This includes closure of large gaps still existing in some data sets (e.g., pollen, diatoms, biomarker, diatom isotopes), improvement of the data densities and thus time resolutions (almost all but XRF scanner and MSC logger data), and employment of new proxies (e.g., black carbon, tephra dating by Ar/Ar). Many of these data are also needed to verify and, if necessary, improve and revise the existing age model.

Second, it still is a partly open question, how representative the Lake El'gygytgyn record is for the circum-arctic climatic and environmental history. This needs to be tested by comparisons with terrestrial sediment records from different parts of the Arctic, which have a comparable time-resolution, cover at least the last climate cycle, and are investigated with comparably complex approaches. Attempts are currently made by the Norwegian-Russian project CHASE (Climate History along the Arctic Seaboard of Eurasia) and the German-Russian Project PLOT (Palaeolimnological Transect) to recover such records from the Russian Arctic.

Third, in order to decipher the respective roles the Pacific Ocean and the Arctic Ocean have played for the climatic and environmental changes detected in the Lake El'gygytgyn record, the findings need to be compared with comparably long and continuous records from the adjacent oceans. Such records have already been recovered in the northern Pacific Ocean and in the Bering Sea, most recently on the Integrated Ocean Drilling Program (IODP) Expedition 323 in 2009. Until today scientific drilling in the Arctic Ocean is restricted to the ACEX project (Arctic Coring Expedition, IODP Expedition 323), which recovered a drill core from the Lomonosov Ridge in 2004. Unfortunately, the sequence of Pliocene and Pleistocene sediments in this core is highly discontinuous. However, it is planned to recover a more complete and better resolved record during the International Ocean Discovery Program (IODP) Expedition 377 in summer 2018 (STEIN et al. 2015).

Fourth, the likely coincidence of the super interglacials in the Arctic with decays of the Antarctic ice sheets, as suggested by the comparison with the ANDRILL 1B record, still needs to be confirmed and investigated in more detail. This requests new marine drill cores from locations, which are proximal enough to the Antarctic continent to reflect changes in size and volume of the ice sheet, cover significant parts of the Quaternary, in particular those not represented by the ANDRILL cores due to the frequent unconformities in that record, and ideally are distributed around the continent to allow for the investigation of circum-Antarctic similarities and differences in the ice sheet behaviours. Respective records will likely be recovered in the next few years in the course of approved IODP expeditions, in particular expeditions 374 (Ross Sea West Antarctic Ice Sheet History, scheduled for January-March 2018), 379 (Amundsen Sea West Antarctic Ice Sheet History, January-March 2019), and 382 (Iceberg Alley Palaeoceanography, March-May 2019).

And fifth, the geological analyses on the different records need to be accompanied by climate modelling, which explicitly accounts for glacial-interglacial changes in regional sea-level (palaeobathymetry and gateways), sea-ice, land-ice and permafrost distributions, vegetation cover, and meltwater flow in the Arctic. The response of the region's climate and terrestrial ecosystems to a range of interglacial forcing provides a challenge for modelling and important constraints on climate sensitivity and polar amplification.

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