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Climate in continental interior Asia during the longest interglacial of the past 500 000 years: the new MIS 11 records from Lake Baikal, SE Siberia

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Abstract

A synthesis of paleoclimate responses from Lake Baikal during the MIS 11 interglacial is presented based on proxy records from two drill sites 245 km apart. BDP-99 is located in vicinity of the delta of the major Baikal tributary, whereas the BDP-96 site represents hemipelagic setting distant from riverine influence. The comparison of thicknesses of interglacial intervals in these contrasting depositional settings confirm the extended ca. 33-kyr duration of the MIS 11 interglacial. The new BDP-99 diatom biostratigraphic record matches that of the BDP-96-2 holostratotype and thus establishes robust correlation between the records on the same orbitally-tuned timescale.

The first detailed MIS 11 palynological record from the BDP-99 drill core indicates the dominance of temperate boreal (taiga) forest vegetation in the Baikal region throughout the MIS 11 interglacial, since at least 424 ka till ca. 396 ka. The interval ca. 420–405 ka stands out as a “conifer optimum” with abundant *Abies sibirica*, indicative of climate significantly warmer and less continental than today. The closest Baikal analog to this type of vegetation in the current interglacial is at ca. 8–6 ka in the mid-Holocene. The warm conifer phase lasted for ca. 15 ka during MIS 11 interrupted by two millennial-scale cooling episodes.

At both drill sites, the two-peak structure of the MIS 11 diatom abundance profiles reflects the orbital signature of precession in the interglacial paleoclimate record of continental Eurasia. MIS 11 interglacial was characterized by the sustained high level of primary production and accumulation of autochthonous organic matter at both study sites. The responses of paleoclimate-sensitive indices in the mineralogy of the MIS 11 sediments in BDP-96-2 are consistent with those during the Holocene. Illitization of secondary clay minerals in the Baikal watershed was an important process, but it appears to have been subdued during the first half of the MIS 11, possibly due to elevated humidity and muted seasonality of regional climate.

1 Past interglacials as potential analogs to modern and future climates

The ability to predict future changes in global climate is essential for policymaking today and for human well-being in future, it relies on the ability to successfully model climatic conditions known to have existed in the past. Instrumental and even historic records of past climates do not extend beyond the very late portion of the current Holocene interglacial, which lasted some 11.5 kyr since the end of the last ice age. To gain a better understanding of the climate of earlier periods, different geologic archives are studied for paleoclimate proxy records.

The dominant paradigm in paleoclimate research recognizes cyclic changes of global climate as a combined effect of the Earth's orbital configuration (Milankovitch forcing) and internal feedback mechanisms. Thus, the current interglacial is not unique in the sense that more or less similar interglacials have repeatedly occurred in past. Studies of the past analogs of the current Holocene interglacial are therefore important for capturing the natural range of variability of interglacial climates and for testing the current ideas on stability and operational modes of the global climate system. This knowledge is essential for developing new generations of climate models. The closer the apparent past analog is to the Holocene, the more relevant the study of this past interglacial becomes to the discussion of the future climate scenarios.

Even though interglacials have occurred every ~80–100 kyr (3–4 orbital precession cycles apart) during the past 1 Ma, finding a potential analog to the Holocene is not easy: it is important to find periods with similar orbital configurations, which provide analogous principal boundary conditions. Such orbital configuration analogs to the Holocene (a nearly circular orbit and subdued amplitudes of orbital parameter variations, Fig. 1, blue) are few; for instance, only two intervals satisfy the "similar orbital configuration" criterion during the past 1 Ma (MIS 11 and MIS 19 intervals, Fig. 1, red). The last interglacial (Fig. 1, green) is a less likely analog because of high amplitudes of orbital parameter variations (Loutre and Berger, 2003; Loutre, personal communication). Recognition of MIS 11 as a potential analog to the current and possibly future

interglacial in lieu of MIS 5e prompted a number of special sessions and volumes dedicated to MIS 11 in the past decade (e.g. Howard, 1997; Droxler et al., 2003). A number of works made direct comparisons of regional temperature and CO_2 levels during MIS 1 and the present interglacial (EPICA Community Members, 2004; Ruddiman, 2005). The results consistently suggest that the atmospheric CO_2 level (EPICA Community Members, 2004; Raynaud et al., 2005), ice volume and sea surface temperature in North Atlantic (McManus et al., 2003) were indeed quite similar to those during the Holocene, thereby reinforcing the potential analogy.

2 Past interglacials in continental records and the continuous Pleistocene record from Lake Baikal

To gain a perspective on climate of past interglacials it is important to establish a geographic network of sites and compare multiple regional proxy records. In continuous marine oxygen stable isotope records from deepwater depositional setting, the MIS 11 interval is readily recognized from the characteristic high amplitude of the MIS 12–11 transition and from the apparent duration of the $\delta^{18}O$ minimum, which reflects the prolonged interval of low global ice volume. Marine MIS 11 intervals may be confidently correlated over long distances to study the spatial patterns of the past, such as changes in major ocean currents, rates of deepwater formation, past positions of the polar front, ice sheet behavior in high latitudes of the northern hemisphere based on ice-rafted detritus, etc.

In the mid-high-latitude continental records interglacials are recognized as intervals of expansion of thermophilic arboreal flora. However, because sediment deposition on continents changed greatly in response to environmental changes, it is difficult to find sites where long continuous Pleistocene sedimentary records are preserved. None exist in mid-high latitudes in Europe, where glaciations repeatedly obliterated prior sedimentary sequences. In non-glaciated areas long sequences of eolian deposits recorded past glacial-interglacial cycles as alternating loess/soil intervals, yet these sediments preserve few biological proxies. Some of the best continental archives of past interglacials are lake sediments. In addition to preserving pollen records of past interglacials, they contain lacustrine proxies for changes in primary productivity in response to changes in organic matter and nutrient input from respective catchments. In formerly glaciated areas, these lake sediments are found as lenses between the deposits of a prior and the subsequent ice ages. Based on pollen successions and stratigraphic considerations, such intervals are spliced to represent regional histories of past glacial-interglacial cycles and correlated across different regions. Because of the discontinuous nature of the sedimentary records, however, it has been difficult to unequivocally establish correlations of terrestrial interglacials with odd (interglacial) marine oxygen isotope stages. This is true for the MIS 11 interglacial as well (e.g. Nitychoruk et al., 2006).

Long continuous mid-latitude palynological records of several interglacials in a single record at a single site were obtained in southern Europe. Lacustrine sediment sequences in Massif Central, France, in Italy and in Greece include the equivalents of the MIS 11 interglacial (e.g. Tzedakis et al., 1997; Reille et al., 2000). The Lake Baikal sediments in SE Siberia contain the *only* known continuous lacustrine record of several glacial-interglacial cycles to the east of these sites.

3 MIS 11 in the Lake Baikal record and the objective of the current study

The sedimentary record of Lake Baikal is one of the few continental archives containing paleoclimate proxy records of past Pleistocene interglacials in a continuous sedimentary sequence, which accumulated in a relatively stable depositional setting. By now, the MIS 11 interglacial interval in the Baikal record is unequivocally identified and recovered in four drill cores (BDP-96-1, BDP-96-2, BDP-98 and BDP-99) (Fig. 1), of which BDP-96-2 is the most complete and BDP-99 has the highest resolution. Previous studies touching on or specifically dedicated to the MIS 11 proxy responses dealt with biogenic silica content (BioSi) and/or diatoms (Prokopenko et al., 2001a; Karabanov et

al., 2003; Mackay et al., 2008). Here we present new parallel high-resolution records of Lake Baikal productivity proxies and pollen for the MIS 11 interval in the most recent BDP-99 drill core. The key advantages of BDP-99 are (1) highest average MIS 11 sedimentation rate among sampled Baikal sites and (2) the location in the area affected by the suspended load of Selenga River, the main tributary of Lake Baikal (Fig. 2). The latter ensures rich pollen spectra, representative of landscape types in the Selenga catchment. As shown earlier (BDP Members, 2005), palynological spectra in BDP-99 are among the most representative among the Baikal sites: the sediments contain pollen of arboreal species not easily transported by wind (e.g. *Picea, Abies*) and those tending to be poorly preserved (e.g. *Larix*).

Similar to other records in Eurasia, past interglacials in the Lake Baikal region were characterized by the expansion of boreal (taiga) forest consisting of spruce, Siberian pine, fir, Scots pine; birch and larch are typical of more open forest-steppe landscapes. The palynological signals of the interglacials in the continuous Baikal records are thus fully compatible with palynological signatures from discontinuous sections in the formerly glaciated adjacent and more distant regions of Eurasia. The composition of pollen may be quantified into the likely climatic characteristics (temperatures of warm/cold seasons, annual precipitation) using quantitative method of biome reconstruction (Prentice et al., 1996) and modern analog techniques. So far, this has been done for the last interglacial (Tarasov et al., 2005) and for the Holocene (Tarasov et al., 2007); the MIS 11 work based on the results of this study is in progress.

Here we use the Lake Baikal record to pursue two main objectives: (1) discuss the duration and orbital signature of MIS 11 interglacial in the largest continental interior on earth, and (2) discuss the climatic signature of the MIS 11 interglacial based on comparing lacustrine proxy records and sediment mineralogy with the first detailed MIS 11 palynological record. First we cross-check our estimates of the apparent duration of the MIS 11 interglacial in contrasting depositional settings in the Lake Baikal basin and show that the apparent exceptional duration of the MIS 11 interglacial is not an artifact of an age model construction in a single record. Then we discuss how much of the MIS 11 interval in the Baikal record may be regarded as a full-scale interglacial by comparing lacustrine records of biogenic silica and diatoms with new MIS 11 pollen record. Then we discuss which part of the MIS 11 interval (if any) may be regarded as a climatic analog of the Holocene. In addition to biological proxies for terrestrial vegetation and lake primary productivity we for the first time employ proxies for past changes in the weathering conditions in the Baikal watershed.

4 Methods

Diatoms were quantitatively counted using a technique described by Khursevich et al. (2001). Diatom specimens were examined and photographed by oil immersion light microscopy using an Ergaval microscope with a 100x objective (NA=1.25). Samples for palynological analysis were processed as described by Moore et al. (1991); up to 300–1200 arboreal pollen grains were counted; pollen zone boundaries were distinguished visually. The steppe/forest index (SFI) (Traverse, 1988) was adapted to visualize overall changes of landscapes. Because *Ephedra* and Caryophyllaceae are typical members of steppe association in the Baikal region, the modified version of the SFI index was calculated as ratio of the pollen sum of *Artemisia*, Chenopodiaceae, *Ephedra* and Caryophyllaceae to the pollen sum of the above group with tree pollen sum, multiplied by 100.

For CHN and stable isotope analysis, dried sediment was homogenized in an agate mortar, decalcified with 5% HCl in an ultrasonic bath for ca. 45 min at room temperature, repeatedly washed with deionized water, centrifuged at 3000 rpm, and dried at 50°C. Ground 6- to 12 mg samples were analyzed using a VG Optima mass spectrometer interfaced with a Carlo-Erba NC 1500 Elemental Analyzer for simultaneous TOC and TN measurements. Carbon stable isotope ratios are reported as ‰ PDB.

Sediment mineralogy was studied in bulk non-fractionated samples; in order to identify clay minerals (including the mixed-layer phases), the complete experimental X-Ray Diffraction (XRD) patterns were modeled. The details of sample

preparation techniques, modeling algorithm and application of these methods are given by Solotchina et al. (2002, 2009) and Solotchina (2009). XRD patterns were obtained using DRON automated powder diffractometer system with Cu K_α radiation, graphite monochromator. Scans were performed for modeling from 2° to 35° 2Θ with speed of 0.05° 2Θ/s and a counting time of 32 s, for the phase analysis from 2° to 65° 2Θ with the same speed but with a counting time of 3 s. IR spectroscopy was used to determine the contents of feldspar, quartz and amorphous biogenic silica, estimated from the IR transmission spectra recorded on a Specord 75 IR double-beam spectrophotometer in the frequency region 400–4000 cm^{-1}.

5 Age model

The age-depth relationship of the Lake Baikal sedimentary records of the mid-late Pleistocene is best established for the Academician Ridge area, which as a bathymetric high not influenced by either the riverine input or turbidite deposition (Fig. 2). As shown by paleomagnetic event/reversal time scales of the BDP-96 and BDP-98 drill core records retrieved in 320–330 m water depth, Pleistocene sedimentation rates in this area remained remarkably stable at ca. 4±2 cm/kyr (BDP Members, 1997, 2001). The relative stability of sedimentation rates in this area is independently confirmed by radiocarbon dating (Colman et al., 1996; Nakamura et al., 2003) and magnetic paleointensity age models of the late Pleistocene (Peck et al., 1996; Demory et al., 2005). Because of the dramatic variations in Lake Baikal diatom production in response to climate, the Pleistocene glacial-interglacial cycles at Academician Ridge are represented by a distinct pattern of variations in biogenic silica content (BioSi) in sediments. In warm (interglacial) intervals BioSi constitutes up to 40–50% dry sediment weight, in cold intervals diatoms (and hence BioSi) are not present in sediments.

The orbitally-tuned age models for the Lake Baikal records were based on assigning the age tie points to BioSi peaks. Because of the location in high latitudes and in the largest continental interior on earth, the coupled lake-watershed system is highly sensitive to both obliquity and precession components of orbital forcing. Essentially, every precessional cycle of the Brunhes chron may be recognized in the Baikal lacustrine proxy records. Since the original peak-to-peak correlations of the BDP-96-2 BioSi record with ODP-677 (Williams et al., 1997) the age model has evolved. First, 65° N June insolation was used as a tuning target for the "most rapid transitions" in BioSi response (Prokopenko et al., 2001a). This age model was used in the previous Lake Baikal MIS 11 studies (Karabanov et al., 2003; Mackay et al., 2008), where the age of the MIS 11 interglacial was estimated as 426–395 ka. Later, an alternative orbital tuning was suggested based on assigning September perihelia timing to the BioSi peaks (Prokopenko et al., 2006). This approach is more consistent with the observed timing of the BioSi response around independently-dated boundaries (including the Holocene, the last interglacial, top Jaramillo paleomagnetic reversal – see discussion in Prokopenko et al., 2006). Here we use this latest version of the BDP age model; the age of the MIS 11 interval in the updated age model is 429–396 ka. The compatibility of the Baikal MIS 11 age model with those of other global records is illustrated by the comparison with LR2004 marine oxygen isotope stack in Fig. 3: even though no specific adjustments were attempted to match the records, the alignment of the independent LR2004 and Baikal age models is quite remarkable.

The new BDP-99 record presented here was obtained in vicinity of the major tributary of Lake Baikal, in the area of Selenga River delta (Fig. 1); it is currently in 200 m water depth. As shown previously (BDP Members, 2005), sedimentation rates were changing significantly with glacial-interglacial transitions at this site, by a factor of 2–4. With this in mind, we made no effort to orbitally-tune the BDP-99 record in this study. Instead, we first studied the diatom record of the BDP-99 section and identified the same biostratigraphic boundaries as those observed in the orbitally-tuned BDP-96-2 holostratotype section (245 km NE, Fig. 2). Then we assigned the orbitally-tuned age of these boundaries to the new BDP-99 record as a safer way of constructing the MIS 11 age model (see below).

6 The apparent duration of the MIS 11 in the Lake Baikal record

One of the remarkable features of the MIS 11 interglacial is the extended ca. 30 kyr duration (e.g. McManus et al., 2003): in most age models this warm interval corresponds to two precession-driven insolation peaks, twice as long as a typical interglacial. Our previous age models also suggested the ca. 32 kyr duration (e.g. Karabanov et al., 2003). Here we corroborate our prior model using new Baikal data. Table 1 compares the apparent duration of the past three interglacial intervals at two Lake Baikal sites 245 km apart, which represent contrasting depositional settings. As seen in the Table, the average sedimentation rates during interglacials and interstadials remained relatively stable at each of the drill sites, being consistently higher at the BDP-99 site. The thickness of the MIS 11 interglacial intervals in both drill cores is at least twice that of the last interglacial interval; it is similar to the thicknesses of the combined MIS 9e-d-c and MIS 7c-b-a intervals (each corresponding to two precessional cycles). Thus the comparison of thickness of respective interglacial intervals (Table 1) corroborates the assignment of the MIS 11 interglacial interval in the Baikal record to two precessional cycles in the orbitally-tuned age models (Prokopenko et al., 2001a, 2006).

Estimating the duration of past interglacials in continental Eurasia based on BioSi/diatoms in a lake may be questioned as being of limited use, because this is not how interglacials are identified in continental records elsewhere. In addition, because the ecology of the (mostly endemic) Lake Baikal diatoms is not well established, the observed changes in diatom abundance and species composition during past interglacial cycles do not readily translate into climatic parameters (e.g. seasonal temperatures). To answer this potential concern, Table 1 makes a comparison of the apparent durations of past interglacials and interstadials in the Baikal record as estimated from conventional palynological proxies and from the BioSi/diatom proxies.

Table 1 shows that productive diatom flora expanded in the lake at the time of the expansion of forests in the Baikal region. Previously, the close temporal relationship between BioSi/diatom and arboreal pollen proxies for warm regional climate has been established for the radiocarbon-dated Holocene interval (e.g. Prokopenko et al., 2007) and for the paleointensity-dated last interglacial interval, as seen from the comparison of diatom (Rioual and Mackay, 2005) and pollen (Granoszewski et al., 2005) records. For older interglacial and interstadial intervals, the apparent durations (thicknesses) agree in pollen and BioSi/diatom records as well (Table 1). For instance, the close agreement is evident in the well-resolved BDP-99 record, where thicknesses of interglacial intervals estimated independently from pollen composition (Shichi et al., 2007) nearly coincide with those estimated from core lithology (BDP Members, 2005) to within 97±2%. By contrast, in the BDP-96 record, intervals rich in arboreal pollen appear systematically shorter (thinner, 68±8%) as compared with estimates based on the BioSi record (Table 1). This seeming discrepancy is mainly due to the different resolution of the records: BioSi and diatoms were studied at 1–2 cm resolution, whereas pollen was studied at low ca. 10 cm resolution (5–7 samples per warm interval). In addition, because of the location distant from sources of terrigenous input, BDP-96 sediments are not rich in pollen, making palynological records less representative. In the better-resolved record CON01-603-2 in 386 m water depth from the same general area (Fig. 2) the duration (thickness) of the last interglacial interval estimated in diatom and in pollen records nearly coincide (Table 1, MIS 5e*).

The following conclusions are the most relevant to justifying the Lake Baikal age model for the MIS 11 interglacial: (1) regardless of the depositional setting, MIS 11 is the longest/thickest among the last four interglacial intervals, both at Academician Ridge (BDP-96) and in Selenga Delta area (BDP-99); (2) Lake Baikal BioSi is a reliable index of past interglacials in continental interior Asia: durations of the intervals of high BioSi production (accumulation) match the duration of regional forest phases, as seen in the best-resolved records; (3) neither lithology nor sedimentation rate estimates indicate accumulation rate anomalies during MIS 11 at the BDP drill sites. Thus, the increased thickness of the MIS 11 interglacial interval in the Baikal record is a true reflection of an unusual extended duration of this interglacial in continental Eurasia.

7 The new diatom record of the MIS 11 interval from the BDP-99 drill core

The total diatom abundance during MIS 11 in BDP-99 are about twice as low as in BDP-96-2 (Fig. 4), which is consistent with differences in average sedimentation rates (Table 1) and thus with the degree of dilution of biogenic component in sediments with clastic component. The overall two-peak structure of the diatom abundance profile in BDP-99 is similar to that in BDP-96-2 (Fig. 3). Dominant species in the lower part of the BDP-99 record below 6360 cm are *Stephanodiscus distinctus* var. *distinctus* and *S. exiguus* (Fig. 4). Co-occurrence of these species is characteristic of local diatom assemblage zone (LDAZ) 18 in the BDP-96-2 holostratotype Sect. (Fig. 3; Khursevich et al., 2001). At ca. 6340 cm in BDP-99, a rapid increase in the abundance of *S. binderanus* and the decline of*S. exiguus* are observed (Fig. 4). The same change in the diatom assemblage composition was previously observed in BDP-96-2 and recognized as LDAZ 18/17 biostratigraphic boundary at ca. 417 ka (Fig. 3). Above 6120 cm in the BDP-99 record, *S. binderanus* disappears from diatom assemblage at a time of substantial increase in the abundance of *Cyclotella minuta* (Fig. 4). A similar change in the composition of the Baikal diatom assemblage was previously observed in the BDP-96-2 holostratotype as well, where it was recognized as LDAZ 17/16 biostratigraphic boundary at ca. 400 ka (Fig. 3; Khursevich et al., 2001).

Thus, the relative abundance and the succession of co-dominant planktonic species in the new detailed diatom BDP-99 record of the MIS 11 interglacial are essentially the same as those in the holostratotype BDP-96-2 section 245 km NE. It is therefore possible to distinguish the same diatom zones and the respective biostratigraphic boundaries in both records.

The slight differences between BDP-99 and BDP-96-2 biostratigraphic records include (1) the continued presence of *Stephanodiscus exiguus* in BDP-99 above the LDAZ 18/17 boundary, and (2) the decline in the abundance of *S. binderanus* in the second half of the LDAZ 17 interval in BDP-99 (6250–6130 cm, Fig. 4). In addition, a new finding with regard to the composition of diatom assemblage is that individual specimens of *Stephanodiscus* sp. aff. *S. binderanoides* were observed in several horizons of the MIS 11 (Fig. 4). Previously, this taxon of the LDAZ 19 interval (late MIS 12 glacial), was believed to not be present in the Baikal record above the MIS 12/11 transition (Khursevich et al., 2001). In the BDP-96-2 holostratotype section, a relatively low yet still notable abundance of *Synedra acus* var. *radians* (up to 15 mln valves/g sediment) has been observed (Khursevich et al., 2001). Apparently, valves of this taxon were not preserved in sediments at the BDP-99 site.

The establishment of the robust biostratigraphic correlation ties within the MIS 11 interglacial intervals of two Lake Baikal drill cores allows putting both records on the same orbitally-tuned timescale using LDAZ boundaries at 400 ka, 417 ka and the biostratigraphic change at 422 ka (*S. exiguus* expansion) as tie points (Figs. 3, 4). This correlation suggests that the earliest portion of the MIS 11 interglacial interval (ca. 429–424 ka in BDP-96-2, Fig. 3) was not recovered at the BDP-99 site (Fig. 4). As shown below, this conclusion is consistent with palynological record and with organic matter-based productivity proxy signals.

8 Productivity proxy records of MIS 11 interglacial in Lake Baikal

The productivity proxy records based on bulk sedimentary organic matter (TOC, TN, C/N and $\delta^{13}C_{org}$ ratios) at both drill sites are consistent with BioSi/diatom responses in indicating a prolonged interval of high production and accumulation of organic matter (OM) in the lake. By analogy with the independently-dated Holocene and the last interglacial intervals, continuous high OM accumulation maybe interpreted as an indication of full-scale interglacial conditions. At the BDP-96 site, the structures and the trends in productivity proxy records are much stronger pronounced (e.g. two-peak structures of diatom and $\delta^{13}C_{org}$ profiles in Fig. 3) as compared to those at the BDP-99 site (Fig. 4), where the MIS 11 profiles of TOC and $\delta^{13}C_{org}$ are essentially flat. This observation underscores the differences in settings of two drill sites. Because BDP-99 is located in the area of elevated nutrient supply from Selenga River (Fig. 2), primary productivity

and organic matter export from the photic zone here remained quite stable throughout the MIS 11 interval. By contrast, the BDP-96 area, which is distant from riverine input (Fig. 2) appears more sensitive to basinwide mechanisms controlling productivity of this water body. In addition, higher sedimentation rates (Table 1) and shallower depth (200 m) of the BDP-99 site as compared with those of the BDP-96 site (330 m) imply faster settling and burial of primary-produced organic matter. Hence, the effect of degradation (in both the water column and at sediment/water interface) on the composition of sedimentary organic matter may be less pronounced at the BDP-99 site.

The observation of low C/N ratio in Lake Baikal sediments in vicinity of the major river delta (BDP-99) and high C/N at the location distant from terrestrial sources of suspended load (BDP-96) is counterintuitive. This observation lends support to the idea that C/N ratio changes at hemipelagic sites in Lake Baikal are in large part a reflection of internal carbon cycling rather than a measure of a simple mixture of organic matter from two (terrestrial vs. lacustrine) end-member sources (Prokopenko et al., 2009). The lack of close correlation between $\delta^{13}C_{org}$ and C/N variations is also supportive of this idea.

Without getting into much detail, here we discuss the features of the high-resolution MIS 11 productivity proxy records that make them similar to those of the Holocene (Prokopenko et al., 2007) and the last interglacial (Prokopenko and Williams, 2003). One apparent similarity between all three interglacials is that TOC and TN increases at the onset of interglacials occur much more rapidly than the respective increases in BioSi. In addition, in all three cases including the MIS 11 (Fig. 3) the glacial/interglacial transition is associated with a pronounced negative excursion in $\delta^{13}C_{org}$. Similar to the proxy phasing during the Holocene (Prokopenko et al., 2007), the MIS 11 BioSi maximum lags the TOC maximum by as much as several ka (Fig. 3). The apparent decoupling between these basic productivity signals indicates that algal groups other than diatoms played an important role in the lake's primary production, particularly, during the early portions of the respective interglacials. This idea has been confirmed by studies of the biomarker records of the LGM-to-Holocene transition: peak TOC accumulation corresponds to ca. 5–8 ka with significant contributions from green algae and cyanobacteria (Tani et al., 2002), whereas BioSi/diatom peak occurs after 4 ka (Prokopenko et al., 2007).

Similar to the C/N ratio records of the Holocene and of the last interglacial (Prokopenko and Williams, 2003), C/N ratios progressively increased at both BDP study sites during the MIS 11 interglacial (Figs. 3, 4, dashed arrows). This pervasive trend during interglacials in Lake Baikal may be viewed as a reflection of increasing efficiency of the lake's "biological pump": progressively higher amounts of carbon per unit nitrogen were sequestered in bottom sediments. Nitrogen sequestration in bottom sediments during the early MIS 11 was higher than in late MIS 11 interglacial at both BDP-99 and BDP-96 sites.

For the purposes of this study it may therefore be concluded that at pelagic sites in Lake Baikal the succession of productivity proxy responses, their relative phasing and general trends in the sedimentary records of MIS 11, MIS 5e and MIS 1 interglacials have a lot in common. Common features testify that the MIS 11 productivity proxy signals in Lake Baikal are not atypical and adequately reflect changes in the cumulative productivity of the coupled lake-watershed system in continental interior Asia.

It is worth noting here that anomalous excursions are observed in TOC, C/N and $\delta^{13}C_{org}$ in a thin layer 6115–6125 cm in BDP-99 (Fig. 4, brown shading). An unusual signal of isotopically-heavy bulk sedimentary carbon (−17 to −20‰, purple dots in Fig. 4) in this layer is likely due to the presence of detrital carbonates that were not leached out by mild HCl treatment. Previously, series of similar carbonate(dolomite)-bearing layers with anomalous bulk $\delta^{13}C$ were observed in the Selenga Delta area sediments at the BDP-93 site (Fig. 2) and were interpreted to represent local erosional events in the watershed. It was hypothesized that these events were associated with North Atlantic millennial-scale events of the MIS 4-2 interval (Prokopenko et al., 2001b). Even though in the visual description of the BDP-99 drill core the layer 6115–6125 cm does not stand out macroscopically (BDP Members, 2005), it is possible that the TOC/$\delta^{13}C$ signal registered a similar Baikal erosional event at the end of the MIS 11

interglacial, around 400 ka according to the current age model.

9 The first high-resolution palynological record of the MIS 11 interglacial from Lake Baikal

The new high-resolution palynological record of the MIS 11 interval is the centerpiece of our study because of the possibilities of (1) testing prior paleoclimate interpretations of lacustrine proxy responses and (2) quantitative estimates of past climatic parameters based on biomization and modern analog techniques (e.g. Tarasov et al., 2005, 2007). Here we address the former aspect of the palynological record; quantitative reconstructions and the detailed discussion of step-by step changes in Baikal watershed vegetation will be reported elsewhere. Our palynological record in BDP-99 is the first detailed record of a Baikal interglacial beyond the Holocene (Bezrukova et al., 2005 and references therein; Demske et al., 2005) and the last interglacial (Granoszewski et al., 2005).

The proposed correlation of BDP-96-2 and BDP-99 based on diatom stratigraphy (Fig. 4) suggests that BDP-99 drill core did not recover the MIS 12/11 transition and the earliest part of the MIS 11; the likely basal age of the recovered MIS 11 interval is ca. 423–424 ka (Fig. 4). This conclusion is consistent with the observations of a full interglacial-type pollen assemblage dominated by taiga forest species and of high interglacial-type TOC and TN contents at the base of the section (Fig. 4). Furthermore, maximum content of TN at the base of the MIS 11 interval recovered in BDP-99 core is apparently correlative with TN maximum in the earlier part of the MIS 11 interval in the BDP-96-2 (ca. 422–415 ka, Fig. 2).

We visually distinguished 11 pollen zones (PZ) in the Lake Baikal record of the MIS 11-early MIS 10 interval in BDP-99 drill core (Fig. 5). Zones 1 through 4 are characterized by the dominance of coniferous taiga vegetation, similar to the dominant vegetation type around southern Baikal today. According to our age model, this period of "full interglacial"-type conifer forest vegetation has lasted continuously for at least

24 kyr.

In PZ1 at the base of the section, Scots pine (*Pinus sylvestris*) and Siberian pine (*P. sibirica*) are dominant, spruce (*Picea*), fir (*Abies*), larch (*Larix*) and birch (*Betula alba*-type) are present, making the composition of pollen in this interval quite similar to sub-recent pollen spectra. It is therefore likely that regional climate was similar to that of today in a sense of being a climate of a full-scale interglacial.

PZ 2 is characterized by the elevated abundance of *Abies* (fir) pollen, which is indicative of the expansion of dark coniferous forest. Because fir is particularly sensitive to precipitation and temperatures, today this species has a quite limited distribution around Lake Baikal. High abundance of fir throughout the PZ 2 interval of the MIS 11 interglacial therefore indicates milder winter temperatures, higher annual precipitation and less continental climate in the region as compared to those of today. This entire zone may thus be viewed as the "climatic optimum" of MIS 11 in continental Siberia, which lasted for at least 15 kyr (Fig. 5).

PZ 2 is divided into a-b-c portions to highlight the significance of palynological signals at 6245–6260 cm (PZ 2b). The increase in the abundance of *Picea*, *Pinus sibirica*, and, importantly, *P. pumila* pollen in this narrow interval indicates a regional cooling with decreased summer temperatures, lowered evapotranspiration and elevated soil moisture levels. The pollen composition of the following PZ 2c is similar to that of PZ 2a (Fig. 5), thereby indicating the return of a warmer "optimum" climate conditions following the short-term cooling during the PZ 2b interval. The relative increase of *Larix* pollen since PZ 2c onward, however, may be viewed as an indication of strengthening continentality (sesonality) of regional climate in the second half of the MIS 11 interglacial. Zones PZ 1–2a were characterized by elevated abundances of ferns (Polypodiaceae), which are typical of humid dark conifer forests around Lake Baikal, and by very low (to none) content of re-worked pollen. It is possible that even though the composition of the dominant vegetation remained essentially the same, the pattern of drainage in the catchment and/or currents in the lake has changed somewhat in mid-MIS 11 interglacial at PZ 2b/2c boundary.

PZ 3 has the same type of signal as PZ 2b, with increased abundance of *Picea*, *Pinus sibirica* and *P. pumila* pollen (blue arrows, Fig. 5). This interval of a "colder"-type vegetation appears to have lasted longer, though, and hence is distinguished as a separate zone 3. The return of "warmer"-type vegetation with *Abies* in PZ 4a was associated with a substantial increase in the abundance of Scots pine pollen (yellow arrow, Fig. 5). This type of signal may be interpreted as a shift to higher summer temperatures and a reduction in soil moisture; a similar change in vegetation around Lake Baikal at ca. 6 ka was made apparent by the Holocene palynological records (e.g. Demske et al., 2005; Prokopenko et al., 2007).

Zone 4b corresponds to the end of the MIS 11 interglacial as seen from the gradual decline of forest vegetation and the coeval expansion of steppe elements (note the SFI index); at the same time diatom abundance reduces dramatically (Fig. 5). The decline in TOC and TN contents in PZ 4b interval (Fig. 4) occurs in parallel with those of diatoms and forest vegetation. This observation further testifies that Lake Baikal productivity changes (as suggested by either BioSi/diatom or bulk organic matter proxies) is closely related to the climate-driven changes in terrestrial ecosystem and thus serves as a reliable indicator of climatic variations.

About 6070 cm in BDP-99, i.e. after ca. 396 ka in our age model, the vegetation in the Baikal region has changed to a forest-steppe type with high abundance of birch, shrubs and steppe elements such as Artemisia, Chenopodiaceae, Poaceae, etc. Pollen zones 5 through 11 correspond to the gradual MIS 11/10 transition. Although still correlative with the MIS 11 isotope stage (Fig. 3), these zones lie beyond the range of the MIS 11 interglacial and thus beyond the scope of the current contribution. The significance of these palynological signals will be discussed elsewhere. Here we simply note that in the Lake Baikal area the MIS 11/10 transition was not entirely gradual with repeated periods of expansion and retreat of conifer forests in the Baikal region.

10 The promise of millennial-scale climatic signals during the MIS 11 interglacial

Sampled at high-resolution, Baikal proxy records are known to exhibit millennial-and/or centennial-scale (several data points) departures of measured properties from average interglacial values. Such departures in several single-proxy records were used to infer repeated climatic oscillations in the Baikal region. For instance, attempts were made to establish links between the "1.5 kyr"-cycle in the North Atlantic IRD record and the Lake Baikal Holocene records of uranium isotopes (Goldberg et al., 2005) or diatom abundance and oxygen isotope ratios in biogenic silica ($\delta^{18}O_{BioSi}$) (Mackay, 2007). Similar repeated events were believed to have been recognized by Mackay (2007) in Lake Baikal diatom abundance and the derived biovolume records of the last interglacial. Lacking the crosscheck from other proxies at multiple sites, these inferences so far remained largely inconclusive.

The MIS 11 interglacial interval in Lake Baikal provides evidence that low-amplitude oscillations in proxy responses may not be random phenomena. For instance, according to Mackay et al. (2008), the decline in oxygen isotope ratios of biogenic silica ($\delta^{18}O_{BioSi}$) at the end of the MIS 11 interglacial (395–390 ka) represents regional cooling (purple arrow, Fig. 3). This interpretation is consistent with the rapid decline of lake productivity apparent from diatom abundance and productivity proxies (Fig. 3) and with decline of arboreal (conifer forest) vegetation (purple arrow, Figs. 4, 5). By analogy, the earlier, lower-amplitude $\delta^{18}O_{BioSi}$ depletions during MIS 11 interglacial (Fig. 3, blue arrows) may be viewed as representing regional cooling signals as well. The observation that these signals occur at a time of Lake Baikal diatom biostratigraphic changes and the coeval shifts in organic proxy records (in particular, $\delta^{13}C_{org}$) may not be coincidental (Fig. 3). Likewise, as shown by the BDP-99 record, diatom biostratigraphic changes tend to coincide with pollen zone boundaries, e.g. PZ 1/2, PZ 2b/2a and PZ 4a/4b boundaries (Fig. 4). These apparent alignments strengthen the case for the significance of Baikal proxy responses in representing regional climate changes

at sub-Milankovitch resolution. The importance of these relationships in the record of the MIS 11 interglacial will be explored further upon quantification of regional climatic parameters based on the new BDP-99 pollen record.

11 Sediment mineralogy from XRD analysis and indices of weathering in the Lake Baikal watershed during MIS 11

Mineralogy of lake sediments, so far understudied in Lake Baikal watershed because of complicated and labor-intensive methodologies, is nevertheless important for developing regional environmental proxies. For instance, production of biogenic silica (BioSi), which is a major component of Lake Baikal interglacial sediments, is dependent on the balance of dissolved silica in the lake. Production of both BioSi and organic matter, which is dependent on nutrient supply from the catchment, is expected to be responsive to climate-driven changes in regional weathering conditions. A recent synthesis of the LGM-Holocene mineralogical records of the neighboring Lake Baikal and Lake Hovsgol basins (Solotchina et al., 2009) helped identifying key regional indices, which represent the effects of climate change on weathering processes. Here we rely on the conclusions of the cited study in discussing the significance of mineralogical signatures of the MIS 11 interglacial.

The analysis of the complete mineral composition of the MIS 11 interval in the BDP-96-2 record in Fig. 6 indicates that this area of Lake Baikal bottom did not experience dramatic changes in either sediment facies or sources of terrigenous component of the sediments. The lack of dramatic variations in the contents of main clastic components such as quartz, plagioclase, muscovite (Fig. 6) is consistent with the conclusion of a stable depositional setting interpreted from relatively uniform sediment lithology (e.g. Karabanov, 1997; Prokopenko et al., 2001a). During the peak MIS 11 interglacial (compare with BioSi and TOC records, Fig. 6), the relative abundance of quartz is somewhat lower, whereas that of plagioclase is somewhat higher than at the MIS 12/11 and 11/10 transitions. The same relationship has been observed at the BDP-93 site

(Fig. 2) in the detailed record of the LGM-to-Holocene transition (Fig. 2 in Solotchina et al., 2009). Also, similar to the record of the present interglacial (ibid.), the abundance of clastic well-crystallized muscovite during MIS 11 peaks at the glacial/interglacial transition and steadily decreases thereon (Fig. 6). The abundance of secondary clay minerals (mixed-layer silicates+illite+kaolinite) steadily increases (Fig. 6), just like during the Holocene (ibid.). The similarities in these basic trends allow concluding that clastic deposition and weathering of the source material during the MIS 11 interglacial was not in any way anomalous when compared with those during the present interglacial.

The key indices identified in the cited work to represent the relationship between regional climate and weathering in the Baikal watershed were (1) the abundance of expandable (smectite) layers in illite-smectite (referred to as "smectite layer index" hereafter) and (2) the abundance of illite. The commonsense expectation is that warmer climate promotes formation of secondary clay minerals with expandable (smectite) layers. The high-resolution record of clay mineral composition has shown this to be true in Lake Baikal: the smectite layer index faithfully recorded Bølling-Allerød warming and the Younger Dryas (YD) cooling (ibid.). Based on these observations, smectite layer index may be regarded a proxy for enhanced weathering around Lake Baikal during warmer summers. During the MIS 11 interglacial, the smectite layer index rose steadily and remained quite high during the subsequent MIS 10/11 transition (Fig. 6, pink shading).

The abundance of illite (Fig. 6, yellow shading) is related to weathering processes as well because illite is known to form from mixed-layer clay minerals through the process called illitization (transformation of mixed-layer silicates into illite). The sensitivity of this index to climate is apparent from the record of the last deglaciation (Fig. 2 in Solotchina et al., 2009): illite sensu stricto was absent in sediments of the last glacial at BDP-93 site and first appeared in the Bølling-Allerød interval to disappear again during the YD and the YD-to-early Holocene transition before consistently increasing since ca. 9.5^{14}C ka onward. The MIS 11 record shows that illitization in the Baikal watershed was also significant during this interglacial. During the late MIS 12 glacial

the abundance of mixed-layer illite-smectite is at maximum (Fig. 6, brown shading), whereas illite sensu stricto is not present (Fig. 6 yellow shading). With the onset of MIS 11 interglacial (as constrained by the coupled diatom/BioSi and pollen records), the total abundance of the mixed-layer illite-smectite in Lake Baikal sediments becomes a mirror image of the illite abundance, suggesting that illite formed primarily from mixed-layer silicates (Fig. 6).

Both weathering indices in the sedimentary record of BDP-96-2 exhibit a clear trend from minimum values at the beginning of MIS 11 to maximum values at the end of this interglacial (Fig. 6, arrows). The consistent trend toward stronger weathering as suggested by illite abundance and smectite layer index may reflect the overall trend towards maturation and thickening of regional soil profiles during MIS 11, which cumulatively supply increasingly higher amounts of clay minerals as weathering products. A similar trend of continuously increasing illite abundance in the Lake Baikal record from the BDP-93 site (core Ver92/2 GC24, Fig. 2) was observed during the Holocene as well (Fig. 2 in Solotchina et al., 2009).

There appears to be a visual similarity between BioSi and illite profiles during the Holocene (ibid.) and the MIS 11 interglacial (Fig. 6). This observation implies a link between weathering as a source of amorphous silica supplied by surface runoff to the lake and the expansion of diatoms as the dominant group of primary producers. New MIS 1 (Fig. 2 in Solotchina et al., 2009) and MIS 11 records (Fig. 6) reveal this apparent relationship for the first time. This linkage may be expected from the balance estimates: presently, as much as 78% of annual amorphous silica input to the lake via surface runoff is sequestered in bottom sediments (Votintzev, 1961).

The MIS 11 clay mineralogy records make it apparent that illite abundance is closely related to smectite layer index (Fig. 6). A similar close relationship was noted for the record of the past 15 ka (Solotchina et al., 2009) and is not coincidental. Several factors contribute to this relationship. First, higher abundance of expandable (smectite) layers in illite-smectite results in higher rates of illitization (Bethke and Altaner, 1986). Secondly, the 42% smectite layer abundance value is the "magic number": above this threshold the rate of illitization dramatically increases because less fixed potassium is required to transform illite-smectite into illite (Środoń, et al., 1986). Finally, an important mechanism leading to potassium fixation and hence illtization is the repetition of "wetting-drying cycles" (Eberl et al., 1986). Such cycles also enhance potassium extraction and alteration of bedrock minerals in soils and weathering crusts. These arguments were used to suggest an explanation for the differences between clay mineralogy signatures of the early Holocene with cooler and relatively more humid climate and the mid-late Holocene with relatively more arid climate characterized by enhanced seasonality (Solotchina et al., 2009). Applying the same line of argument to the MIS 11 proxy records in Fig. 6, one may conclude that summers during the first half of the MIS 11 interglacial (ca. 429–414 ka) in the Baikal region were relatively cooler and more humid as compared with those of the second half of the MIS 11 interglacial (ca. 414–396 ka). The implications for changes in effective moisture (humidity) from clay mineralogy proxies (Fig. 6) appear consistent with the implications from terrestrial vegetation changes suggested by the palynological record at PZ 2b/2c boundary (Fig. 5).

Summarizing the results of the XRD analysis and modeling of the Lake Baikal MIS 11 interglacial sediments we conclude that the composition of clastic component was quite similar to that during the Holocene interval, revealing no anomalies and thus no evidence for dramatic changes in the depositional setting. The composition of the main mineral phases and the records of the key climate-sensitive weathering indices are in reasonable agreement between MIS 11 and MIS 1 intervals, thereby making the comparison of these records meaningful.

Overall, the abundance of illite and the smectite layer index during MIS 11 at the BDP-96 site are lower than those during the Holocene at the BDP-93 site (Fig. 2 in Solotchina et al., 2009). Given the distance between sites (Fig. 2), we do not overemphasize the significance of this observation. We note, however, that from the standpoint of mineralogy proxies only the late MIS 11 interglacial (ca. 404–400 ka) appears analogous to mid-late Holocene. For the most part, MIS 11 interval in the Lake Baikal mineralogical record appears more like the early part of the Holocene. In terms of

climatic interpretation of clay mineralogy this implies higher effective moisture and less contentality (seasonality) of regional climate as compared with the regional climate of the past 6 kyr. These conclusions are in fair agreement with the implications from the BDP-99 palynological record (Fig. 5), which shows the prolonged interval of dark coniferous taiga indicative of humid climate with muted seasonality (PZ 1–3) followed by what appears to be drier and more seasonal climate of the very late part of the MIS 11 interglacial (PZ 4a).

12 Conclusions

Understanding past climate of the MIS 11 interglacial is important given that the earth's orbital configuration during this interglacial is the most recent analog to the orbital configuration of the current interglacial. Finding well-resolved paleoclimate records of the MIS 11 on land is difficult because of the discontinuous nature of most continental sedimentary archives. Lake Baikal, the deepest in the world, is one of the few basins in mid-high latitude Eurasia which preserved continuous sequences of several Pleistocene climatic cycles. The MIS 11 interglacial interval in Lake Baikal is well constrained and recovered at several sites.

The Baikal record has a robust orbital time scale constructed based on lacustrine productivity records. This age model is independent, i.e. it is not a correlation-based derivative of some other regional age model. Among multiple paleoclimate proxies preserved in Baikal sediments, pollen is very important as it makes possible to establish correlations with other regional records from Eurasia, in which palynological records are used for identifying past interglacials. In the best-resolved Baikal records including those reported here, the estimates of the duration of past interglacials derived from lacustrine productivity records (biogenic silica, diatom abundance, organic matter content) closely agree with those derived from palynological records.

As shown by the records from two contrasting depositional settings in the lake, MIS 11 interval in the Baikal record is the thickest among the last four interglacial intervals. Because this interval was not associated with anomalies in lithologic composition, sediment mineralogy and/or sedimentation rates, the thickness of the MIS 11 interglacial interval in Lake Baikal is an adequate representation of the extended duration of this interglacial, which corresponds to two precession peaks in the orbital age model.

The MIS 11 interglacial interval in two drill cores 245 km apart was characterized by nearly the same composition of planktonic diatom assemblage. The same pattern of changes in the relative abundance and the same succession of co-dominant planktonic species confirmed the basin-wide nature of the interglacial planktonic diatom assemblage in Lake Baikal and allowed identifying biostratigraphic boundaries to correlate the records and establish the common age scale for two distant drill core records.

Productivity proxy signals in bulk sedimentary organic matter at both BDP-99 and BDP-96 drill sites indicated sustained high accumulation rates of organic matter indicative of prolonged stable interglacial conditions. The relative lead of OM-based proxy signals relative to biogenic silica at the onset of the MIS 11 interglacial and the trend of increasing C/N ratio during the interglacial appear quite similar to those in the Holocene records. BDP-99 proxy records in the vicinity of the delta of the largest Lake Baikal tributary were least variable suggesting high sustained level of primary productivity. Terrestrial organic matter does not appear to be a dominant source of bulk OM in the MIS 11 sediments and either of the drill sites.

Palynological record from the BDP-99 drill core indicates that coniferous forests continuously dominated in the region during the MIS 11 interglacial. The current age model constrains the duration of this forest phase at ca. 424–396 ka (the lowermost portion of the MIS 11 interval ca. 429–424 ka is believed to not have been recovered in the BDP-99 drill core). The distinct feature of the MIS 11 terrestrial vegetation record is a prolonged (ca. 420–404 ka) interval of “dark conifer optimum” with substantial abundance of fir (*Abies sibirica*). Because of the sensitivity of this species to seasonal temperatures and the requirement of high precipitation, this “optimum” interval was likely characterized by a climate warmer than today with subdued seasonality, warm snowy

winters and temperate humid summers. During the Holocene, forests of a somewhat similar composition (yet, with lower *Abies* abundance) existed around Lake Baikal at ca. 8–6 ka (Tarasov et al., 2007; Bezrukova et al., 2008). From the viewpoint of the potential MIS 11-Holocene analogies, the new BDP-99 palynological record suggests that for the most part the MIS 11 interglacial was characterized by warmer and less continental climate. A shift to a more modern-type vegetation with a more substantial participation of pine and larch has occurred only towards the end of the MIS 11 interglacial, ca. 404 ka in our age model. Several intervals of the MIS 11 record are characterized by pollen composition indicative of regional cooling episodes.

In marine oxygen isotope records, the gradual δ^{18}O change during the early MIS 11 above Termination V may be viewed as evidence for a longer-than-usual global deglaciation at a time of subdued amplitudes of orbital forcing (e.g. Fig. 2). In this view, the extended deglaciation contributes to the total estimated duration of the MIS 11 interglacial making this estimate excessive. The new palynological record from Lake Baikal provides an important constraint on this line of argument by indicating that above 50° N in continental Eurasia the vegetation of a full-scale interglacial was established no later than 424 ka.

The sediment mineralogy record of the MIS 11 interglacial studied in the BDP-96-2 drill core indicates a rather stable depositional setting with no apparent dramatic variations in sources of the mineral component of Baikal sediments. Two key climate-sensitive indices of weathering in the Baikal watershed, the smectite layer index and the abundance of illite, exhibit general trends consistent with the changes in the composition of secondary clay minerals during the Holocene. Similar to the Holocene, illitization was apparently an important process in the Baikal watershed during MIS 11. The current understanding of the nature of weathering indices in the Baikal record suggests that the first half of the MIS 11 interglacial could have been characterized by more humid and likely cooler summers as compared with those of the late Holocene. This inference is consistent with the changes observed in the BDP-99 palynological record.

Historically, linking marine and terrestrial records has been difficult, particularly in the time range beyond the last interglacial, where age model uncertainties become difficult to resolve in discontinuous records. Lake Baikal drill cores provide a new type of a continental record. On one hand, the complete "continental" set of paleoclimate proxies (from sediment mineralogy and lake productivity to diatom stratigraphy and pollen) make it possible to establish correlations with stratigraphic blocks of the discontinuous continental archives; on the other hand, robust orbitally-tuned time scale allows reliable correlation with individual stages and substages in marine oxygen isotope records. The current Lake Baikal MIS 11 contribution may be viewed as an important case study underscoring the potential and the significance of marine-terrestrial correlations as a tool for reconstructing climates of the past interglacials.

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Table 1. Thickesses of the interglacial/interstadial intervals of three interglacial cycles at BDP-96 and BDP-99 drill sites in Lake Baikal, and the apparent sedimentation rates.

Drill	MIS	Duration	Thickness of intervals in parallel proxy records, cm					Sed.
core (site)	substage in Baikal record[1,2]	orbital model[2], kyr	biogenic silica record[2]	quantitative diatom abundance[3]	semi-quantitative diatom abundance[7]	arboreal pollen record[4]	Ratio of thickness in pollen vs diatom records	rate cm/kyr
BDP-96-2	5a	14 kyr	68 cm	74 cm		–		4.9
	5c	12 kyr	62 cm	70 cm		–		5.2
	5e	13 kyr	73 cm	77 cm		54 cm	74%	5.6
CON01-603-2	*5e**	*11 kyr*[5]	–	*106 cm*[5]		*97 cm*[6]	**92%*	*9.6*
	7a	14 kyr	60 cm	64 cm		34 cm	57%	4.3
	7c	10 kyr	52 cm	52 cm		33 cm	64%	5.2
	7e	10 kyr	54 cm	56 cm		35 cm	65%	5.4
	7a+b+c	34 kyr	150 cm	150 cm		119 cm	79%	4.4
	9c	10 kyr	52 cm	48 cm		–		5.2
	9e	13 kyr	66 cm	83 cm		–		5.1
	9e+d+c	29 kyr	149 cm	157 cm		~100 cm	67%	5.1
							68±8%	
	MIS 11	33 kyr	166 cm	174 cm		–		5.0
BDP-99	5a	14 kyr	–	–	137 cm	133 cm	97%	9.8
	5c	12 kyr	–	–	159 cm	154 cm	97%	14.5
	5e	13 kyr	–	–	153 cm	146 cm	95%	11.8
	7a	14 kyr	–	–	–	127 cm		
	7c	10 kyr	–	–	–	100 cm		
	7e	10 kyr	–	–	122 cm	120 cm	98%	12.2
	7a+b+c	34 kyr	–	–	279 cm	273 cm	102%	8.2
	9c	10 kyr	–	–	92 cm	87 cm	95%	8
	9e	13 kyr	–	–	97 cm	94 cm	97%	7.5
	9e+d+c	29 kyr	–	–	254 cm	253 cm	100%	8.8
							97±2%	
	MIS 11	33 kyr	–	>284 cm	>284 cm	>284 cm		> 8.6

* The estimated duration of the Lake Baikal equivalent of MIS 5e interglacial in core CON01-603-2 is based on paleointensity tie points. Sedimentation rates in BDP-96-2 are estimated from BioSi record. Sources for estimates of duration and thickness: [1] Prokopenko et al. (2001a); [2] Prokopenko et al. (2006); [3] Khursevich et al. (2001); [4] Shichi et al. (2007); [5] Rioual and Mackay (2005); [6] Granoszewski et al. (2005); [7] BDP Members (2005).

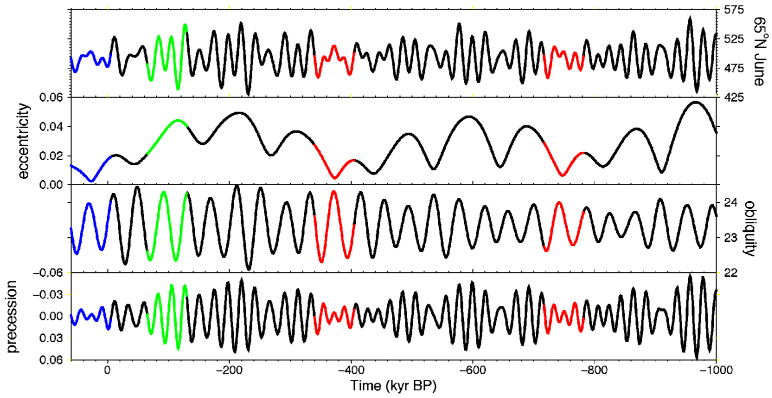

Fig. 1. Cyclic changes of orbital parameters and the northern hemisphere high latitude insolation during the past 1 Ma (Berger et al., 1993). Red portions of respective curves are the closest analogs to the orbital configuration at present and in nearest future (blue); green portion corresponds to the last interglacial, an unlikely orbital analog of the Holocene (Loutre and Berger, 2003). The figure courtesy of M.-F. Loutre.

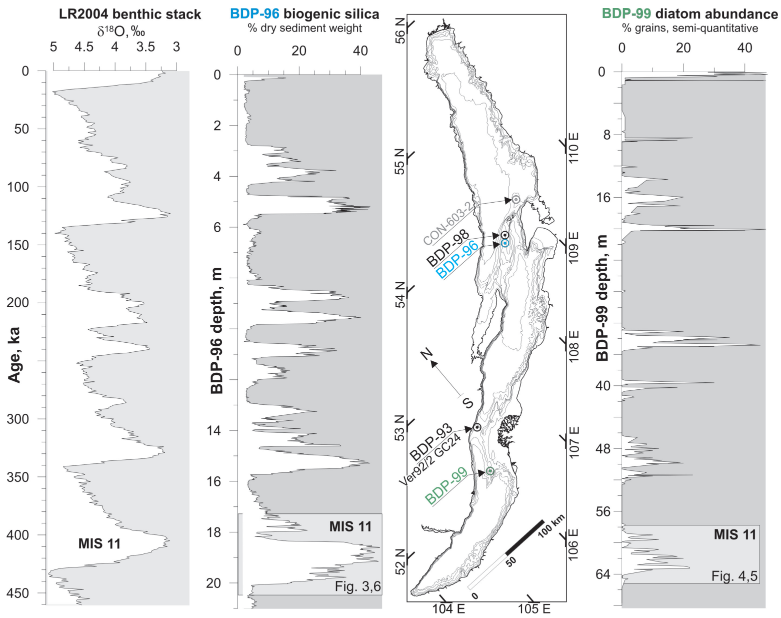

Fig. 2. Bathymetric map of Lake Baikal showing sediment core locations and the records of the last four climatic cycles reflected by biogenic silica and diatom abundance at the BDP-96 and BDP-99 drill sites. The records are plotted to depth (note the difference in scales) and compared with the LR2004 benthic marine oxygen isotope stack (Lisiecki and Raymo, 2005).

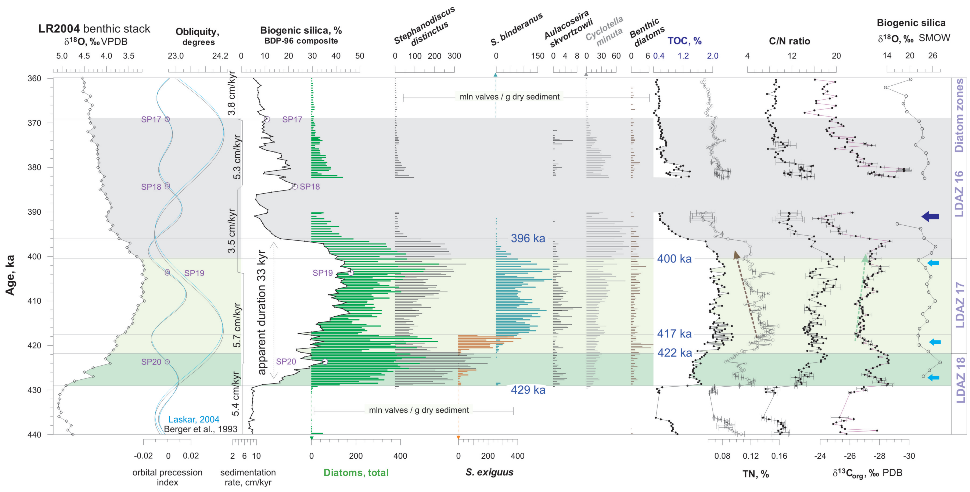

Fig. 3. Lake Baikal productivity proxy records and diatom biostratigraphy of the holostratotype section BDP-96-2 plotted to the orbitally-tuned timescale constructed by assigning the September Perihelia (SP) timing to biogenic silica peaks (Prokopenko et al., 2006). The tuned ages of the major biostratigraphic boundaries (horizontal lines) are used as age control points in the BDP-99 record in the following Figures. Note the precessional two-peak structure in the Lake Baikal diatom abundance, the relatively stable apparent sedimentation rates suggested by the age model, and a good agreement of Baikal age model for the MIS 11 interglacial with an independent LR2004 age model. Orbital parameter solutions are from Berger et al. (1993) and Laskar (2004). The δ^{18}O of Baikal diatoms (Mackay et al., 2008) records the cooling at the end of the MIS 11 interglacial (purple arrow), and, possibly, earlier, less significant cooling episodes (blue arrows).

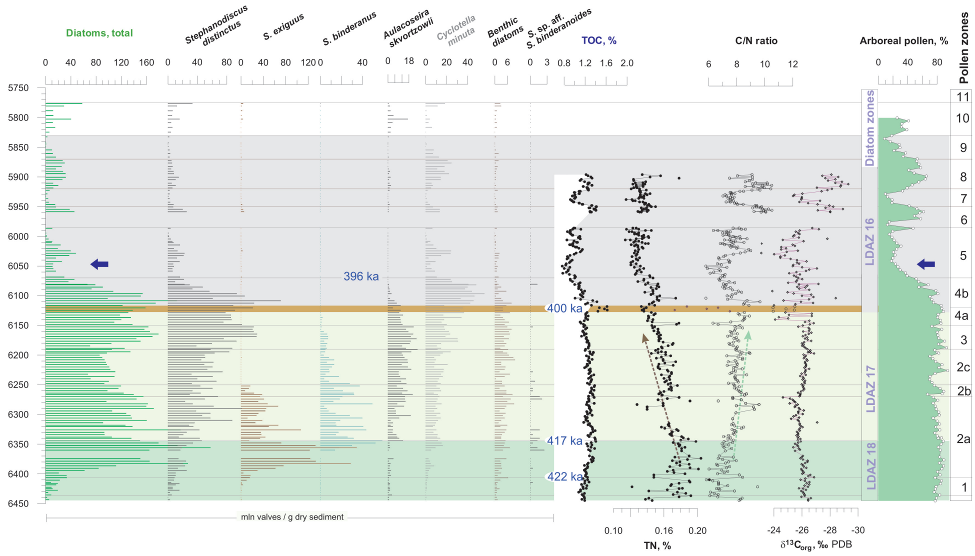

Fig. 4. Diatom abundance, species composition and productivity proxy records of the MIS 11 interglacial interval in the Lake Baikal BDP-99 drill core. Age control points are assigned based on biostratigraphic correlation with BDP-96-2 (Fig. 2). The MIS 12/11 transition is believed to not have been recovered in this section. The abundance of arboreal pollen (compare with Fig. 3) underscores the good agreement between lacustrine and terrestrial responses to the onset and decline of interglacial conditions in the Baikal area. Brown shaded bar marks the interval with anomalous $\delta^{13}C_{org}$ and C/N signals (see text).

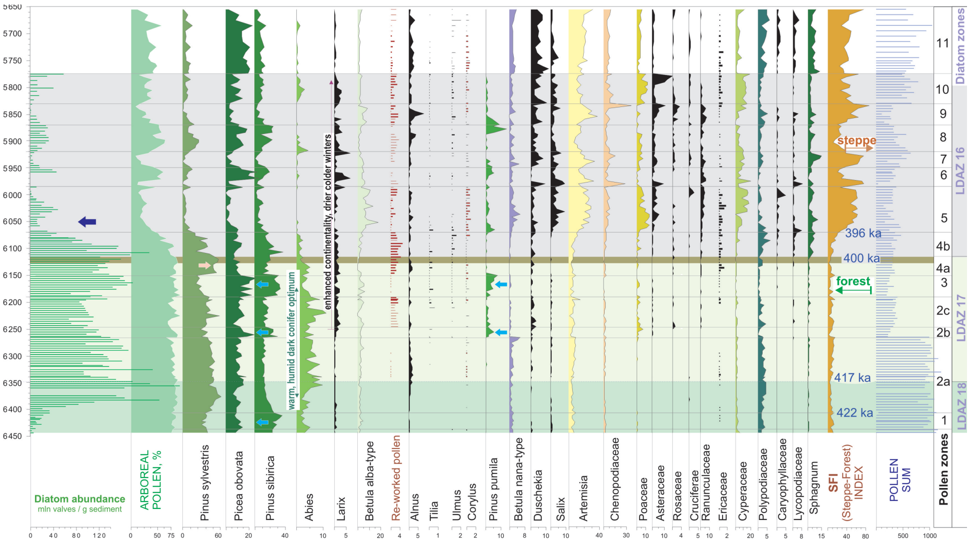

Fig. 5. Palynological record of the MIS 11 interglacial from the Lake Baikal BDP-99 drill core. Age control points are assigned based on diatom biostratigraphic correlation of BDP-99 (Fig. 4) with BDP-96-2 (Fig. 3). Coniferous forest dominated in Lake Baikal region throughout the MIS 11 interglacial until ca. 396 ka (zone 4b); zone 2 represents the prolonged "conifer optimum" indicative of warm snowy winters and temperate humid summers. Repeated cooling episodes (blue arrows) are apparent from changes in the abundance of dominant conifers.

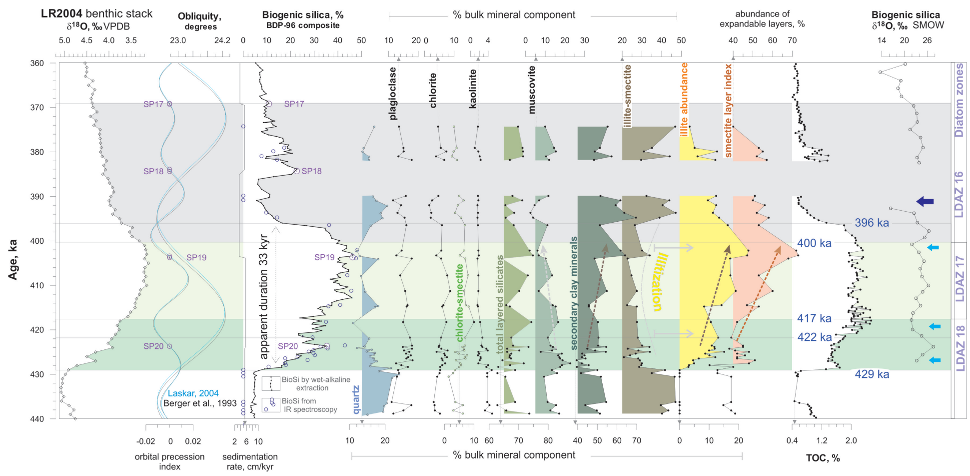

Fig. 6. The complete composition of the bulk mineral component of the MIS 11 sediments in the BDP-96-2 drill core compared with biogenic silica and bulk organic carbon records. The lack of dramatic variability in the abundance of clastic components (quartz, plagioclase, chlorite, muscovite) indicates stable depositional setting at the site and relative stability of the source area in the watershed. The appearance of illite in Baikal sediments with the onset of MIS 11 interglacial signals active illitization in the watershed: mixed-layer illite-smectite is transformed into illite. Maximum values of illite abundance and smectite layer index are observed at the end of MIS 11; this pattern is similar to the behavior of these indices in mid-late Holocene (see text). Note that kaolinite is not an index of warmer climate in the Baikal watershed since it behaves as a clastic mineral with maximum abundance during late MIS 12.