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Lake Baikal Record of Continental Climate Response to Orbital Insolation During the Past 5 Million Years

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The sedimentary record of biogenic silica from Lake Baikal in south-central Siberia suggests that this region of central Asia was impacted by two major cooling episodes at 2.8 to 2.6 and 1.8 to 1.6 million years ago. The spectral evolution of this continental interior site parallels the evolutionary frequency spectra for various marine oxygen isotope records. In the Baikal record, the 41,000-year obliquity cycle is particularly strong from 1.8 to 0.8 million years ago; variance in the 100,000-year eccentricity band increases during the past 0.8 million years. The expected precession frequency of 23,000 years is highest during the past 400,000 years. The modulation of the predicted 23,000- and 41,000-year insolation forcing by the 100,000- and 400,000-year eccentricity bands indicates that the transfer of variance from the precession and obliquity frequencies to the eccentricity part of the spectrum occurred in the Eurasian continental interior, as well as in tropical and high-latitude ocean sites.

Simulations of the response of Earth's climate system to changes in both external (*1–3*) and internal boundary conditions (*4–9*) have led to new understanding of the evolution of the Asian monsoonal system and African and Arabian continental aridity and moisture patterns through time. The general pattern of the Asian climate response for the past 30 thousand years (ky) is fairly well known from lake piston cores (*10*), and for the past 2.6 million years (Ma), it is known from the Chinese loess sections (*11, 12*). However, long, high-resolution sedimentary sections with multiple climate proxies have not been available for the high-latitude, continental interior regions of central Eurasia. Energy balance modeling (*3*) has suggested that the temperature responses of this region may have been as high as 14°C during glacial-interglacial fluctuations of the past 800 ky. These model projections are based on a linear response to orbitally induced variations in seasonal insolation due to the 23-ky precession cycle with some contribution from the 41-ky obliquity cycle according to the Milankovitch theory (*13*). The recent recovery of sedimentary records for the past 5 Ma from Lake Baikal, in south-central Siberia (*14*), provided an opportunity to test climate model projections on the response of central Eurasian watersheds and ecosystems to external orbital forcing and internal climate system feedbacks, as well as to provide a stratotype for continental paleoclimate studies.

Lake Baikal is the world's largest and deepest freshwater lake (*15*). Because Lake Baikal is located in the continental interior, its hydrodynamic system and biological productivity are sensitive to solar energy variations (*16*), which in turn are accurately recorded through the flux of biogenic silica and diatom abundance to the bottom sediments (*17–20*). To develop an understanding of Baikal's response to paleoclimate processes, we adopted a strategy similar to that used in the study of marine records by studying Baikal cores with multiple climate proxies (*21–23*) and detailed accelerator mass spectrometry radiocarbon dates for the past 25 ky (*24, 25*). Spectral analysis of records spanning the past 250 ky (*22, 25*) has provided evidence that orbital frequencies are embedded in and resolvable from the Baikal record (*26*).

From January to April 1996, a Russian scientific drilling team successfully recovered a sedimentary record spanning the past 5 Ma from a deep-water topographic high known as the Academician Ridge (*27*). In Baikal Drilling Program 1996 (BDP-96) hole 1, 93% of the core was recovered in the upper 119 m. Because rotary drilling was used to complete drilling to a total subbottom depth of 300 m, coring recovery averaged 61% from 119 to 192 m subbottom (for technical reasons, only logging was done between 192 and 300 m). In hole 2, 99% of the core was recovered with an advanced hydraulic piston corer (APC) to a subbottom depth of 100 m. Comparison of detailed inclination profiles for holes 1 and 2 with a reference geomagnetic polarity time scale for the Neogene (Fig. 1, A through C) (*28–30*) reveals that the basal age is about 5 Ma; robust reversal boundaries provide 13 age control points. A plot of the age-depth relation based on these geomagnetic polarity boundaries shows that the hemipelagic accumulation rate is a nearly constant 4 cm

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ky^{-1} over the past 5 Ma and that there are no major hiatuses or disconformities (Fig. 1D). Diatom-rich and diatom-poor sediments (Fig. 1E) alternate in the core, which is indicative of the restructuring of the Baikal ecosystem as a result of glacial-interglacial climate changes during the late Pleistocene (*17–20*). Previous work has shown that the diatom abundance and biogenic silica records for the BDP-96 cores can be used to reveal the basic structure of the Plio-Pleistocene glacial-interglacial cycles for south-central Siberia over the past 5 Ma (Fig. 1, E and F) as compared with the evolution of global ice volume for the past 5 Ma from Ocean Drilling Program (ODP) site 846 (*30*) (Fig. 1G). A comparison of the polarity age model for the past 2.45 Ma with that derived from correlation of the BDP-96 biogenic silica record with the ODP site 846 $\delta^{18}O$ record (Fig. 1H) shows that the correlation only shifts the BDP-96 record a few thousand years or less and confirms that the sedimentation rate is uniform at this site and that there are no signs of disconformities.

A general cooling trend of the Northern Hemisphere can be seen in the BDP-96 diatom record (Fig. 1E). For example, glacial clays in the upper 70 m of the core (the past 1.6 to 1.7 Ma) are nearly barren of diatoms (0 to 5%), whereas clays between depths of 115 and 192 m have diatom contents ranging from 5 to 15% (*31*). Climates were warm, seasonal contrast was low, and diatom abundance was uniformly high during most of the Gilbert and Gauss epochs, from 4.6 to 2.9 Ma. This trend is accentuated near the top of the Olduvai chron and punctuated by two strong cooling episodes in the late Pliocene at about 2.8 to 2.6 and at 1.8 to 1.6 Ma, coincident with the Plio-Pleistocene boundary (*32*) (Fig. 1E). After a major cooling in central Asia from 2.8 to 2.6 Ma, the record implies that climates of the Baikal region warmed again from 2.5 to 1.8 Ma. The major cooling episode from 1.8 to 1.6 Ma coincides with the present stratigraphic position of the Pliocene-Pleistocene boundary, whereas the earlier episode (2.8 to 2.6 Ma) occurs during a time when many geological records indicate a major but reversible (not permanent) change in the climate system (*32*). The robust geochronology for the Lake Baikal record demonstrates that a major cooling at the Plio-Pleistocene boundary in central Eurasia set the stage for the further climatic deterioration during the Pleistocene. It has been suggested that, in other areas, the older late Pliocene cooling event marks the Plio-Pleistocene boundary when glacial ages were initiated and marine $\delta^{18}O$ values increased (*6, 7, 33, 34*).

After the Plio-Pleistocene boundary, Northern Hemisphere glaciation increased during the Brunhes and late Matuyama chrons. We performed a spectral analysis (*35*) of the high-resolution biogenic silica record for the past 2.45 Ma in 400-ky intervals stepped every 100 ky to compare the periodicities in the Baikal record with changes observed in the marine $\delta^{18}O$ record (Fig. 2). The Baikal and marine time series exhibited a similar progression in the spectral domain. From 2.45 to 1.6 Ma, low-period components ranging from 166 to 333 ky are present, perhaps indicative of the 400-ky eccentricity band, and the 100- and 41-ky frequencies are weak. The 41-ky obliquity band becomes dominant from 1.8 to 0.8 Ma with variance in the 100-ky eccentricity band increasing during the past 0.8 Ma. Precession frequencies do not become visible in the Baikal spectrogram until the past 400 ky (Fig. 2). Lake Baikal is centered in the region of central Eurasia where energy balance modeling (*3*) has sug-

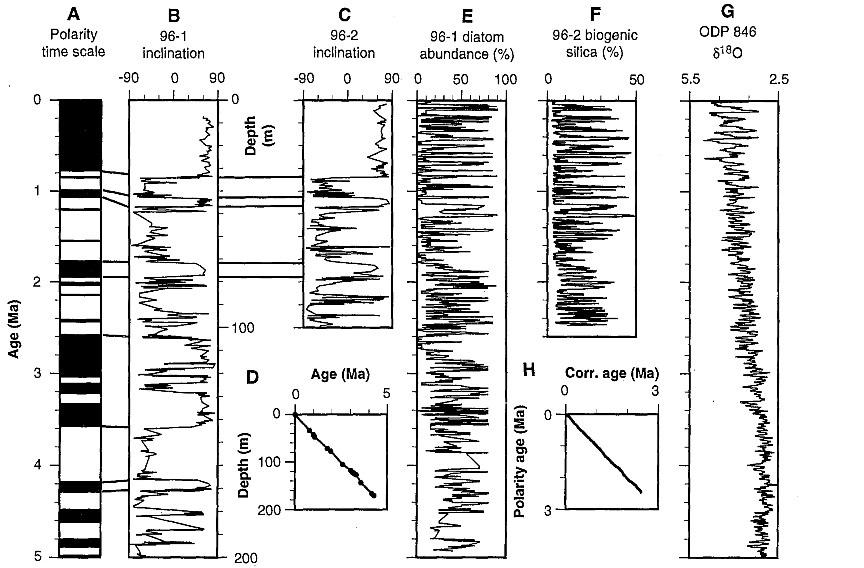

Fig. 1. (**A**) Reference geomagnetic polarity time scale (*30, 43*) correlated to the (**B** and **C**) inclination profiles for BDP-96 Leg II holes 1 (B) and 2 (C) from the Baikal Drilling Project after demagnetization at 5 mT. (**D**) Polarity reversal and event boundaries provide 13 age control points that reveal a constant and continuous sedimentation rate of 4 cm ky^{-1} over the past 5 Ma. (**E**) Diatom abundance as determined from smear slide analyses reveals pronounced alternating diatom-rich and diatom-poor sediments. (**F**) Biogenic silica content of sediment determined by a procedure modified from (*42*). (**G**) The $\delta^{18}O$ record for ODP site 846 (*30*) for comparison with the diatom abundance record of BDP-96 hole 1. (**H**) Mapping function resulting from the inverse correlation (corr.) of the biogenic silica record of BDP-96 hole 2 to ODP site 677 ($\delta^{18}O$) record as shown in Fig. 2 (*34*). The sample resolution of the BDP-96 paleoclimate proxies is generally 2 cm; therefore, the resolution is about 500 years.

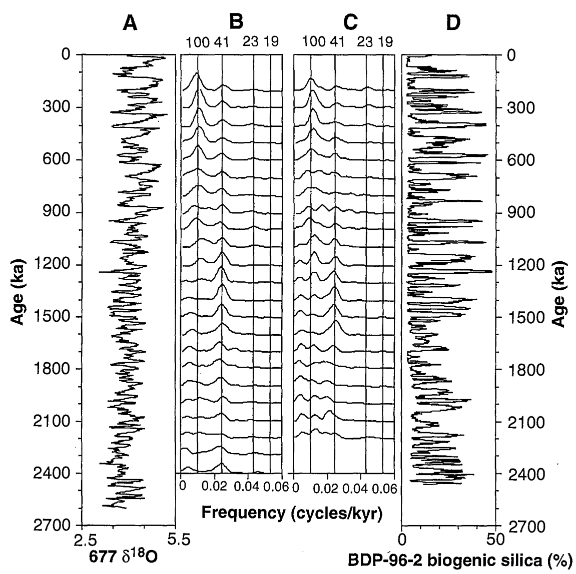

Fig. 2. (**A** and **B**) The spectral evolution in the orbitally tuned oxygen isotope ($\delta^{18}O$) record of ODP site 677 as a proxy for global ice volume (*34*) as compared with (**C** and **D**) the evolutive power spectra for the 2.45-Ma Baikal biogenic silica climate proxy. The numbers at the top of (B) and (C) indicate 1000-year bands as described in the text.

gested that the seasonally dominated precession signal should have its greatest impact on glacial-interglacial temperature changes. We thus expected that precession forcing at both the 23- and 19-ky bands would be much larger than at the 41-ky obliquity and 100-ky eccentricity bands (Fig. 2B). Eccentricity modulation of the precession signal thus appears to be an important factor in the spectral evolution of climate in this interior continental region.

To examine the 100-ky period in more detail, we made chronostratigraphic and spectral comparisons of the Baikal paleoclimate record for the past 800 ky (Brunhes chron) with the predicted summer maximum air temperature record for Siberia (65°N) from energy balance modeling (*1*), the $\delta^{18}O$ record of ODP site 677 (as a proxy for global ice volume) (*34*), and a composite magnetic susceptibility record from Chinese loess sequences (*12*) (Fig. 3, A through H). With or without tuning to orbital frequencies, the Baikal biogenic silica record exhibits all of the marine isotopic stages and substages in terms of both the shape and relative intensity, much more so than in the less detailed record of magnetic susceptibility from the Chinese loess sequences. An especially impressive feature of the Baikal record for the past 400 ky is the abrupt changes resembling full glacial-like conditions in the substages of interglacial stages 5, 7, and 9. The evolutive time series (Fig. 2) shows that these events occur when the expected precession frequency of 23 ky is most prominent. Further spectral analysis comparison of the Brunhes chron portions of the various climate records (Fig. 3, E to H) shows that the relative variance in the continental BDP-96 and marine ODP site 677 records is similar (Fig. 3, E and G). Correlation of the Baikal record to the marine record (*36*) improves the relative variance of the 23-ky band in the power spectrogram.

The observed response of the Baikal biogenic silica proxy is different from that in the predicted summer temperature model, which shows a linear response to insolation for the Baikal region (Fig. 3, E and F). Because seasonal temperature changes over land can be characterized as a fast response of the climate system (*37*) and because the biogenic silica response is also thought to be fast, because of its relation with the regional insolation-energy balance by way of the hydrodynamic system of Lake Baikal (*16*), we initially expected that the spectrograms of biogenic silica signals would show a linear response to precession forcing. Such differences between modeled and observed geological responses, especially in the eccentricity band (100 ky) and in the marine $\delta^{18}O$ record, are usually attributed to internal feedback mechanisms in the ocean-atmosphere-cryosphere system (*38*), truncation (clipping) of the climate proxy signal (*39, 40*), or possibly model limitations (*3*). Instead of showing a clear linear response, the Baikal biogenic silica record shows a nonlinear response, similar to the marine $\delta^{18}O$ but not quite as nonlinear as the response of the marine record because the 23-ky variance is actually slightly higher in the continental interior record than in the marine $\delta^{18}O$ record. The relatively clipped nature of the Baikal biogenic silica record does not preclude the possibility that some climate feedback plays a role in producing this nonlinear response. Because Lake Baikal's biological productivity is independent of ice sheet size or changes in ocean circulation and atmospheric CO_2 concentrations and because the lake's heat capacity is not large enough to account for the damping effect on the seasonal precession forcing, we speculate that part of the 100-ky modulation can be explained by an albedo feedback effect. Substantial glacial-interglacial albedo changes are expected in the Baikal region because of large-scale vegetation changes. For example, steppe vegetation replaced interglacial Boreal forests during glacial periods (*17, 19, 41*). Our results support the suggestion (*40*) that some truncation mechanism shifted the predicted 41- and 23-ky insolation forcing into the modulating 100-ky eccentricity band. What the exact internal climate components involved in this interaction are is not clear at this time.

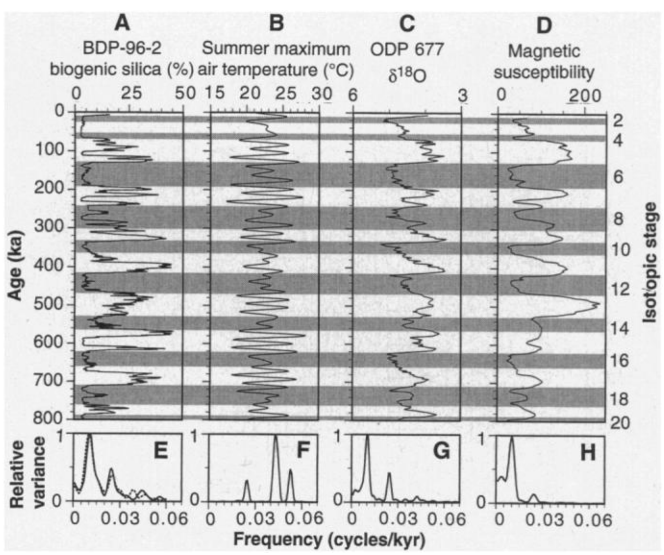

Fig. 3. Comparison of (**A**) the Baikal paleoclimate record for the past 800 kyr (correlation of the BDP-96 hole 2 biogenic silica proxy) for the Brunhes chron with (**B**) the predicted summer maximum air temperature record for Siberia (65°N) from energy balance modeling (*3*), (**C**) the $\delta^{18}O$ record of ODP site 677 as a global ice volume proxy (*34*), and (**D**) a composite magnetic susceptibility record from Chinese loess sequences (*12*). (**E** through **H**) The power spectralgrams for the Brunhes time series corresponding to (A) through (D).

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deepens to 500 m, the diatom blooms do not occur, and production between glacial and interglacial periods changes by up to two to three orders of magnitude [M. N. Shimaraev, N. G. Granin, A. A. Zhdanov, *Limnol. Oceanogr.* **38**, 1068 (1993)] in response to insolation orbital forcing. Through this model, biogenic silica and diatom abundance become two excellent proxies within a multiple proxy data set including magnetic susceptibility, lithogenic flux, pollen-spore composition changes, and diatom assemblage changes.
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26. Lake Baikal's geographic position in the largest continental interior of the world, unaffected by the type of large-scale glacial ice sheets that greatly disturbed sediments at similar latitudes on North America, Europe, and western and far eastern Siberia, makes it an ideal sedimentary archive in the International Geosphere-Biosphere Program Pole-Equator-Pole (PEP-II) transect through Asia as part of the Past Global Changes (PAGES) program. The purpose of the PAGES PEP transects is to construct a global network of sites on each of the continents that is analogous in some ways to the available array of deep-sea sites. In the case of the PEP sites, potential archives are tied to specific features and boundary conditions of the atmosphere-hydrosphere-cryosphere system. Lake Baikal is positioned to determine the expansion of the Siberian high-pressure system, incursions of the Asian monsoon, and moisture transport emanating from the Barents Sea and other parts of the Arctic.
27. The BDP-96 Leg II drill site is located at 53°41′48″N, 108°21′06″E. An APC was used to drill in 321 m of water where multichannel seismic reflection profiles showed thick and continuous sedimentary sequences. The APC cores were retrieved in 2-m–long sections in 58-mm–inside diameter plastic liners.
28. The paleomagnetic study was done on oriented 5-cm^3 subsamples with a stepwise, alternating-field demagnetization, which indicated that a viscous remanence component was removed at demagnetizing fields between 2.5 and 5 mT.
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31. Just as the average diatom content of the silica-poor clays increases downcore, indicating warming, so does the character of the coarse material: In the upper 60 m, the coarse material, although still rare, is more angular as contrasted with the more rounded grains in the lower part between 115 and 192 m. In addition, rare coarse sand lenses occur in the upper 60 m, typical of glacial ice-rafted material found in glacial sediments in other studies of piston cores (*19*, *22*).
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36. The biogenic silica data, generally sampled every 2 cm (~500 years), were placed on the polarity age model (Fig. 1D) and linearly interpolated to an even spacing of 500 years. An inverse correlation method, CORPAC [D. G. Martinson, W. Menke, P. Stoffa, *J. Geophys. Res.* **87**, 4807 (1982)], was used to correlate the Baikal silica record to ODP site 677 $\delta^{18}O$ (*31*). The initial coherence *C* between the two records ($C = 0.23$) attained a high degree of coherence ($C = 0.65$) and 43% shared variance after inverse correlation with four coefficients. The mapping function resulting from this correlation (Fig. 1H) shows no sign of major unconformities or of excessive correlation. The biogenic silica analytical method was modified from (*42*).
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Biomass Collapse in Amazonian Forest Fragments

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Rain forest fragments in central Amazonia were found to experience a dramatic loss of above-ground tree biomass that is not offset by recruitment of new trees. These losses were largest within 100 meters of fragment edges, where tree mortality is sharply increased by microclimatic changes and elevated wind turbulence. Permanent study plots within 100 meters of edges lost up to 36 percent of their biomass in the first 10 to 17 years after fragmentation. Lianas (climbing woody vines) increased near edges but usually compensated for only a small fraction of the biomass lost as a result of increased tree mortality.

Habitat fragmentation affects the ecology of tropical rain forests in many ways, such as altering the diversity and composition of fragment biotas, and changing ecological processes like nutrient cycling and pollination (*1*, *2*). Recent evidence indicates that fragmentation also alters rain forest dynamics, causing sharp increases in the rates of tree mortality, damage, and canopy-gap formation, apparently as a result of microclimatic changes and increased wind turbulence near forest edges (*3*). Here we demonstrate that in central Amazonian rain forests, fragmentation is having an equally measurable effect on above-ground biomass. Given that more than 15×10^6 ha of tropical forest are being cleared and fragmented annually (*4*), a decline of biomass in forest remnants could be a significant source of greenhouse gases such as CO_2, released upon decay.

The study area, an experimentally fragmented landscape spanning about 20 km by 50 km, is located 80 km north of Manaus, Brazil (2°30′S, 60°W), at an elevation of 100 to 150 m. Between 1980 and 1986 a series of replicate forest patches of 1, 10, and 100 ha in area were isolated by clearing and often burning the surrounding vegetation to create cattle pastures. A total of 39 permanent, square, 1-ha study plots were established in four 1-ha fragments, three 10-ha fragments, and two 100-ha fragments, and 27 identical control plots were located in nearby continuous rain forest. The plots in the fragments were stratified so that edge and interior areas were both sampled. More than 1000 tree species have been identified in the study plots (*5*).

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