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Biogenic silica records from the BDP93 drill site and adjacent areas of the Selenga Delta, Lake Baikal, Siberia

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Abstract

Biogenic silica contents of sediments on the lower Selenga Delta and Buguldeika saddle in Lake Baikal show distinct fluctuations that reflect changes in diatom productivity, and ultimately, climate. The pattern of the upper 50 m of the section, dating from about 334 ka, is similar to that of the marine oxygen-isotope record, increasingly so as the younger sediments become progressively finer grained and less locally derived with time. The last two interglaciations are marked by biogenic silica abundances similar to those of the Holocene. The equivalent of marine oxygen-isotope stage 3 is distinctly intermediate in character between full glacial and full interglacial biogenic silica values. Following near-zero values during the last glacial maximum, biogenic silica began to increase at about 13 ka. The rise in biogenic silica to Holocene values was interrupted by an abrupt decrease during Younger Dryas time, about 11 to 10 ^{14}C ka.

Introduction

Lake Baikal, Siberia, has attracted considerable recent attention because of its potential paleoclimate records. This deep (1600+ m) rift lake is dilute (< 100 mg·l^{-1} total dissolved solids) and oligotrophic, and is volumetrically the largest lake in the world. Paleoclimate records from Lake Baikal are valuable because of the long (ca. 30 m.y.), continuous sedimentary sequence beneath the lake; its relatively high latitude, its continental-interior setting, and its highly seasonal climatic regime. The sediments of Lake Baikal have yielded paleolimnological and paleoclimatic records based on a wide variety of proxies, including sediment magnetic properties (Peck et al., 1994), biogenic silica contents (Colman et al., 1995; Williams et al., 1997), and uranium geochemistry (Edgington et al., 1996). The biogenic silica content of the sediments was one of the first proxies recognized as responding to glacial-interglacial cycles (Granina et al., 1993). Biogenic silica primarily reflects diatom productivity in Lake Baikal, which in turn is controlled by limnological factors such as water temperature, length of ice-free season, turbidity, and nutrient availability (Colman et al., 1995). The results of studies of diatom biostratigraphy (Bradbury et al., 1994; Julius et al., 1997) are generally compatible with those from studies of biogenic silica (Colman et al., 1995), but biogenic silica is a simpler measure of overall productivity.

Most of the well-documented paleoclimate and paleolimnological records for Lake Baikal have come from Academic Ridge, which is isolated from turbidites and river influence and receives only a slow rain of hemipelagic sediment. Sedimentation rates on the ridge appear to be remarkably constant (ca. 4 cm kyr^{-1}), which allows correlation of changes in sediment properties with other climatic records, such as the marine oxygen-isotope record (Peck et al., 1994; Colman et al., 1995; Edgington et al., 1996). However, direct dating of these sediments, beyond the range of radiocarbon dating, is not presently feasible, although paleomagnetic stratigraphy from a long core drilled in 1996 on Academic Ridge (Williams et al., 1997) supports the constancy of sedimentation rates and the ages extrapolated from them, back as far as 5 m.y.

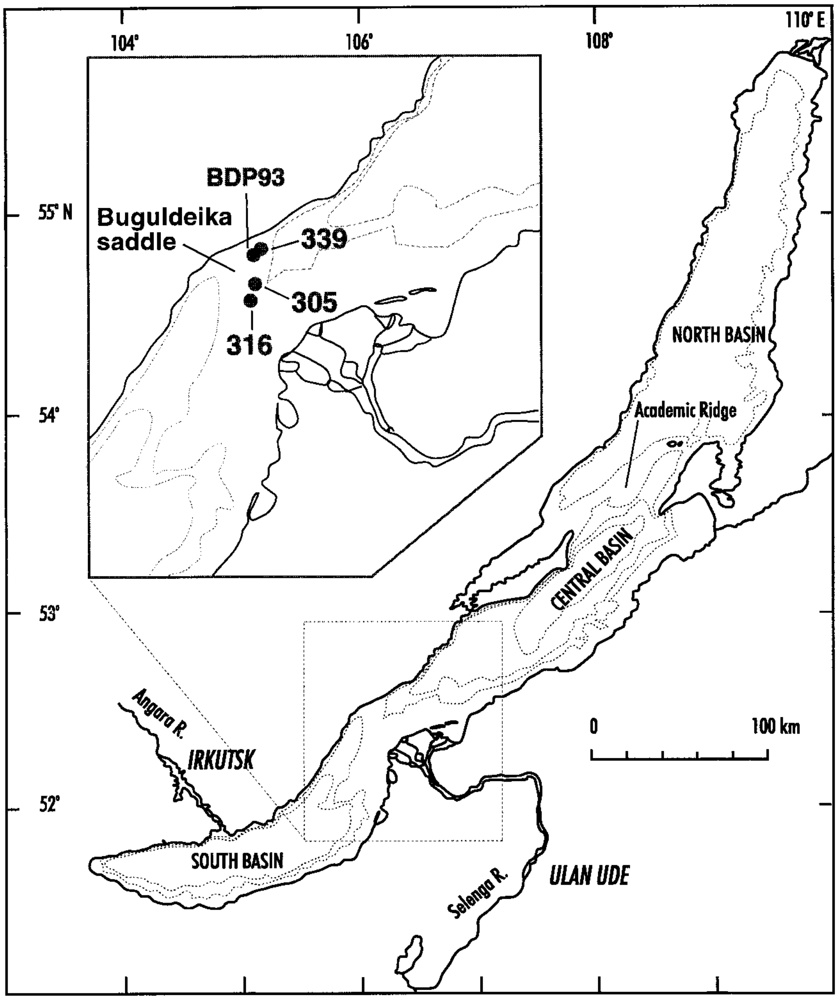

Figure 1. Map of Lake Baikal showing locations mentioned in the text. Bathymetric contour interval is 500 m. Inset shows the locations of sites for BDP93, 305, 316, and 339.

Lake Baikal contains a wide variety of sedimentary environments, some of which have faster sedimentation rates than Academic Ridge, while maintaining a primarily fine-grained hemipelagic character (Colman et al., in press). Prominent among these areas are the lower Selenga Delta and the Buguldeika saddle (Figure 1). During ship-based field operations in 1990 through 1992, box, gravity, and piston cores (as much as 10 m long) were collected from several sites on the lower Selenga Delta (Colman et al., 1994). In 1993, two 100-m drill holes were drilled and cored in 354 m of water on the Buguldeika saddle (BDP-93 Baikal Drilling Project Members, 1997 [hereafter BDP93 Members, 1997]). This paper reports the results of biogenic silica analyses performed on samples from those cores.

Methods

Gravity and piston cores from sites 305, 316, and 339 were analyzed for biogenic silica at sample intervals of about 5 cm. Details of the lithologies and properties of these cores are reported in Colman et al. (1994). The basic biogenic silica data for these cores, among others, were reported by Carter & Colman (1994). The upper parts of some piston cores were not recovered, but the missing intervals were mostly covered by gravity (trigger) cores taken at the same time. Corrected depths for the piston cores with missing tops were estimated from correlations of magnetic susceptibility profiles (Colman et al., 1994). Magnetic susceptibility variations in these cores are distinct and coherent, allowing precise depth correlations among cores (Peck et al., 1996).

The first of two drill holes on Buguldeika saddle (BDP93-1) was sampled at coarse intervals for reconnaissance studies, and the results of a wide variety of analyses, including biogenic silica, were reported in BDP93 Members (1997). These analyses showed that the character of the sediment changed at about 50 m below the lake floor. Below 50 m, the core was coarser-grained, with more irregular grain size and geochemistry, different clay minerals, and lower biogenic silica contents relative to the upper 50 m. Consequently, we sampled the upper 50 m of the second drill core (BDP93-2) in more detail (about every 16 cm) for biogenic silica analyses that are reported here.

In the main group (A) of biogenic silica measurements, silica was extracted from the sediments in a strong sodium carbonate solution, after oxidation and acid-leaching, following the methods of Mortlock & Froelich (1989). Both silica and aluminum in solution were measured by inductively coupled plasma (ICP) methods. Raw (‘uncorrected’) biogenic silica measurements were corrected for clay-mineral dissolution using measured aluminum values and known silica-aluminum ratios in fine-grained clay minerals from Lake Baikal. Details of these methods are described in Carter & Colman (1994). The resulting data from the two BDP93 holes are referred to as BDP93-1A and BDP93-2A, respectively.

A second group (B) of measurements were also made on samples from BDP93-1 (BDP93-1B). Biogenic silica was extracted using a similar method, and silica was measured by spectrophotometry. These analyses were well correlated with the uncorrected values from group A, but had systematically lower absolute values.

Chronology

Several studies (Peck et al., 1994; Colman et al., 1995; Edgington et al., 1996; Williams et al., 1997) have shown that a variety of parameters in Lake Baikal sediments correlate well with the dated paleoclimatic record of marine oxygen-isotopes (Imbrie et al., 1984; Martinson et al., 1987), and that such correlations can help with time scales for Lake Baikal records. However, for the purposes of this paper we wish to construct an age-depth model that is as independent as possible of direct correlations between Lake Baikal climate proxies and the marine isotope record. We thus base our age model for BDP93 and nearby cores on a combination of radiocarbon ages and paleomagnetic relative intensity correlations. For the upper part of the section, accelerator-mass spectrometer (AMS) radiocarbon ages on total organic carbon provide reliable ages, although problems with detrital carbon and with contamination exist (Colman et al., 1996). We used the corrected ages for both cores at BDP93 (those not rejected by Colman et al., 1996), converting the depths in BDP93-1 to the depth scale of BDP93-2 on the basis of correlation of magnetic susceptibility profiles (Col-

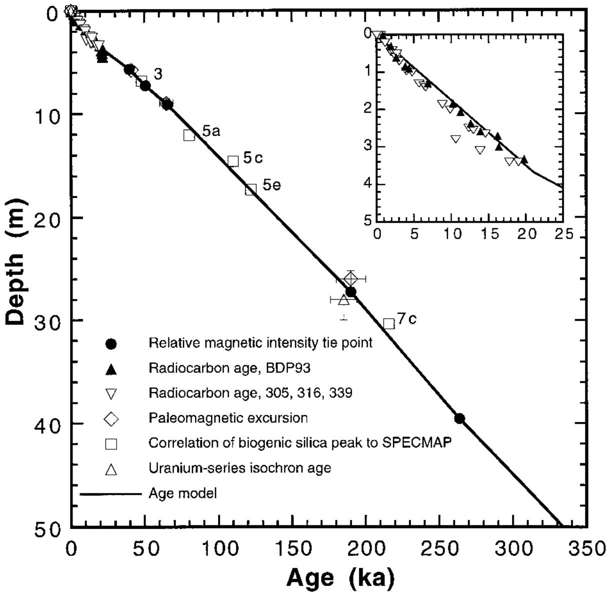

Figure 2. Age-depth model for the Selenga Delta area. Depths were converted to those in BDP93-2 using magnetic susceptibility profiles (Peck et al., 1996). Radiocarbon ages are ‘accepted’ values from Colman et al. (1996). Paleomagnetic excursion data and tie points for correlation of relative magnetic intensity profiles to dated marine cores are from Peck et al. (1996 and unpub. data). The age-depth model was constructed from a linear regression through the radiocarbon ages (0–21 ka), interpolation between the relative intensity tie points (21–264 ka), and extrapolation of the average rate of sedimentation for 0–264 ka (14.8 cm ky^{-1}) to 50 m (338 ka); these points are shown as solid symbols. Other age information (open symbols), not used in the age model, include (1) a Uranium-series isochron age (Sandimirov & Pampura 1995); (2) correlations of apparent magnetic excursions to those dated elsewhere (Peck et al., 1996 and unpub. data); and (3) correlations (this paper,stages labeled) of biogenic silica peaks to the marine oxygen-isotope record (Imbrie et al., 1984; Martinson et al., 1987). See text and Table 1 for additional explanation.

Table 1. Control points for depth-age model

Depth) (m)	Age (ka)	Basis (See text)
0	0	Sediment surface
3.68	21.0	Sedimentation rate of 17.5 cm kyr^{-1} from linear fit of ^{14}C ages $<$ 21 ka
5.66	39.6	Relative paleomagnetic intensity correlation
7.26	50.3	Relative paleomagnetic intensity correlation
9.10	65.1	Relative paleomagnetic intensity correlation
27.26	190	Relative paleomagnetic intensity correlation
39.58	264	Relative paleomagnetic intensity correlation
50.00	338	Extrapolation of average sedimentation rate for 0–264 ka (14.8 cm kyr^{-1})

man et al., 1996; Peck et al., 1996). The resulting age-depth plot (Figure 2) is remarkably linear for the last 30 000 or more years, although the ages scatter considerably beyond 21 ka. The mean sedimentation rate is 17.5 cm kyr^{-1} for the last 21 ka, which we used to estimate ages for depths less than 3.68 m (Table 1). Ages from sites 305, 316, and 339 were not used in the age model, but were transferred to the depth scale of BDP93-2 and plotted for comparison (Figure 2).

Sediments in the Selenga Delta area have been shown to faithfully record the relative intensity of the earth's magnetic field, and the pattern of changes in relative intensity can be correlated to those in dated marine cores (Peck et al., 1996). These correlations are entirely based on comparisons among relative intensity profiles. However, the time scale for the marine cores is based on the marine isotope record. Therefore, our time scale depends on the overall accuracy of the SPECMAP time scale, which is generally well accepted, but does not depend on paleoclimatic correlations to that time scale. We used tie points for the relative intensity correlations from Peck et al. (1996 and unpub. data) as age horizons between 39.6 ka and 264 ka (Table 1) and linearly interpolated between them. Below 264 ka (39.58 m), we used the mean sedimentation rate from 0–264 ka (14.8 cm kyr^{-1}), yielding an age estimate of 338 ka for a depth of 50 m.

Several other types of data provide support for our age model but were not used to construct it. Three excursions in paleomagnetic direction were identified by Peck et al. (1996), who correlated them with dated excursions elsewhere. The ages and depths of the excursions are consistent with our age estimates (Figure 2), but were not used in our age model because their unique identification is uncertain. Also, a uranium-series isochron age of 185 ± 9 ka was obtained by Sandimirov & Pampura (1995) on bulk sediment from the interval from 26 to 30 m in core BDP93-1. This age was not used in our model because the method is experimental and carries large uncertainties, but the age is supportive of our age model (Figure 2).

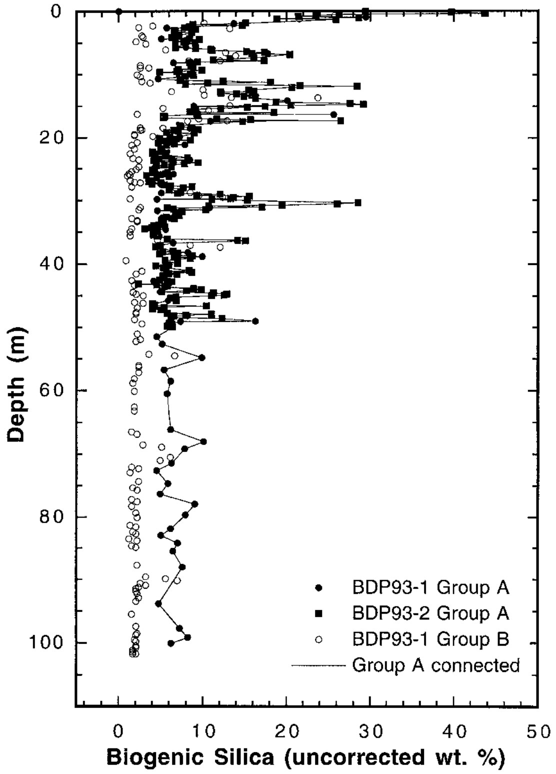

Figure 3. All biogenic silica measurements for BDP93, plotted against depth in BDP93-2. All measurements are uncorrected for clay-mineral dissolution. See text for explanation of group A and B analyses.

Results

All uncorrected biogenic silica values for BDP93-1 and BDP93-2 are plotted in Figure 3 for comparison. Depths for BDP93-1 were converted to equivalent depths in BDP93-2, based on correlation of magnetic susceptibility profiles, as described in the Methods section. Because the biogenic silica analyses are low and irregular below 50 m, and because the overall sediment character is different below 50 m (BDP93 Members, 1997), we focus on the upper 50 m of the BDP93 record. The group B analyses (see Methods) are correlative with (proportional to) the others, and after the proportionality has been applied (Figure 3), they are comparable. However, detailed comparison of the two data sets reveals differences that are not easily accounted for, so subsequent discussion and analysis includes only the group A data.

Comparison of the upper part of the BDP93 profile with those of cores at sites 305, 316, and 339 shows clear similarities in the records for the upper parts of the sedimentary sequence throughout the Selenga Delta area (Figure 4). These similarities suggest a coherent regional sedimentation pattern that is not greatly disturbed by local erosion or turbidite deposition. The data also suggest relatively uniform sedimentation rates among the sites, except for site 316. Site 316, which is located on the crest of a fault scarp, appears to have a lower sedimentation rate (Colman et al., 1996). The profiles all show relatively high values of biogenic silica in the upper meter or so, underlain by sediments with near-zero biogenic silica. Further down, several coherent zones of high and low biogenic silica are present.

Using the magnetic susceptibility profiles of Peck et al. (1996), cores from different sites in the restricted area of the Selenga Delta can be matched by depth. Using the depth scale of BDP93-2 as a reference, the depths of the other cores were ‘corrected’ using the susceptibility profiles. Use of a common depth scale increases the coherence among the records. Not only are the first-order fluctuations between high and low biogenic silica values readily matched, but secondary peaks and other details of the profiles are reproduced in each core. For example, the decrease in biogenic silica upward from the peak at about 12 m in BDP93 is interrupted by a small increase, followed by a decrease to near zero values. This sequence of values is reproduced at sites 339 and 316.

Because of the apparent coherence of the records, we stacked (averaged) them to produce a composite profile. Values in each profile were first linearly interpolated to even 10-cm depth intervals (BDP93-2 depth scale). Then, at each 10 cm interval, the values for the four sites were averaged to produce a single, composite curve (Figure 4, ‘stack’). Below a depth of 13 m, the limit of cores from sites 316 and 339, the record is entirely derived from BDP93.

Discussion

On Academic Ridge, where sedimentation rates are slow and nearly constant, the record of biogenic silica is highly correlated ($r^2 = 0.71$) with the marine oxygen-isotope record (Colman et al., 1995). Compared to the rate of about 4 cm kyr^{-1} on Academic Ridge, rates in the Selenga Delta area are faster by a factor of 3–5 (13–19 cm kyr^{-1}, 14.8 at BDP93) and are somewhat more variable (Colman et al., 1996).

Using the age model in Figure 2, the biogenic silica vs. depth stack from the Selenga Delta area (Figure 4) was converted to a biogenic silica vs. age record and compared to the marine oxygen-isotope record (Imbrie et al., 1984; Martinson et al., 1987) (Figure 5). This comparison would not be valid if the age model had been constructed using correlations between Lake Baikal climate parameters and the marine record. However, as discussed in the Chronology section, the Lake Baikal age model depends on the accuracy of the time scale for the marine oxygen-isotope record, but it does not depend on correlation of the marine paleoclimate record with the paleoclimate record from Lake Baikal.

Comparison of the biogenic silica record from Lake Baikal with the marine oxygen-isotope stages (Figure 5) shows that stages 1 through 6 are distinct, although the 5-part structure of stage 5 is somewhat less obvious. The equivalent of stage 5a has a secondary peak, and the equivalent of stage 5e appears to be disrupted into multiple peaks and to have lower than expected (lower than stage 5c) values. The distinctive, near-zero values for stage 5d (Colman et al., 1995; Edgington et al., 1996; Karabanov et al., in press) are reproduced.

The well-known saw-tooth character and terminations of the marine oxygen isotope record (Broecker & van Donk, 1970) are not well represented in the biogenic silica record of Lake Baikal. In particular, the equivalents of stages 2, 3, and 4 form a symmetrical series of low-high-low peaks, respectively. The biogenic silica record has a more spikey character than the marine record, and is increasingly ‘clipped’ by the

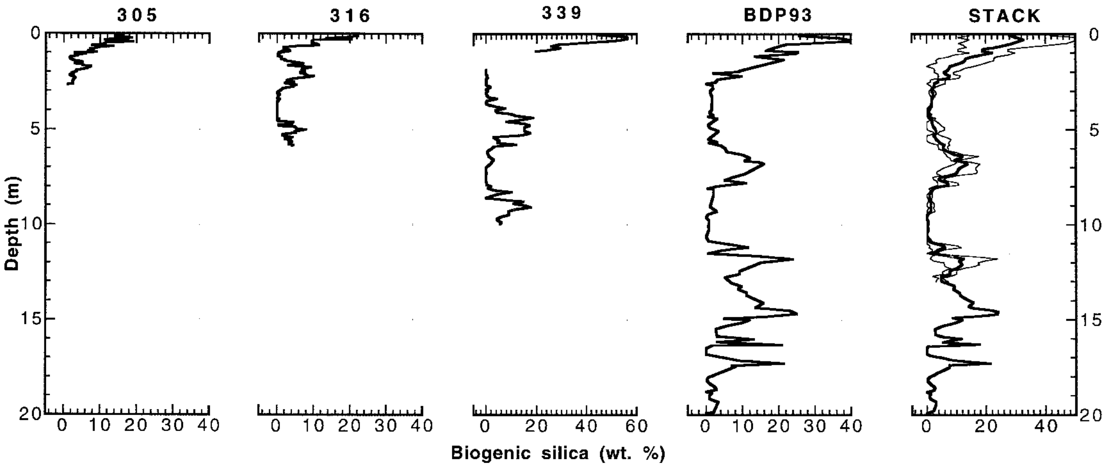

Figure 4. Biogenic silica (group A, corrected for clay mineral dissolution) for core sites 305, 316, 339, and the upper part of BDP93, plotted against depth in the respective cores. BDP93-1 and BDP93-2 have been combined and plotted on the depth scale of BDP93-2. The STACK record is a result of conversions of depths in each core to those of BDP93-2, using magnetic susceptibility profiles (Peck et al., 1996), followed by interpolation of biogenic silica values to common depth points, and averaging of the resulting values. The thin lines represent ±1 standard deviation of the average.

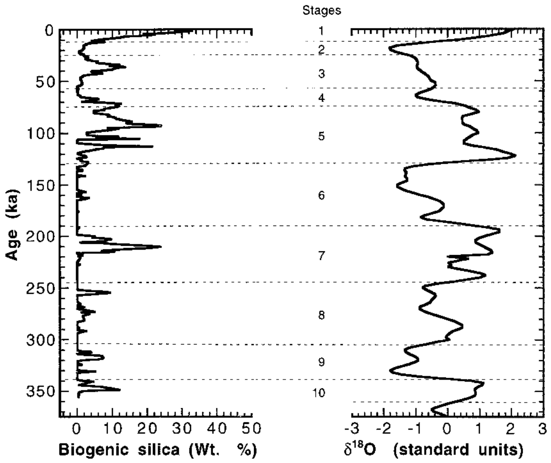

Figure 5. Biogenic silica values plotted against age, calculated from the age-depth model in Figure 2, compared to the marine oxygen-isotope record (Imbrie et al., 1984; Martinson et al., 1987). The youngest 100 kyr of biogenic silica values are from the STACK profile in Figure 4; the remainder are from BDP93-1 and -2 only. Stage numbers are marine oxygen-isotope stages and horizontal dashed lines are their boundaries.

constraint of zero biogenic silica content beyond the equivalent of stage 5.

We correlate biogenic silica peaks at 6.8, 12.1, 14.6, 17.3, and 30.4 m in the composite biogenic silica record (Figure 4) with oxygen-isotope stages 3, 5a, 5c, 5e, and 7c, respectively (Figure 5). If these correlations are correct, then we can compare our independent age estimates for these peaks with ages for the corresponding peaks in the marine oxygen-isotope record. In Figure 2, the depths of the peaks are plotted against the corresponding isotope-stage ages. The points plot very close to our age model, lending it additional support.

The similarity between the biogenic silica record for the Selenga Delta area and the marine oxygen-isotope record appears to degrade in the older part of the record. Low values of biogenic silica occur during stage 6, but the internal structure of the stage is difficult to recognize. The characteristic multiple peaks of stage 7 appear to be represented by a single major peak in the biogenic silica record, flanked by small secondary peaks. Below the stage 7 peak, visual correlation of the biogenic silica record with the marine oxygen-isotope record becomes increasingly difficult.

The progressive increase in the similarity between the biogenic silica record at BDP93 and the marine oxygen-isotope record is in accord with the initial interpretations based on coarse resolution samples for multiple proxies from the drill hole (BDP93 Members, 1997). This interpretation suggested that the lower 50 m of the core represents mostly turbidites and fluvial sediments from the Buguldeika River. The upper 50 m of the sequence was interpreted to represent increased admixture of fine-grained sediment originating from the Selenga River, and the change was attributed to subsidence of the Buguldeika horst block on which the drill hole was located. Our data suggest that the increase in the influence of the Selenga River source was progressive, such that the site accumulated more hemipelagic sediment with time, and that turbidite sediments became more distal and fine-grained with time. The overall biogenic proportion of the sediment increased with time, especially during interglacial periods. During glacial periods, it was always low, but intervals of zero preservation of biogenic silica became progressively shorter.

The paleoclimate signal in the upper part of the record is interpreted to result primarily from variation in diatom productivity (Colman et al., 1995). Biogenic silica values approaching those of the Holocene are preserved from the last two interglacial periods, although the detailed structures of these two periods vary from that of the marine oxygen-isotope record. The equivalent of marine oxygen-isotope stage 3 is well expressed, but has biogenic silica values significantly less than either the Holocene or the last two interglaciations. This observation suggests that stage 3 in Siberia was interstadial rather than interglacial in character.

The transition from last glacial maximum to the Holocene is recorded by biogenic silica values increasing from near-zero values beginning at about 13 ka to high and progressively increasing values through most of the Holocene, before decreasing somewhat in the latest Holocene. The glacial-interglacial transition is interrupted by several fluctuations, the most prominent of which is a decrease that occurs at about 10 ^{14}C ka, suggesting a cooling event reminiscent of the Younger Dryas. This decrease is a feature observed in almost all cores, both in the Selenga Delta area (Figure 4) and on Academic Ridge (Carter & Colman, 1994). However, in most cores, the fluctuation is not well resolved or not well dated. To investigate the possibility that the decrease in biogenic silica at about 10 ka might represent Younger-Dryas-age cooling, we analyzed closely spaced samples from BDP93-2 (Figure 6). The measurements define a distinct decrease in biogenic silica during a period of overall increasing values in the glacial-interglacial transition. The radiocarbon age control (Figure 6; Colman et al., 1996) suggests nearly constant sedimentation rates through this period, and leaves little doubt that the event occurred between about 10 and 11 ^{14}C ka.

The decrease in biogenic silica, and by inference diatom productivity, between 10 and 11 ^{14}C ka probably resulted from a cooling episode, in the same way that diatom productivity decreased during glacial intervals (Colman et al., 1995). The timing suggests a correlation with the Younger Dryas cooling event, which is increasingly documented as a global event (Peteet, 1995a, b). This is the first clear evidence of a Younger-Dryas-age cooling event from Lake Baikal, although Younger Dryas equivalents have been observed in pollen records from other Asian continental-interior sites (Velichko et al., 1997; Andreev et al., 1997) and in the Chinese loess record (An et al., 1993; Weijian et al., 1996).

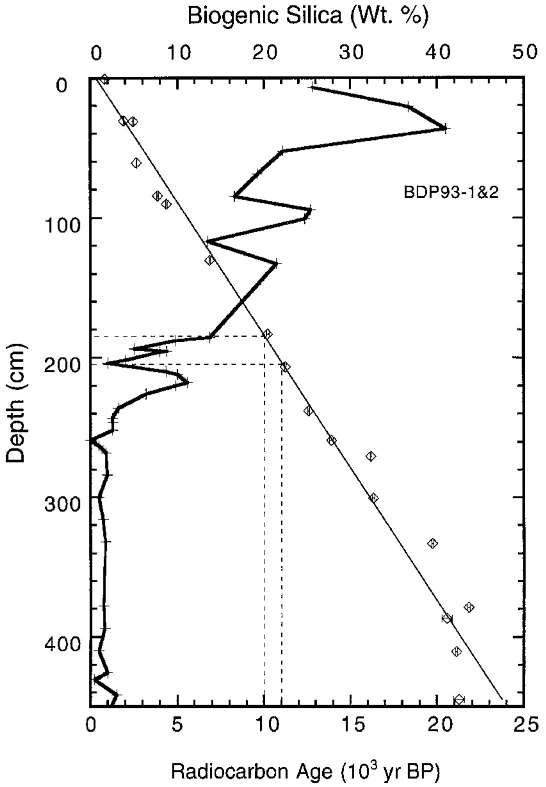

Figure 6. Detail of biogenic silica values for the last ca. 25 ka from BDP93-1 and -2. Biogenic silica, heavy line and crosses; radiocarbon ages, diamonds (error bars indicate ±1 sigma counting error). Solid straight line through radiocarbon ages is least-squares best fit to the ages. Dash lines are projected from 10 and 11 ^{14}C ka on the age scale (the conventional age limits for the Younger Dryas event) to the age-depth curve and then to the depth scale.

Several fluctuations in biogenic silica occur in Holocene sediments in Lake Baikal. One or two decreases in biogenic silica occur in the middle Holocene sections of most cores, and almost all cores show a decrease to modern values in the latest Holocene (Figures 4 and 6; Carter & Colman, 1994). Although it is tempting to correlate such fluctuations with Holocene climatic changes elsewhere, more detail and better time control is needed to make such correlations convincing.

Conclusions

Biogenic silica profiles from the Selenga Delta area of Lake Baikal provide a record of diatom productivity and inferred climate for the highly seasonal, continental setting of Siberia. A robust time scale, independent of climatic correlations, is available from radiocarbon ages and from relative magnetic intensity records, although age control for the latter depends on the accuracy of the SPECMAP time scale. From our analysis of these dated biogenic silica records, we conclude:

1. Separate cores from the general Selenga Delta area yield coherent biogenic records for the last 100 kyr, and the upper 50 m of the drill holes at BDP93 extend the record to about 350 ka.
2. The biogenic silica record from the Selenga Delta area is closely correlated with the marine oxygen-isotope record for the past 200 kyr or more, although the biogenic silica record is ‘clipped’ by zero values and does not have the saw-tooth character of the marine oxygen-isotope record.
3. The correspondence between the biogenic silica record of the Selenga Delta area and the marine oxygen-isotope record decreases with depth in the BDP93 cores, probably because the earlier sequence is coarser, and more locally derived.
4. The equivalent of marine oxygen-isotope stage 3 is distinctly intermediate in character between full glacial and full interglacial biogenic silica values.
5. Diatom productivity in Lake Baikal decreased abruptly during the period from about 11 to 10 ^{14}C ka, probably due to cooling associated with the Younger Dryas event.

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