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ORIGINAL PAPER

Overview and significance of a 250 ka paleoclimate record from El'gygytgyn Crater Lake, NE Russia

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Abstract Sediment piston cores from Lake El'gygytgyn (67°N, 172°E), a 3.6 million year old meteorite impact crater in northeastern Siberia, have been analyzed to extract a multi-proxy millennial-scale climate record extending to nearly 250 ka, with distinct fluctuations in sedimentological, physical, biochemical, and paleoecological parameters. Five major themes emerge from this research. First the pilot cores and seismic data show that El'gygytgyn Crater Lake contains what is expected to be the longest, most continuous terrestrial record of past climate change in the entire Arctic back to the time of impact. Second, processes operating in the El'gygytgyn basin lead to changes in the limnogeology and the biogeochemistry that reflect robust changes in the regional climate and paleoecology over a large part of the western Arctic. Third, the magnetic susceptibility and other proxies record numerous rapid change events. The recovered lake sediment contains both the best-resolved record of the last interglacial and the longest terrestrial record of millennial scale climate change in the Arctic, yielding a high fidelity multi-proxy record extending nearly 150,000 years beyond what has been obtained from the Greenland Ice Sheet. Fourth, the potential for evaluating teleconnections under different mean climate states is high. Despite the heterogeneous nature of recent Arctic climate change, millennial scale climate events in the North Atlantic/Greenland region are recorded in the most distal regions of the Arctic under variable boundary conditions. Finally, deep drilling of the complete depositional record in Lake El'gygytgyn will offer new insights and, perhaps, surprises into the late Cenozoic evolution of Arctic climate.

Keywords Paleoclimate · Paleolimnology · Arctic · Beringia · Chukotka · El'gygytgyn

This is the *first* in a series of eleven papers published in this special issue dedicated to initial studies of El'gygytgyn Crater Lake and its catchment in NE Russia. Julie Brigham-Grette, Martin Melles, Pavel Minyuk were guest editors of this special issue.

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Introduction

The Arctic is currently experiencing environmental warming and change at rates unprecedented in historical times causing wholesale ecosystem migrations (Bradley et al. 2003; Grebmeier et al. 2006; Overpeck et al. 2005). Large international programs (e.g., ACIA 2005; SEARCH 2005) have been launched to monitor this change and develop models for predicting the magnitude and regional repercussions of future environmental change. Without question, the polar regions play a major role in the global climate system, balancing the input of solar energy to the tropics thereby influencing both oceanic and atmospheric circulation through strong feedback interactions involving ocean, atmosphere, cryosphere, and terrestrial processes (Otto-Bliesner et al. 2006; Overpeck et al. 2006). In fact, much Arctic research today is anchored in the premise that accurate predictions about future climate evolution and related environmental change depends on our capacity to document and recognize the function of the Arctic region in modulating past change under different climate-forcing conditions, including those possibly forced on the Arctic from the tropics (Clement and Cane 1999; Cane and Clement 1999). Robust predictions of a warmer future (IPCC 2001; Overpeck et al. 2006) require a geologic perspective on the dynamic range of environmental change in the high latitudes, especially given polar amplification during previous interglacial periods and past intervals of rapid change (CAPE 2006).

Teleconnections and the propagation of change between the Arctic and the global climate system can only be assessed by comparing well-dated Arctic terrestrial, marine, and ice-core climate archives, especially over several glacial/interglacial cycles when Milancovitch and millennial scale forcings of Northern Hemisphere boundary conditions were altered (cf., Stott et al. 2002). Long marine records are relatively common, yet few long terrestrial records exist in the Arctic with a temporal resolution *at least* as good as the deep marine record. Emphasis on the higher resolution millennial-scale paleoclimatic marine records of the Arctic gateway regions (e.g., Wolf and Thiede 1991; Keigwin et al. 1994; Rea et al. 1995; Spielhagen et al. 1997, 2004; Keigwin 1998; Helmke et al. 2002; Backman et al. 2004), and the arguably shorter records available from the Greenland Ice Sheet (e.g., Grootes et al. 1993; Johnsen et al. 2001; North Greenland Ice Core Project members 2004) provide compelling justification for study of lengthy continuous lacustrine records in the Arctic.

Long high-resolution multiproxy lake records that evaluate the terrestrial response to regional global change are rapidly emerging from both the northern and southern hemisphere (e.g., Colman et al. 1995; Cohen et al. 2000; Baker et al. 2001a, b; Wang et al. 1991; Seltzer et al. 2002; Anselmetti et al., in press). Millennial scale records are also rapidly emerging from areas of the tropics and subtropics for comparison (e.g., Behl and Kennett 1996; Schulz et al. 1998; Hughen et al. 2000; Peterson et al. 2000; Wang et al. 2001; Stott et al. 2002; Koutavas et al. 2002; Lea et al. 2000, 2003; Burns et al. 2003) causing scientists to rethink the role of the tropics vs. the high latitudes in climate change on millennial and finer time scales.

Across the Arctic borderlands, El'gygytgyn Lake uniquely contains a sediment record comparable to these other archives. After all, El'gygytgyn Crater (67.5°N and 172°E; Fig. 1) was formed by a meteorite impact 3.6 million years ago (Layer 2000). At that time, most of the Arctic was forested at least periodically all the way to northern Ellesmere Island, the Arctic Ocean lacked sea ice, and the Greenland Ice Sheet did not exist in its present form (Brigham-Grette and Carter 1992 and references therein). In fact after the meteorite hit, nearly a million years passed before the first glaciation of the Northern Hemisphere began (cf. Haug et al. 2005). Perhaps what makes it unique is that this meteorite landed nearly in the center of what was to become Beringia—the largest contiguous landscape in the Arctic to have escaped Northern Hemisphere glaciation (Fig. 2), consequently creating a lake basin that would continuously chronicle the longest terrestrial record of paleoclimate in the circumarctic.

The purpose of this special issue is to summarize what is known of the modern Lake El'gygytgyn basin and to synthesize studies of a pilot core first taken to determine the scientific promise of this exceptional lake system for deep drilling as a key northern hemisphere archive of past environmental change. The papers are based on results from the first 2 of 3 American–German–

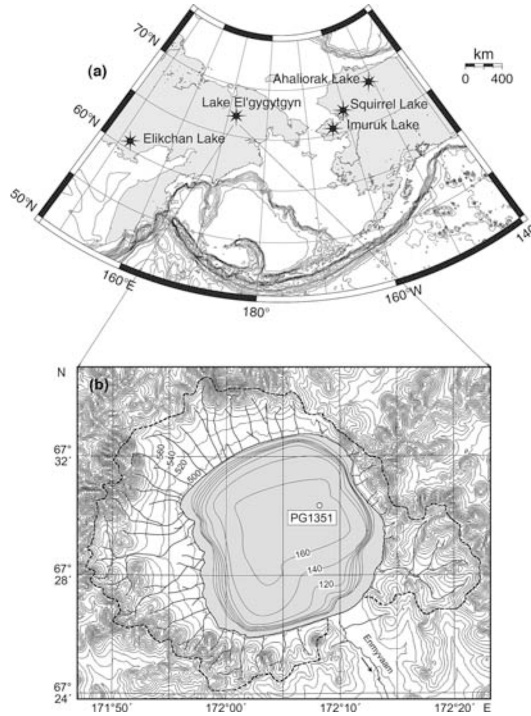

Fig. 1 Location of Lake El'gygytgyn, 100 km north of the Arctic Circle in northeastern Russia. (**a**) Location of Lake El'gygytgyn relative to other key lacustrine basins in Beringia with long sediment records including Elikchan Lake (65 kyrs, Lozhkin and Anderson 1996); Imuruk Lake (130 kyrs, Colinvaux 1964); Squirrel Lake (180 kyrs, Berger and Anderson 2000); Ahaliorak Lake (130 kyrs, Eisner and Colinvaux 1990, Anderson and Brubaker unpublished). (**b**) Topography of El'gygytgyn crater and bathymetry of the modern lake system showing the location of core PG1351

Fig. 2 Arctic geography showing the extent of large ice sheets during the Last Glacial Maximum, 20 ka BP, and the position of Lake El'gygytgyn (*solid star*) within the largest contiguous terrestrial area to have escaped Northern Hemisphere glaciation. Small valley glacier complexes in mountainous regions are not shown. Open stars in the Sea of Okhotsk (Nürnberg and Tiedemann 2004), deep Bering Sea (Beth Caissie unpublished), Arctic Ocean–Lomonosov Ridge (Backman et al. 2004), Greenland (Johnsen et al. 2001) and off the coast of Portugal (Chappell and Shackleton 1999) highlight key marine and ice core records to be used for evaluating teleconnections and the regional vs. global aspects of the paleoclimate record from Lake El'gygytgyn

Russian expeditions to the lake. Sediment cores were initially taken from the center of the lake in May, 1998, using gravity and percussion piston corers and the 2 m thick lake ice as a coring platform (Fig. 1). Core PG1351 from a water depth of 170 m penetrates about 13 m of the lake sediment record.

Preliminary results from this core were first reported at the Fall AGU in 1999 and 2000. Nowaczyk et al. (2002) published the first core chronology based upon magnetic susceptibility measurements, optical luminescence ages, and radiocarbon ages suggesting that the 13-m long sediment represented nearly 300 ka of record. This promising chronology and paleoclimate record developed by the scientific party provided the impetus for a major summer program in 2000 that began studies of the modern lake system and its catchment. The primary goal of this program was to conduct the first seismic reflection surveys of the bedrock and sediment stratigraphy but also to learn about the modern limnology, geomorphology, surficial stratigraphy, Holocene sedimentology, lake hydrology and meteorology in addition to ground-truth remote sensing efforts and DEM development (Nolan et al. 2002). First results of a major spring and summer-long field campaign to the lake in 2003 to improve the resolution of the seismic data, collect new piston cores, and continue process studies are reported in other publications (Melles et al. 2005; Cremer and Wagner 2003; Cremer et al. 2005; Gebhardt et al. 2006; Juschus et al. in press; Schwamborn et al. in press). This paper provides a simple overview of Lake El'gygytgyn and its significance, and summarizes the major findings detailed in this volume.

Background

Modern Lake El'gygytgyn is about 170 m deep and 12 km in diameter, and sits inside of a crater roughly 18 km in diameter (Fig. 1b). Located some 100 km north of the Arctic Circle in the middle of the remote Anadyr Mountains of Chukokta, the basin is rarely visited by people and remains inaccessible by road (Fig. 3). The crater itself is one of the best-preserved on Earth for its size (Dietz and McHone 1976; Dence 1972), and the lake is one of only a handful formed inside an impact crater (Lehman et al. 1995).

El'gygytgyn Lake is surrounded by a nearly flat-lying sequence of Late Cretaceous ignimbrites, rhyodacite to andesite tuffs and basalt within the Okhotsk–Chukotka Volcanic Belt which extends ~3,000 km from Chukotka Peninsula to northern China (Gurov and Gurova 1979). The bathymetry resembles a simple flat-bottomed bowl, with shallow shelves 5–10 m deep around one third of the lake terminated by steep slopes to depths of 150 m grading across a low sloping floor to the deepest point in the center at about 170 m (Fig. 1b). The surface of the lake at 495 m altitude remains ice covered for ~9 months of the year with open water historically documented as early as mid-July and as late as mid-October (Nolan et al. 2002). The approximately 50 streams draining into the lake are mostly less than 5 km long, and limit the catchment to within the crater rim which is composed of hills reaching an altitude of 850–950 m; the Enmyvaam River exits the lake to the south draining eventually into the Anadyr River and the Bering Sea; rivers just north of the crater rim drain to the East Siberian Sea. The presence of Pliocene fluvial terrace deposits, found interbedded with ejecta along the exiting Enmyvaam River valley (Belyi et al. 1994; Glushkova 1993; Glushkova et al. 1994), indicates that (1) the crater has remained an open lacustrine basin since the time of impact and (2) the outlet has been downcutting over time. Moreover, studies of the glacial geology and regional Quaternary stratigraphy indicate that the crater and surrounding hills escaped Cenozoic glaciation (Arkhipov et al. 1986; Glushkova 1992, 2001; Brigham-Grette et al. 2004). Without doubt, El'gygytgyn Lake is totally unique as a location for acquiring a 3.6 million year-long terrestrial arctic paleoclimate record.

Fig. 3 Photo of Lake El'gygytgyn taken from the crater rim looking toward the north from the south end of the lake, August 2000. Photo courtesy of Matt Nolan, University of Alaska-Fairbanks

The vegetation surrounding the El'gygytgyn basin today is dominated by willow shrubs and lichen tundra. Mean July temperatures are in the range of +4 to +8°C a and January temperatures range from –32 to –36°C, measured at the nearest meteorological station some 250 km to the north of the lake in Pevek. Modern tree line is positioned roughly 150 km to the south and west of the lake.

Vegetation and the environmental history of the Chukotka region shift in direct response to changes in atmospheric circulation, the size of Northern Hemisphere ice sheets, sea ice extent, and the maritime influence of the Arctic Ocean and the Bering Sea (Bartlein et al. 1991, 1998; Brigham-Grette et al. 2004). Analysis of synoptic-scale atmospheric circulation patterns using instrumental data from across Alaska and eastern Siberia emphasizes distinct contrasts in the temperature and precipitation patterns between western and eastern Beringia under different circulation regimes (Mock et al. 1998; Mock 2002). While knowledge of the synoptic patterns offer a conceptual framework for understanding climate model simulations of past change, these patterns can be tested against the growing body of paleodata that demonstrate the true spatial and temporal contrasts in records from either side of the Bering Strait (Lozhkin et al. 1993; Anderson and Brubaker 1994; Anderson et al. 1997).

Volume highlights

The papers in this volume are organized to first provide the science community with the necessary background information about the Lake El'gygytgyn region, the basin and its catchment. In addition, the papers include the first results of multidisciplinary studies on the 13 m core PG1351 recording the last few glacial/interglacial cycles. These data provide us with a geologic ''dip stick'' of what we can likely expect from a sedimentary record to be acquired by deep drilling back to the time of impact.

Nolan and Brigham-Grette (2007) summarize the hydrology and regional meteorology of the catchment based upon local instrumental observations, a time series of temperature measurements from the center of the lake, and local vs. regional NCEP (National Centers for Environmental Protection) reanalysis data. Their paper summarizes what is known of the duration of lake ice cover, possible controls on sedimentation and factors influencing the past limnology of the lake system. Lakeside meteorological data combined with regional instrumental data illustrates that the past 15 years have included some of the warmest years and warmest winters in historical times. This picture of the modern physical setting is followed by a synthesis by Glushkova and Smirnov (2007) of the geomorphic evolution of the landscape around Lake El'gygytgyn including an assessment of the role of regional tectonics in controlling past lake levels and rates of outlet incision. Moreover, they suggest as a hypothesis, that the Lagerny Creek drainage into the lake may actually represent a second impact crater, nearly simultaneous with the impact 3.6 million years ago that created Lake El'gygytgyn.

Future deep drilling at Lake El'gygytgyn requires a comprehensive seismic survey to assess the thickness of the sedimentary record, its architecture, as well as the structure of the underlying impact crater and fallback stratigraphy. Niessen et al. (2007) report the results of seismic investigations completed in 2000. This work outlines evidence for dividing the sedimentary record into two sequences—an upper stratified sequence overlying an acoustically unstratified unit. Using an average sedimentation rate of 5–6 cm/thousand years calculated from cores discussed in this volume, the base of the stratified unit may, in fact, coincide with the onset of Northern Hemisphere glaciation 2.6–2.7 Ma. This suggests that sedimentation during the early history of the crater may have been 2–3 times faster, a notion consistent with an erodable debris-covered landscape, lacking in permafrost during the relatively warm mid-Pliocene.

Lake sediment sequences clearly lack much significance for regional and global paleoclimate research if they are not dated properly. This is especially true for sequences that extend beyond the useful range of ~30 ka obtained from radiocarbon (Fairbanks et al. 2005) and even more difficult in arctic settings where permafrost can delay by thousands of years the delivery of organic materials to the lake basin. In this volume, Forman et al. (2007) report on the details of using optically stimulated luminescence (OSL) on the fine silt faction from core PG1351 to provide numerical ages for comparison with radiocarbon ages, paleomagnetic event stratigraphy, and the newly tuned age model presented by Nowaczyk et al. (2007). The sediments in Lake El'gygytgyn reportedly reach saturation in the deeper portions of the core making it difficult to obtain realistic luminescence ages beyond ~200 ka. Nowaczyk et al. (2002) reported the first age model for core PG1351 using magnetic events, pollen stratigraphy and OSL to constrain the age of physical changes in magnetic susceptibility. Given that the ignimbrites in the catchment yield high magnetic susceptibilities, the measured sediment susceptibility record is now known to represent the residual susceptibility resulting from vertical shifts in the position of the paleoredox boundary at or near the sediment/water interface creating changes in oxic/anoxic conditions. In this volume, Nowaczyk et al. (2007) have revised their original chronology by tuning the record to precession within the constraints of key tie points provided by other proxies. The largest changes in numerical age from the original chronology published by Nowaczyk et al. (2002) are for the deeper portions of the core below the last interglacial (>627 cm sediment depth) such that the basal age of core PG1351 is now estimated at 250 ka, rather than 300 ka. The tuning of the record to precession also has important implications for directly comparing the Lake El'gygytgyn record with other well-documented time-series recording regional as well as global scale climate change.

Changes in the geochemistry of the lake sediments provides some of the clearest answers we have concerning what actually might be controlling changes in magnetic susceptibility as well as other proxies. Our collective working hypothesis continues to be that changes in the duration of lake ice cover in summer determines whether the water column in the deepest parts of the lake is oxygenated, as well as the position of the redox boundary. For example, the glacial mode is characterized by anoxic conditions (at least at the sediment/water interface), likely caused by lake ice that did not completely melt in the summer, limiting wind-induced waves and seiches and perhaps encouraging thermal and chemical stratification. The interglacial mode is characterized by an open water season with complete mixing and oxygenation. These modes are not exclusively restricted to true glacial and interglacial conditions, but also to a continuum of warm periods during true glacial times and cold periods during true interglacial periods, for example. In the paper by Melles et al. (2007), they have developed four construed modes of climate variability that correspond to changes not only in seasonal lake ice duration but also to changes in snow cover on the lake ice, as a by-product of changes in summer air temperatures and regional solid precipitation. These four modes are arguably oversimplified, but they provide the simplest explanation (cf. Ockham's Razor) for understanding the direction and magnitude of changes in parameters such as total organic carbon, total nitrogen, biogenic silica and the $\delta\,^{13}$C ratio of total organic carbon in core PG1351.

Our results thus far seem to strongly suggest that climate-driven lake ice cover duration is the dominant control on lake biogeochemistry. Moreover, for reasons related to sedimentation rate, pollen flux and diatom abundance, we surmise that even during glacial summers, motes and fractures in the ice cover provided a viable means for sediments to be delivered to the lake system and for a limited ecosystem to exist just under the ice canopy. Modeling efforts for understanding links and feedbacks between ice duration and seasonal energy balance are ongoing. What we do not understand is whether the record reflects near-total lake anoxia or anoxia limited to the sediment/water interface, or whether spatial variations in biological production varied through time. What is also not clear is the extent to which decomposition of organic matter in the bottom sediments consumes dissolved oxygen and dictates pervasive anoxic conditions with or without persistent lake ice cover during full glacial conditions. Ongoing studies are investigating the role of microbial activity in mediating diagenesis as well as related issues (Petsch et al., unpublished).

While the biogeochemistry provides essential aspects to understanding the depositional history at Lake El'gygytgyn, Asikainen et al. (2007) present some of the most detailed results concerning the sedimentology and clay mineralogy of the record. This paper presents a bioturbation index for the entire 13 m record of core PG1351 that tracks interpreted changes in anoxia modeled after Behl and Kennett (1996) for the Santa Barbara Basin. In addition, they describe changes in grain size and clay mineralogy for the record of the last 65 ka leaving little doubt that in Lake El'gygytgyn, grain size varies little over time and exerts inconsequential control over changes in the magnetic susceptibility record, especially changes in magnetic susceptibility that amount to variations of nearly two orders of magnitude. These changes in magnetic susceptibility are simply too large to be controlled by changes in the flux of magnetic minerals to the lake. Rather, this paper confirms that magnetite dissolution occurs repeatedly during glacial/cooler intervals, as first suggested by Nowaczyk et al. (2002). This paper also hints at the origin for peculiar interclasts observed in the sediments that may have their origins as cryoconites in the lake ice canopy (e.g., Laybourn-Parry et al. 2001).

Minyuk et al. (2007) describe the first inorganic geochemistry work of core PG1351 noting that in a family of oxides there are clear climate-related patterns linked to suggested shifts in hydrology, atmospheric circulation, and the intensity of mechanical weathering. They suggest that data regarding subtle increases in the concentration of Nb and Y might be interpreted as periodic increases in eolian sediment supply from outside the basin. Unidirectional increases in these two trace elements coincides with the timing of Marine Isotope Stage 4 and could be related to the widespread deposition of organic rich eolian sediments known as *yedoma* in Siberian Russia. Vivianite, on the other hand, occurs throughout the cores without regard to climate. Rather, shifts in this secondary diagenetic mineral are more likely a function of phosphorus liberated during diagenesis from fish, iron oxyhydroxides, and decaying organic detritus.

Two of the most traditional paleoclimate proxies used in interpreting lake sediment records are pollen and diatom time-series. Lozhkin et al. (2007) bring their extensive experience from working on lake records throughout western Beringia to interpreting the vegetation record and changing paleoecology documented in Lake El'gygytgyn. They show first that, as in the past, the lake today is faithfully recording robust regional changes in climate and not just local basin noise. Moreover they demonstrate that the early Holocene (Holocene Thermal Maximum, cf. Kaufman et al. 2004) and the last interglacial (senso stricto) were the warmest portions of the last 250 ka. In particular, the last interglacial in NE Russia was likely characterized by July temperatures 4–8°C warmer than present and January was also warmer and wetter than now, consistent with regional data assembled for the western Arctic (CAPE 2006).

Lozhkin et al. (2007) also suggest alternative ways of interpreting the geochronology of the record from PG1351 given the premise that the vegetation zones expressed in the pollen assemblages can be used directly for suggesting warm vs. cold climate intervals that inherently correspond with the traditional marine oxygen isotope record. They argue there must be problems with the chronology of Nowaczyk et al. (2007), because their age model otherwise suggests that warm plant taxa sometimes persisted under cool climates and cool taxa persisted under some warm climates, a requirement they dismiss. The largest, though not the only mismatch between the OSL/precessionally tuned-MS chronology and the palynologically derived chronology is the interpretation of where to place the MIS 5a/4 stage boundary (~75 ka BP) within the stratigraphy. While Lozhkin et al. (2007) place it at 448 cm in core PG1351 based upon a large decrease in tree and shrub pollen and synchronous increase in herb pollen (their Fig.5), Nowaczyk et al. (2007), instead place this time boundary at ~340 cm (their Fig. 4). This 108 cm difference of opinion represents an offset of ca. 30 kyrs, much more than a single marine isotopic stage. In fact, if the Lozhkin et al. (2007) chronology were correct, it would require that OSL ages at 271 cm, 321 cm and 460 cm, equal to ~62 ka, 63.5 ka, and about 104 ka (Forman et al. 2007) be ignored along with the interpreted Blake event at 495 cm (Nowaczyk et al. 2002) and notion of tuning the extrapolated timescale to Northern Hemisphere precession (Nowaczyk and Melles 2007). Moreover, the palynologically interpreted timescale places an age of nearly 300 ka at the bottom of the PG1351 whereas Nowaczyk et al. (2007) now place the basal age closer to 250 ka. Forthcoming are new optical luminescence ages determined by a different lab (F. Preusser, University of Bern) on cores taken in 2003 that are consistent with the age estimates of Forman et al. (2007) and Nowaczyk et al. (2007) as well as tephrochronology age estimates for ashes found at roughly 275 cm (~50 ka) and 800 cm (~180 ka) depth (Juschus et al. unpublished).

Science can be about compromise as well as agreeing to disagree until additional data can test the alternative chronologies. While as editors we openly favor the chronology and tuning presented in this volume by Forman et al. (2007) and Nowaczyk et al. (2007), the discrepancy raises intriguing questions as to why, assuming this chronology is correct, would the vegetative response to changes in regional climate be so dramatically different from what we infer from the changes in lake hydrology, geochemistry and lake ice cover? Do these data present us with no-analog scenarios that result from differences due to changes in precipitation as opposed to dramatic changes in seasonal temperature? New GCM modeling techniques can be used to test the mechanisms responsible for the seemingly different timing of climatic change influencing lake ice cover vs. vegetation in different parts of the western Arctic, especially around the end of the last interglacial during the 5e/5d transition and the 5a/4 transition. This can be best accomplished via an integrated model-data study, focusing on the response of Beringian climate and ice volume over this interval to changing orbital parameters, circumarctic ice sheets, greenhouse gas concentrations, sea ice distributions, and sea surface temperatures. Given field evidence for the rapid expansion of valley glaciers in some parts of western and central Beringia during and at the end of the last interglacial (Brigham-Grette et al. 2001; Kaufman et al. 2001), ongoing modeling efforts will be key to examining the time-evolving response of Beringian climate, glacier mass balance and vegetation feedbacks (cf. DeConto and Pollard 2003a, b; Pollard and DeConto 2005; Thorn and DeConto 2005) and to explaining the enigmatic response of vegetation in contrast to other proxies.

Cherapanova et al. (2007) wrap up the volume by summarizing the diatom stratigraphy of core PG1351. They show that diatoms remain abundant throughout most of the 250 kyr record of PG1351 and that even during the Last Glacial Maximum (MIS 2), planktic diatoms remain abundant. Changes in the benthic/periphytic communities provide the most important index of habitat change, probably reflecting changes in lake level over time. What is particularly important is that biogenic silica remains at levels of at least 4% sediment weight (Melles et al. 2007) and diatom abundance is rarely zero throughout the 250 ka record of core PG1351. Unlike the biogenic silica record from Lake Baikal which falls to zero during all inferred cold periods (cf. Colman et al. 1995), the surface waters in Lake El'gygytgyn apparently remained productive during glacial intervals, probably due to favorable light conditions and oxygenated habitat under a fractured but nearly continuous lake ice cover *without* much snow cover. Western Beringia, in general, is thought to have been very arid during glacial intervals (Siegert and Marsiat 2000; Brigham-Grette and Gualtieri 2004; Brigham-Grette et al. 2004). Conversely, intervals in the core with both low diatom abundance and low biogenic silica most likely represent intervals when perennial ice cover was also accompanied by heavier snow falls impeding light penetration (cf., Melles et al. 2007).

Discussion

As one colleague put it, if Lake El'gygytgyn were located on the road system in Alaska, it would likely be the most well-studied watershed in the Arctic. However, its location in remote NE Siberia has led to the untapped potential of the lake to add to our understanding of the evolution of change in the Arctic climate system. The papers contained in this volume reflect the richness of the sediment archive preserved in Lake El'gygytgyn. Five major themes emerge from the research carried out so far.

Unprecedented continuous record of past climate

One of the most outstanding hallmarks of El'gygytgyn Crater Lake is that the basin contains what is expected to be the longest, most continuous terrestrial record of past climate change in the entire Arctic. The seismic data presented by Niessen et al. (2007) and Gebhardt et al. (2006) demonstrates first of all, that the sedimentary basin fill of ~350 m since the time of impact is uninterrupted by either regional glaciation or dessication. The morphology and stratigraphy of fluvial terraces along the outlet of the Enmyveem River concur with this interpretation suggesting that the lake outlet has been active and downcutting since the time of impact (Glushkova and Smirnov 2007). Moreover, the geomorphic data, satellite photos, and surficial mapping of Chukotka also supports the impression that the crater basin has never been under glaciation (Glushkova 2001).

The seismic data from Lake El'gygytgyn indicates that the post-impact basin fill consists of 2 seismic units, including a massive lower unit 250 to 190 m thick overlain by an uninterrupted, acoustically stratified upper unit at least 170 m thick (Neissen et al. 2007; Gebhardt et al. 2006).

Regionally robust climate signal

One of the most important characteristics about Lake El'gygytgyn is that the catchment records widespread change. Processes operating in the El'gygytygn basin lead to changes in the limnogeology and the biogeochemistry that reflect robust changes in the regional climate and paleoecology over a large part of the western Arctic. The meteorological and limnological data of Nolan and Brigham-Grette (2007) as well as the palynological data of Lozhkin et al. (2007) demonstrate a coherent relationship between locally derived data from the basin and regional syntheses of climatological factors and past pollen and regional vegetation changes.

Rapid climate change

Thirdly, the pilot core discussed in this volume dates back to over 250 ka and records intervals of rapid change. It already represents by far the longest continuous lake record in the circumarctic. The core documents not only past glacials and interglacials, but also short-term climate events (Shilo et al. 2001; Asikainen et al. 2007; Minyuk et al. 2007). Four different lake modes can be distinguished that reflect relatively warm, peak warm, cold and dry, and cold but more moist climate states across NE Siberia (Melles et al. 2007). While temporal variations between glacial/stadial and interglacial/interstadial settings are thought to be controlled predominantly by variations in regional summer insolation, the intensity of the warm periods and the wetness of the cold periods are likely influenced by more irregular alterations in the atmospheric circulation patterns. Furthermore, millennial-scale climate changes are recorded in the high-resolution magnetic susceptibility data (Nowaczyk et al. 2002; Nowaczyk et al. 2007). These data bear strong similarities to the $\delta^{18}O$ record from Greenland Ice Cores (GISP/GRIP), with the occurrence of a Younger Dryas-like (YD) event, stronger Dansgaard/Oeschger-Heinrich tandems and all substages of MIS 5 (Fig. 4). The existence of teleconnections to the North Atlantic is also indicated by an intra-substage 5d warming at Lake El'gygytgyn at ~115 ka (Fig. 4) similar to that seen in records from parts of the North Atlantic (Keigwin et al. 1994; Chapman and Shackleton 1999), and a "YD-like" event at the stage 5/6 transition seen in many Northwest European records (Seidenkrantz 1993). What is already apparent is that the cores from Lake El'gygtygyn suggest so far that some rapid change events (millennial-scale variability) may be unique in frequency to the last glacial cycle. This notion needs to be further tested.

Looking ahead, the potential length and likely fidelity of new records derived from deep drilling may allow us to evaluate for the first time in the Arctic the frequency, timing and perhaps the amplitude of rapid change events extending back several millions of years without losing fine scale resolution. What was the style and dynamics of glacial/interglacial change over the duration of the late Cenozoic "41 ka world" and Pleistocene "100 ka world"? How will this record compare with other long records from the North Atlantic and North Pacific, and especially with the tropical oceans? Can we use these comparisons to evaluate teleconnections and leads and lags relative to shifts in insolation forcing?

Regional and global teleconnections

The potential for evaluating teleconnections mentioned above under different mean climate states is probably the fourth most important aspect emerging from this research. After all, high-resolution paleoclimate records of millennial and finer time scales are needed from different parts of the Earth to identify the mechanisms and linkages that produce the spatial heterogeneity found in records of past change. Regional change and spatial differences in climate patterns are critical to assessing the societal impacts of future change. The amplified warming of the modern Arctic over what is globally observed highlights the role of the polar regions in modulating feedbacks involving ice, ocean, and atmospheric processes (ACIA 2005).

Even though Lake El'gygytgyn is located in the remote Russian Arctic where paleoclimate data are sparse, the variety of proxies reported here suggest links between the tropics, the North Pacific and the North Atlantic (Fig. 2). For example,

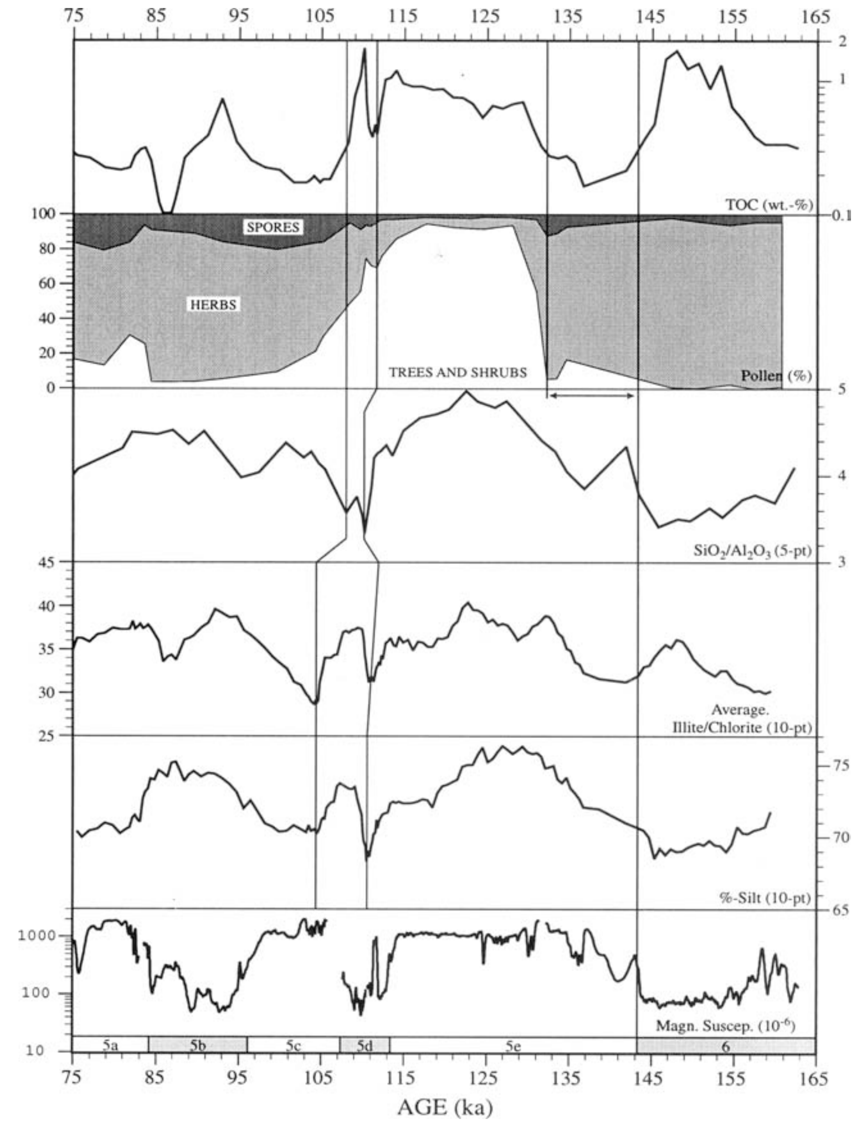

Fig. 4 Last interglacial shifts in clay mineralogy and %silt relative to magnetic susceptibility, Si/Al ratios, pollen and total organic carbon (Apfelbaum 2004)

evidence suggests millennial scale teleconnections exist between tropical sea surface temperatures in the western Pacific and D/O events in the North Atlantic (Stott et al. 2002; Koutavas et al. 2002). These changes likely produced changes in the North Pacific system that may have influenced the climate over NE Russia (Mantua and Hare 2002). While there are most likely linkages to the tropics that cause shifts in the Aleutian Low, it is harder to understand what can shift the large Siberian High (cf. Bartlein et al. 1998). Shifts in the mean location and strength of these systems related to orbitally driven changes in continental cooling and the changing distributions of sea surface temperatures and sea ice will be a focus of climate modeling studies (e.g., Elia et al. 2004).

Spatial heterogeneity is an inherent aspect of climate change that presents a challenge to the science community. Situated 100 km north of the Arctic Circle, El'gygytgyn lies in a region that like Greenland, has been cooling according to annual means in recent decades, in stark contrast to significant warming over most of the Asian and North American continents, including Alaska (Chapman and Walsh 1993; Walsh 2002). Moreover, Nolan and Brigham-Grette (2007) show that winter temperatures are rising on average similar to Greenland (Comiso 2003). In fact, our records from Lake El’gygytgn (Fig. 5) suggest that this regional similarity also exists on millennial timescales. Cooling (or better put, nonwarming,) in Chukotka is related to its proximity to the Siberian High and the Aleutian Low (Mock et al. 1998). The Aleutian Low is a fundamental part of the atmospheric system thought to have produced climatic changes across western North America, e.g., in Marine Isotopic Stage 3 (MIS 3) that are similar in pattern to Dansgaard-Oeschger (D/O) events in the North Atlantic. The strength of the Aleutian Low is intimately linked to systematic changes in the tropics as reflected by analyses of variations in the robust Pacific-North American pattern (or PNA) vs. other features like the decadal- El Niño like pattern (Vimont et al. 2003). The systematics that produce the PNA pattern are known by atmospheric scientists to have robust linkages over long millennial time scales with global circulation (Hartmann et al. 2000), allowing an evaluation of interhemispheric teleconnections under variable boundary conditions. Because of its proximity to this low, the Lake El’gygytgyn record has the potential to provide us with information on its strength and position over the past 3.6 million years.

The data from Lake El’gygytgyn will eventually allow us to test the fidelity of teleconnections within the circumarctic Earth system for global scale fingerprints of climate change, especially where enough records exist for the last full glacial/interglacial cycle (Fig. 1a). Among the most influential factors affecting western Beringia and Lake El’gygytygyn was the position of large ice sheets in the circumarctic, combined with regional changes in sea level and sea ice (Brigham-Grette et al. 2004). This was especially true given that this vast landscape was positioned ‘‘downwind’’ of large ice sheets in Scandinavia and the Eurasian north, themselves creating widespread aridity during full glacial conditions (Siegert et al. 2001, Fig. 2). Moisture extracted from the westerlies by these ice sheets left little but strong dry winds, which combined with the polar easterlies, to sweep the landscapes of NE Russia. No doubt this influence also altered seasonal shifts in some circulation features off the North Pacific like those that are seen today, shifts that likely in the past influenced seasonal temperature and interacted with effective moisture.

Late Cenozoic climate evolution

Of prime interest to the scientific community is determining why and how the Arctic climate system evolved from a warm forested ecosystem

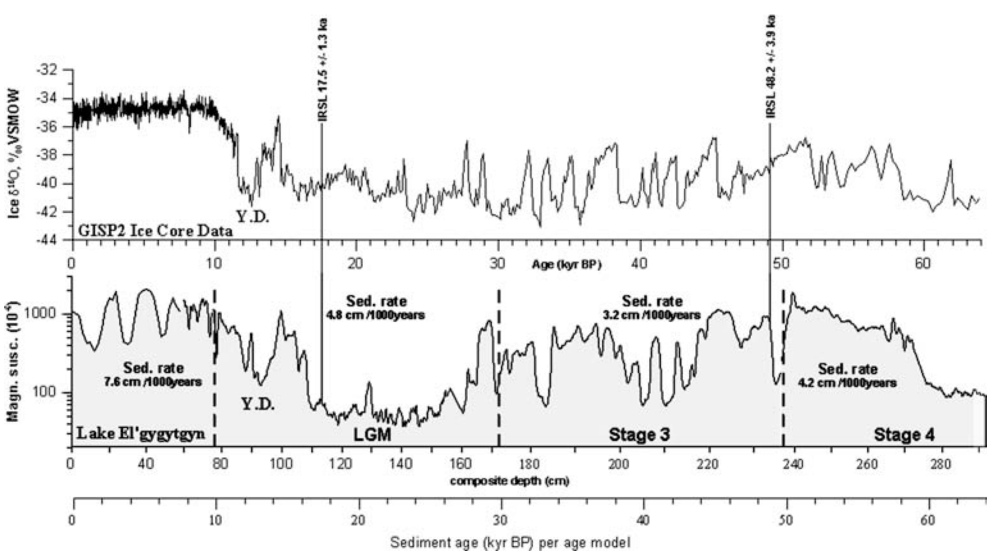

Fig. 5 Change during the last glacial cycle. Comparison between magnetic susceptibility (MS) and the Greenland ice core record. MS is a proxy for changes in anoxia driven by changes in seasonal lake ice cover, in turn a function of temperature and insolation (Asikainen et al. 2007)

into a cold permafrost ecosystem between 2 and 3 million years ago. A continuous depositional record in a lake just north of the Arctic circle (as defined by the earth's tilt) provides a means of determining, from a terrestrial perspective, how the Arctic climate evolved and adjusted from Milankovich-driven glacial/interglacial cycles every 41 kyr and, later, every 100 kyr. Our present understanding of Lake El'gygytgyn as a system suggests we can interpret higher resolution climate change events across NE Asia on centennial to millennial scales and test for atmospheric teleconnections with other long climate records worldwide (Fig. 2). Such comparisons will offer insight into the dynamic mechanisms behind these teleconnections or the lack thereof, and an understanding of the conditions for permafrost formation and stability through time, especially in the context of modern warming.

The concepts developed here provided the impetus for our field investigations in 1998, 2000 and 2003, for a capstone ICDP workshop in 2001 and workshop synthesis in 2004 to fully explore the potential of future science at Lake El'gygytgyn. Future comparisons between the depositional record of Lake El'gygytgyn and newly acquired IODP-ACEX marine record from the Lomonosov Ridge (Backman et al. 2004; Moran et al. in press) will offer new insights and, perhaps, surprises into the late Cenozoic evolution of Arctic climate. The work will also facilitate modeling efforts to evaluate to role of CO_2 forcings in altering Arctic climate, especially since the mid-Pliocene (Haywood and Valdes 2004). Compared to the Lomonosov Ridge record, the scientific payoff in knowledge gained by eventually drilling at Lake El'gygytgyn will be equally as great, especially given more continuous records and the higher sedimentation rates in this lacustrine system (330+ m vs. ~70 m for the same 3.6 My interval); hence this affords an outstanding opportunity to gain new knowledge about Arctic change. What is more, the work fills a critical spatial gap given that regions of the western Arctic are particularly underrepresented in circumarctic and global assessments of Cenozoic climate.

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