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Introduction to

“Progress towards reconstructing past climate in Central Eurasia, with special emphasis on Lake Baikal”

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Introduction

Over the last 150 years, Central Eurasia has experienced the largest increase in global warming. The IPCC (2001) special report on regional impacts of climate change suggests that a doubling of CO₂ concentration will further act to exacerbate changes in biogeography, productivity, water quantity and water quality. Yet in this region, both experiments with quasi-realistic climate models and palaeoclimate reconstructions from proxies in natural archives are underrepresented. Given the remoteness of Central Eurasia (far from ice sheet and oceanic influences) it is not prudent to simply extrapolate climate change signals from the Atlantic or Pacific regions. Hence there is an important gap in our knowledge of how large-scale climate processes, such as the North Atlantic Oscillation and interactions between the Westerlies and monsoons affect such continental regions.

Important to the concept of climate change studies are palaeoecological programmes to test models, improve model parameterisation and to place these recent trends in climate variability into the perspective of longer timescales. In this context, Lake Baikal, located in southern Central Siberia, is one of the most exciting lakes for climate change research, as shown by successful international scientific efforts during the last 15 years under umbrella programmes such as the Baikal International Centre for Ecological Research (BICER), and the Baikal Drilling Project (BDP) (Grachev et al., 1997; 1998; Kuzmin et al., 2001, Kashiwaya, 2003)- ICDP Programme and IGBP PAGES-PANASH initiatives. Previous studies covering glacial – interglacial time-scales clearly show the orbital control on the sediment parameters revealing pronounced precession and eccentricity cyclicity (Colman *et al.* 1995; Williams *et al.*, 1997, Kashiwaya *et al.*, 2001). However, the Lake Baikal sedimentary archive also has the potential to sensitively record climate changes at high temporal resolution (decadal to centennial) over more recent timescales. Despite the intense concern over the environmental and ecological impacts of anthropogenic inputs into lakes, the

potential of these effects obscuring the palaeoclimate record will be restricted to only the uppermost sediments given the relatively short time frame of human impacts in this region.

In 1999, an interdisciplinary workshop was held in Potsdam, Germany: *1st Baikal-Sed meeting: an International Workshop on Sedimentology of Lake Baikal – recent and subrecent sedimentation*.

During the course of this meeting it became evident that many of the uncertainties raised by the sedimentary records could only be fully appreciated by (i) carefully selecting sites in the lake that ensured minimal impacts from secondary processes such as turbidity currents, (ii) developing an accurate age model for the last 150 ka, and (iii) linking these records more to processes that occur in the water column and catchment of this exceptionally deep lake. It was clear that a new interdisciplinary programme was needed to address the issues identified at the meeting, and in 2001 the EU Framework 5 project *CONTINENT* (EVK2-CT-2000-0057) was launched (<http://continent.gfz-potsdam.de>). Selected recent results from these studies were presented at a special session of the EGS-AGU-EUG joint assembly in Nice, France in April 2003. The focus of the session, which resulted in this special issue, was on interglacial climate variability in Eurasia during the last 150 kys, and associated termination periods.

2. Organisation and contents

The special issue consists of three parts: In the first section, the authors are dealing with processes that control proxy formation and transport through the water column. In the following section, papers are presented that address many of the prerequisites for paleoclimate studies such as (i) selecting optimal coring sites and (ii) the development of a robust age model for the sediment sequences. The final section contains papers that detail the palaeoclimatic reconstructions from the Lake Baikal sediment records.

The 20 papers included in this special volume highlight progress in reconstructing palaeoclimates at high-resolution, in central Eurasia, from biological and abiotic proxies held in lacustrine archives during the last two interglacials and associated termination periods. The papers also demonstrate that the quality of the interpretations can be improved by increasing our understanding of the processes that control the inclusion of these proxies into the sedimentary archive. The majority of the contributions are focussed on Lake Baikal. However, Asian monsoon systems do not directly impact the lake, and so we have also commissioned two studies from the Qilian Mountain region of Northwest China, which provide some of the few lacustrine records of palaeoclimate extending back through Marine Isotope Stage 2 and MIS 3.

The first section of the volume outlines progress in determining the processes that control proxy formation and transport through the water column of Lake Baikal. In this context, it is important to highlight two important characteristics of the physical limnology of the lake. Firstly, the water column of Baikal may be divided into two main zones based on temperature profiles and water exchange processes: an upper zone (epilimnion) down to 250 m depth, beneath which lies a lower zone, from 250 m down to the bottom sediments, where water temperatures are almost constant at 3-4 °C. Secondly, although Lake Baikal is the deepest lake in the world (INTAS Project 99-1669 Team, 2002), unlike many other deep lakes, its water column is fully oxygenated down to the bottom sediments.

In any lake, the sedimentary record consists of allochthonous and autochthonous components. In Lake Baikal by far the majority of water input in the lake is from rivers (over 80%) running through a catchment of an estimated 540,000 km². It therefore becomes important to be able to monitor the relative contributions of allochthonous and autochthonous components in lake water itself. Heim et al. (this issue) describe for the first time the application of Sea viewing Wide Field of view Sensor (SeaWiFS) satellite data to monitor the occurrence in Lake Baikal of (i) suspended matter as a proxy for terrigenous input to the lake and (ii) primary productivity in the lake via estimations of chlorophyll measurements. Transport of autochthonous and allochthonous material through the deep-water column can be effectively monitored by the deployment of trap mooring arrays consisting of integrating and sequencing traps. As we will see below, diatom algae are the most exploited biological proxy in Lake Baikal sediment records, but it is also possible to reconstruct other algal populations present in the lake by determining carotenoids, chlorophylls and their degradation products, thereby improving the potential for interpreting palaeoclimate records. However, in order to understand how the fossil pigments relate to the standing crops, Fietz et al. (this issue) show that in the south basin at least, as much as 72 % of the pigments are lost in the water column, and this figure increases to 99 % before final burial in the sediment record. Such findings have important implications when inferring palaeoclimate reconstructions. Lake Baikal is large, at over 600 km in length, and there are distinct limnological and climatological differences between the north and south basins. Russell & Rosell-Melé (this issue) used organic biogeochemistry to explore spatial differences in organic matter in the lake by determining the major lipid biomarker classes, as biomarkers have been shown to be particularly useful in marine palaeoecological studies. Their findings confirm that significant differences exist between the input and preservation of organic matter between the north and south basins, linked to climate, i.e. the length of ice cover in the lake, input and preservation. Thus site selection in the lake is also important when interpreting

palaeoclimate records. Central to organic matter preservation and decomposition is the role of bacteria, which are also important in promoting diatom dissolution (e.g. Bidle & Azam 1999). Straskrbová et al. (this issue) estimate that bacteria use approximately 20 % - 40 % of primary production within 24 hours between water depths of 2 m to 20 m under the ice. These findings are crucial therefore to understanding how potential proxies make it into the sedimentary record, and further work is currently being undertaken on bacterial populations in the lake.

Diatoms are the most important primary producers in Lake Baikal, especially after ice break-up in late spring, early summer. Up until recently, it has been assumed that sedimentary assemblages of diatoms mirror standing crops, but Battarbee et al. (this issue) highlight that only c. 1 % of the diatom crop makes it into the sedimentary record. Furthermore, the extent of dissolution appears to be species-specific, affecting more finely silicified, cosmopolitan taxa to a greater degree than the more robust endemic species. Monitoring studies indicate that cosmopolitan populations have increased in recent years, possibly as a response to global warming, yet this signal is not picked up in the sediment record due to dissolution, again confirming that sedimentary records of algae in Lake Baikal do not simply reflect past standing crops. In a previous study, Ryves et al. (2003) demonstrated that while some dissolution of diatoms occurs in the water column, by far the majority occurs at the sediment surface water interface. This is likely to be connected to the fact that a diverse community of animals live on the bottom sediments, resulting in bioturbation, which will break up the diatom frustules while they feed on available organic matter. Martin et al. (this issue) present evidence that concentrations of animal individuals (and therefore bioturbation) are higher in the shallow water regions than in the abyssal plains. However, although one potential recommendation could be that such abyssal plains are the best place for coring due to minimal bioturbation, these regions are however strongly influenced by turbidity currents, rendering them not suitable for high-resolution palaeoclimatic studies (e.g. Colman et al. 2003). Thus underwater highs appear as the best compromise because they are virtually free of turbidites or bottom-water currents and bioturbation is still moderate below the dimictic zone of the lake.

Monitoring of different nutrients in the lake is important in order to provide important information on potential controls on e.g. diatom populations in the lake. Müller et al. (this issue) assessed mass balances of some of the major components in the lake, including organic carbon, nitrogen, phosphorus and biogenic silica, from the water column into the surface sediments. Results here indicate that the nutrient budgets are smaller in the north basin than the south, as are particulate fluxes of particle bound N, P and Si_{bio}, which tie in well with previous studies on the lake. Spatial

dissolution is also an important factor, for example high phosphorus dissolution in the Maloe More (Müller et al. this issue) helps to explain some aspects of the spatial distribution of diatoms in this region (Mackay et al. 2003). Interestingly, mass balances for Si_{bio} are not balanced, and more work is needed to understand the processes going on here.

One of the central ideas of the CONTINENT programme was to find sites within Lake Baikal that were affected by minimal disturbance from e.g. turbidity flows, tectonic activity, or winnowing caused by bottom-water currents. The programme therefore focussed on three isolated highs: Vydrino Shoulder and Posolsky Bank in the South Basin and Continent Ridge in the North Basin (Charlet et al. this issue). Reflection seismic survey data and side scan sonar data were collected from each site, allowing high-resolution profiles to be constructed. Together with a variety of long cores (up to 11 m) analysed from each site, Charlet et al. (this issue) were able to demonstrate the importance of high resolution site surveying prior to coring for palaeoclimatic studies. Briefly, these studies were able to estimate the amount of clastic material being delivered to all three sites (e.g. only about 30% for the Continent Ridge), the extent of sediment reworking due to bottom-water currents (e.g. this does not appear to be significant on the crest of the Continent Ridge), the nature of tectonic activity on sediment processes (all sites are affected to some degree), the impact of turbidites (which are minimal on the crests of the Posolsky Bank and Continent Ridge), and that the Vydrino Site is much more complex than previous bathymetric maps suggested. Overall, Charlet et al. demonstrate that these underwater highs potentially contain the best, uninterrupted sedimentary sequences for palaeoclimatic studies in Lake Baikal, particularly in comparison to previous cores taken from the crests of inter-basin highs such as the Academician Ridge the Buguldeika Saddle. The quality of these cores were further confirmed by investigating in detail the bulk magnetic parameters at each site, after possible diagenetic processes that affect rock magnetism in the sediments of Lake Baikal were fully characterised and accounted for (Demory et al. this issue A). The palaeomagnetic information provided by Demory et al. (this issue B) has enabled the construction of a 200 ka long synthetic palaeointensity record for central Eurasia. Crucially, Demory et al. (this issue B) demonstrate that through events such as the Iceland Basin palaeomagnetic excursion, compelling evidence is provided that palaeoclimate records from Lake Baikal ought not to be directly tuned with $\delta^{18}\text{O}$ marine records as has been done in most previous studies.

So far we have highlighted the usefulness of understanding the processes that control the formation and delivery of potential climatic proxies through the water column and into the bottom sediments of

Lake Baikal. We also demonstrated the benefits of careful site selection in order that palaeo records are (as far as possible) long, uninterrupted sequences from which we can develop robust, independent chronologies using a variety of techniques. Given that all these pre-conditions are satisfied, we have confidence in the palaeoclimatic interpretations highlighted below.

Firstly, we will focus on the Kazantsevo period between c. 128 ka to 117 ka, which is co-incident with the Eemian in Europe. This period has increasingly been the focus of many palaeoclimatic studies, most recently in a special issue of this journal (van Kolfschoten et al. 2003). Samples at a centennial resolution were analysed for both pollen (Granoszewski et al. this issue) and diatoms (Rioual et al. this issue). Both records indicate that the Kazantsevo lasted for approximately 11 ka (c. 128 – 117 ka), similar to studies in northwest Europe. The pollen record shows that Termination phase 2 was characterised by cool wet conditions, before conditions became warm and moist, marking peak interglacial conditions. Both records also indicate a mid-interglacial cool, dry period (at c. 119.5 ka - 120ka), confirming that the mid-Eemian cooling identified in European sequences has a much wider distribution. However, this mid-interglacial cooling event did not mark the end of the interglacial, although both proxies indicate that conditions become subsequently cooler and drier.

Between the Kazantsevo interglacial and the Holocene interglacial, we detected one further warm period, coincident with the interstadial MIS 3. This record is important as it represents one of the few well-resolved diatom profiles for MIS 3 in Lake Baikal. In a multiproxy study examining diatoms, C/N ratios and $\delta^{13}\text{C}$ values from the Continent Ridge site, Swann et al. (this issue) find evidence for Heinrich events 4 and 5, resulting in a cooler climate and decreased diatom productivity in the lake. This is in contrast to evidence found for Heinrich events 6-2 in sediments from the inter-basin high, the Buguldeika Saddle (Prokopenko et al. 2001), close to the Selenga Delta between the south and middle basins. However, evidence at this southern site is related to catchment erosional events, but as Charlet et al. (this issue) indicate in their paper, the Continent Ridge site receives very little input from the catchment in comparison to those sites close to the Selenga River.

Perhaps one of the most intensively studied time-periods in terms of palaeoclimate in the northern hemisphere is the Late Glacial – Holocene transition and associated periods, and here we present new, well resolved records for the Lake Baikal region. Important in this respect is the development of a new ^{14}C AMS chronology from pollen concentrates in the sediments (Piotrowska et al. 2004), which significantly improves on other radiocarbon chronologies in the lake (e.g. see Colman et al.

1996). Morley et al. (this issue) apply for the first time, the relatively novel technique of oxygen isotope composition of diatom silica ($\delta^{18}\text{O}_{\text{DIAT}}$), which is especially useful in Lake Baikal as carbonates are mostly detrital and either very diluted or absent. Results suggest that at the Vydrino Shoulder during the Late Glacial, $\delta^{18}\text{O}_{\text{DIAT}}$ values fell from c. 27.0‰ to 20.6‰ as climate became colder into the Younger Dryas. This is likely to be related to changes in circulation patterns in the region, with an intensification of winter anticyclonic conditions resulting in a shift in the balance between inputs of isotopically low winter precipitation in the north (i.e. increased snow) and isotopically high summer precipitation in the south of the lake (i.e. decreased rainfall). With the onset of warmer Holocene conditions, $\delta^{18}\text{O}_{\text{DIAT}}$ values increased again. However, pollen analyses at all three sites (Demske et al. this issue) confirm that during the Bølling/Allerød time equivalent, climate over the Lake Baikal region became cooler and drier, to the extent that three cold events can be recognised in the sediment records, and are coincident with cooling periods identified by oxygen isotope records in the GISP2 core. Crucially, given the accuracy of the dating and level of resolution undertaken in this study, when one compares the pollen data from the three sites in Lake Baikal to events from the Greenland ice cores, many similarities can be determined, confirming that through teleconnection processes, events in the North Atlantic, such as Dansgaard-Oeschger events 1 and 0, are expressed in central Eurasia (Demske et al. this issue). Recognised cooling events throughout the Holocene in the subpolar North Atlantic are also expressed in these data, and work is currently underway to quantify changes in temperature and humidity from the pollen data already obtained.

Given the interest in climate variability over the last 1000 years, Mackay et al. (this issue) applied a previously developed diatom-inferred snow model (Mackay et al. 2003) to highly resolved, recently deposited sediments in the south basin close to the Vydrino Shoulder. However, their study has also taken into account the preservational differences in diatom species by Battarbee et al. (this issue) above, and they have applied correction factors to the dominant phytoplankton in the sediment record. By improving the record this way, the Medieval Warm Period, the Little Ice Age and a period of recent warming (from c. 1750 AD) can all be determined, highlighting the importance of investigating processes that can affect the transport and incorporation of proxies into the sedimentary record in palaeoclimate studies.

A further consequence of the impact of bioturbation on Lake Baikal sediments is that they are not annually laminated, despite the lake being very deep and having a strong seasonal component. Furthermore, given the relatively slow accumulation of sediments across much of Lake Baikal, even

when sectioned into millimetre intervals, resolution is at best at the sub-decadal level. Boës, et al. (this issue) have attempted to partly compensate for this by developing a core polymerisation technique and applying grey-scale (GS) measurements on thin sections, that allows the observation of laminations in the sedimentary record over the Late Glacial and Holocene periods. They suggest that the GS measurements can be used as a palaeoproductivity proxy at ultra-high resolution. Results confirm other proxy data, in that increases in productivity are associated with e.g. the Bölling and Alleröd periods, while reduced productivity periods are associated with cooler periods, including the Older Dryas, the intra-Alleröd cool period and the Younger Dryas. Fagel et al. (this issue) explore the potential of using the phosphate mineral vivianite (as depicted in Fig 5(3) Boës, et al. (this issue)) as another indicator of palaeoproductivity in Lake Baikal. Vivianite formation can either be authigenic or diagenetic, and in Lake Baikal, due to the oxygenation of the water column throughout the lake, its production must be diagenetic, therefore limiting its use as an indicator of palaeoproductivity. However, at the Continent Ridge, layers of vivianite concretions may be indicative of low, changing sedimentation regimes, and work is underway to explore these possibilities further.

The final two papers in this special issue focus on the palaeoenvironmental record from Lake Luanhaizi, a small alpine lake in the Qilian Mountains of NW China. The papers are tied: the first details the chronology, lithology and ostracod record of two cores spanning the period from MIS3 up to the late Holocene (Mischke et al. this issue). The second paper is another multiproxy study focusing on changing vegetation composition in and around the lake from aquatic plant macrofossils, pollen, C/N ratios, $\delta^{13}\text{C}$ values and *n*-alkane biomarkers (Herzschuh et al. this issue). Both studies provide further evidence that during MIS 3 in the Tibetan Plateau, climate conditions were warm and wet, almost to levels experienced in the Holocene (e.g. as indicated by extensive *Picea* forests in the region (Herzschuh et al. this issue). This is in contrast to the MIS 3 record for Lake Baikal (e.g. Swann et al. this issue), and is likely to be related to the influence of strong summer monsoons at this time, which although extending across the Tibetan Plateau, do not reach Lake Baikal. Furthermore, these studies add to the evidence against a large ice sheet being present on the Tibetan Plateau during the Last Glacial Maximum, as previously suggested by e.g. Kuhle et al. (2003).

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