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A high-resolution mid-Pleistocene temperature record from Arctic Lake El'gygytgyn: a 50 kyr super interglacial from MIS 33 to MIS 31?

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ABSTRACT

Previous periods of extreme warmth in Earth's history are of great interest in light of current and predicted anthropogenic warming. Numerous so called "super interglacial" intervals, with summer temperatures significantly warmer than today, have been identified in the 3.6 million year (Ma) sediment record from Lake El'gygytgyn, northeast Russia. To date, however, a high-resolution paleotemperature reconstruction from any of these super interglacials is lacking. Here we present a paleotemperature reconstruction based on branched glycerol dialkyl glycerol tetraethers (brGDGTs) from Marine Isotope Stages (MIS) 35 to MIS 29, including super interglacial MIS 31. To investigate this period in detail, samples were analyzed with an unprecedented average sample resolution of 500 yrs from MIS 33 to MIS 30. Our results suggest the entire period currently defined as MIS 33–31 (∼1114–1062 kyr BP) was characterized by generally warm and highly variable conditions at the lake, at times out of phase with Northern Hemisphere summer insolation, and that cold "glacial" conditions during MIS 32 lasted only a few thousand years. Close similarities are seen with coeval records from high southern latitudes, supporting the suggestion that the interval from MIS 33 to MIS 31 was an exceptionally long interglacial (Teitler et al., 2015). Based on brGDGT temperatures from Lake El'gygytgyn (this study and unpublished results), warming in the western Arctic during MIS 31 was matched only by MIS 11 during the Pleistocene.

1. Introduction

Placing predicted future climate change into a broader context necessitates detailed paleoclimate reconstructions that extend beyond the last glacial period, especially from high latitudes where such changes are expected to be the largest (Stocker et al., 2013). The term "super interglacial" has been used to describe periods in the past that appear to have been characterized by exceptionally warm conditions (DeConto et al., 2012; Melles et al., 2012; Pollard and DeConto, 2009), and as such are of great interest when searching for analogues of future climate. One such period is Marine Isotope Stage (MIS) 31, defined as 1.082–1.062 million years before present (Ma BP) by Lisiecki and Raymo (2005) (NB: in this study we refer to MIS boundaries as defined by the LR04 stack). Paleoclimate records from this period are desirable because MIS 31 falls beyond the current temporal range of the Antarctic ice cores, yet occurred during the Pleistocene, when the climate system and oceanographic gateways were generally similar to today's.

MIS 31 was characterized by the highest summer insolation receipts at high latitudes of the past 1.2 Ma (Laskar et al., 2004), as well as some of the lowest oxygen isotopic values in the composite LR04 benthic stack (Lisiecki and Raymo, 2005). It has been identified as a period of extreme warmth in the southern high latitudes (e.g. Maiorano et al., 2009; Teitler et al., 2015) and is also the last time strong proxy evidence is available for a collapse of the West Antarctic Ice Sheet (WAIS) (McKay et al., 2012; Naish et al., 2009; Villa et al., 2012). In the Northern Hemisphere (NH), the vast majority of paleoclimate reconstructions that cover this period are marine sediment records, with notable exceptions being sediments from Lake Baikal (Khursevich et al., 2005) and the Chinese loess archives (e.g. Sun et al., 2010). However, no high-resolution terrestrial paleotemperature reconstructions from MIS 31 currently exist.

Here we present data from the Lake El'gygytgyn (northeast Russia) sediment record, which provides continuous coverage of MIS 31 (Melles et al., 2012). Our high-resolution brGDGT-based paleotemperature reconstruction spans MIS 33–31 (∼1114–1050 kyr BP) at a time step of approximately 500 years. We find that MIS 31 in the Arctic experienced some of the warmest temperatures of the Pleistocene, but that peak warmth occurred out of phase with local summer insolation. Additionally, it appears that glacial conditions preceding this interval, during glacial stage 32, were short-lived in the Arctic. This finding partially echoes recent evidence from the Southern Hemisphere (Teitler et al., 2015), where it was suggested

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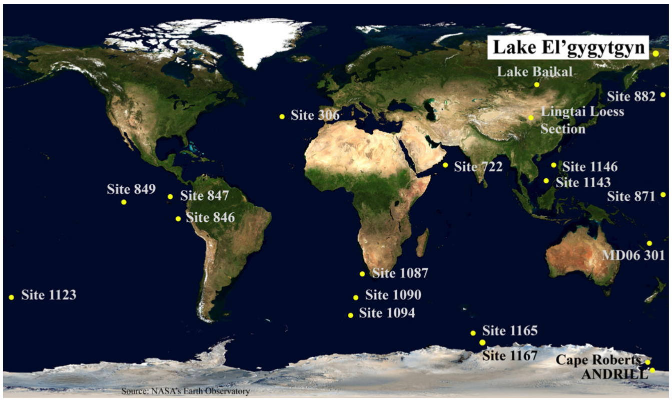

Fig. 1. Approximate location of Lake El'gygytgyn in NE Siberia and other locations relevant to this study. Background image source: NASA's Earth Observatory.

that MIS 32 was warm at southern high latitudes and should be relegated to a stadial period instead of a glacial stage. The global signature of MIS 33–31 is discussed and potential teleconnections that could link changes in Antarctica and Lake El'gygytgyn are explored.

2. Site description

The composite sediment core from Lake El'gygytgyn is exceptional in that it provides an archive of terrestrial paleoclimate covering the past 3.6 Ma (million years) from within the Arctic Circle (Fig. 1) (Brigham-Grette et al., 2013). This site has already provided numerous insights into high latitude climate over the Plio-Pleistocene (Brigham-Grette et al., 2013; Melles et al., 2012; Climate of the Past Special Issue: Initial results from lake El'gygytgyn, western Beringia: first time-continuous Pliocene–Pleistocene terrestrial record from the Arctic), and MIS 31 has been identified as one of over a dozen "super interglacials" within this record. Warm conditions during this interval have been identified in other proxy reconstructions from Lake El'gygytgyn, such as pollen-based paleotemperatures, total organic carbon and biogenic silica concentrations, and elemental ratios (Melles et al., 2012).

Lake El'gygytgyn is located approximately 100 km north of the Arctic Circle in northeastern Siberia (67.5°N, 172°E) (Fig. 1) and was created 3.58 ± 0.25 Ma by a meteorite impact (Layer, 2000). The lake has a diameter of 12 km, with a total surface area of 110 km^2, and is 170 m deep. Today, the continental Arctic climate leads to tundra vegetation occupying the surrounding catchment and ice cover on the lake for 10 months of the year (Nolan and Brigham-Grette, 2007). The lake is classified as oligotrophic to ultra-oligotrophic, with full overturning occurring during the summer leading to an oxygenated water column throughout the year (Melles et al., 2012; Nolan and Brigham-Grette, 2007). Measurements from a thermistor string deployed in the lake indicates water temperatures vary from 0 to 4 °C (Nolan and Brigham-Grette, 2007). Measured air temperatures at the lake over the calendar year 2002 indicate a mean annual air temperature (MAAT) of −10.3 °C, with a maximum temperature of 26 °C and a minimum of −40 °C. Average temperatures in July were ∼10 °C, which was shown to be representative of the broader region (Nolan and Brigham-Grette, 2007).

The lake was drilled during the winter of 2008/2009, resulting in a composite sediment sequence of ∼320 m. The age model for the core is based primarily on magnetostratigraphy and tuning of paleo-productivity proxies to the benthic oxygen isotope stack and insolation curves (Haltia and Nowaczyk, 2014; Nowaczyk et al., 2013). Age uncertainty during the MIS 31 section of the core is, therefore, related to uncertainties in the LR04 stack (estimated to be up to 6 kyr from 1 to 3 Ma), but Nowaczyk et al. (2013) note that "relative age assignments to the reference records should have a precision of ∼500 yr since many (3rd order) tie points were derived from the insolation reference record, which has a higher temporal resolution". Identification of MIS 31 in the composite sequence is aided by the presence of the Jaramillo paleomagnetic reversal (0.991–1.073 Ma) (Haltia and Nowaczyk, 2014). For further details the reader is referred to Nowaczyk et al. (2013). Sedimentation rates were relatively high during the Pliocene (∼50 cm kyr^{-1}), and then decreased during the Pleistocene (∼4–5 cm kyr^{-1}), with brief intervals of much higher sedimentation (Supplementary Materials) (Melles et al., 2012). During the MIS 35–29 study interval, the sedimentation rate varies from ∼5–30 cm kyr^{-1} (Supplementary Materials). The MIS 31 section of the core spans approximately 100 cm.

3. Methods

For this study 143 sediment samples (∼1–8 g dry mass) were taken spanning MIS 29–35 (approx. 1010–1145 kyr BP). The majority of samples from MIS 33 to MIS 31 were taken at centimeter increments, resulting in a sample resolution of ∼500 years per sample. The sediment was freeze-dried and homogenized using a mortar and pestle before lipid extraction.

A total lipid extract (TLE) was obtained using a Dionex accelerated solvent extractor (ASE 200). Samples were extracted with a dichloromethane (DCM)/methanol (9:1, v/v) mixture at 100 °C. The TLE was then separated into two fractions, apolar (9:1 DCM:hexane, v/v) and polar (1:1 DCM:methanol), using alumina oxide column chromatography. Polar fractions were filtered in 99:1 hexane:isopropanol using a 0.45 μm PTFE syringe filter. A C_{46} GDGT internal standard was added to all polar fractions prior to analysis.

BrGDGTs were identified and quantified via high performance liquid chromatography – mass spectrometry using an Agilent 1260 HPLC coupled to an Agilent 6120 MSD following the methods of Hopmans et al. (2000) with minor modifications (Schouten et al., 2007). For compound separation a Prevail Cyano column (150 × 2.1 mm, 3 μm) was used. Two solvent mixtures were used as eluents: mixture A) 100% hexane; mixture B) 90% hexane, 10% isopropanol (v/v). Samples were eluted with 10% mixture B for 5 minutes, which was then linearly increased to 18% mixture B from minutes 5 to 39, and finally increased to 100% mixture B for 1 minute. Scanning was performed in selected ion monitoring (SIM) mode. Concentrations were calculated by comparing brGDGT HPLC-MS chromatogram peak areas with peak areas of a known concentration (C_{46} GDGT standard added to every sample run). These values were then normalized to the mass of sediment extracted.

Further paleoenvironmental conditions were reconstructed using two indices based on brGDGT concentrations as originally defined by Weijers et al. (2007). The first is the cyclization ratio of branched tetraethers (CBT) (Eq. (1)). This index measures the relative amount of cyclopentyl moieties in the branched GDGTs, which Weijers et al. (2007) found to be correlated to pH. The second index, the Methylation of Branched Tetraethers (MBT), measures the presence of methyl branches at the C-5 and C-5′ positions and was found to be positively correlated to MAAT, and to a lesser extent, negatively correlated to pH (Eq. (2)). By combining these two indices, Weijers et al. (2007) were able to produce a robust paleotemperature proxy for soil-derived brGDGTs. In recent years this MBT/CBT relationship has been expanded to include lake sediment samples, yielding numerous lake specific calibrations (e.g. Loomis et al., 2012; Pearson et al., 2011; Sun et al., 2011; Tierney et al., 2010). For this study the calibration of Sun et al. (2011) (Eq. (3)) was applied to reconstruct temperature. In equa-