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A rock-magnetic record from Lake Baikal, Siberia: Evidence for Late Quaternary climate change

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Abstract

Rock-magnetic measurements of sediment cores from the Academician Ridge region of Lake Baikal, Siberia show variations related to Late Quaternary climate change. Based upon the well-dated last glacial–interglacial transition, variations in magnetic concentration and mineralogy are related to glacial–interglacial cycles using a conceptual model. Interglacial intervals are characterized by low magnetic concentrations and a composition that is dominated by low coercivity minerals. Glacial intervals are characterized by high magnetic concentrations and increased amounts of high coercivity minerals. The variation in magnetic concentration is consistent with dilution by diatom opal during the more productive interglacial periods. We also infer an increased contribution of eolian sediment during the colder, windier, and more arid glacial conditions when extensive loess deposits were formed throughout Europe and Asia. Eolian transport is inferred to deliver increased amounts of high coercivity minerals as staining on eolian grains during the glacial intervals. Variations in magnetic concentration and mineralogy of Lake Baikal sediment correlate to the SPECMAP marine oxygen-isotope record. The high degree of correlation between Baikal magnetic concentration/mineralogy and the SPECMAP oxygen-isotope record indicates that Lake Baikal sediment preserves a history of climate change in central Asia for the last 250 ka. This correlation provides a method of estimating the age of sediment beyond the range of the radiocarbon method. Future work must include providing better age control and additional climate proxy data, thereby strengthening the correlation of continental and marine climate records.

1. Introduction

The Baikal rift zone in southeastern Siberia is one of the major continental rifting provinces of the world. In these rift zones, the continental crust is being thinned and extensional forces are separating the crust. Both asthenospheric diapirism (active rifting) and intraplate stresses associated with the Himalayan collision (passive rifting) have been proposed as the cause for the development of the Baikal rift [1–5]. The Baikal rift zone consists of a series of structurally controlled basins separated by structurally high terrain. The largest basin, the Baikal depression, is the deepest continental depression on earth and is occupied by Lake Baikal, the world's deepest (1620 m) and most voluminous (23,000 km^3) lake (Fig. 1) [7].

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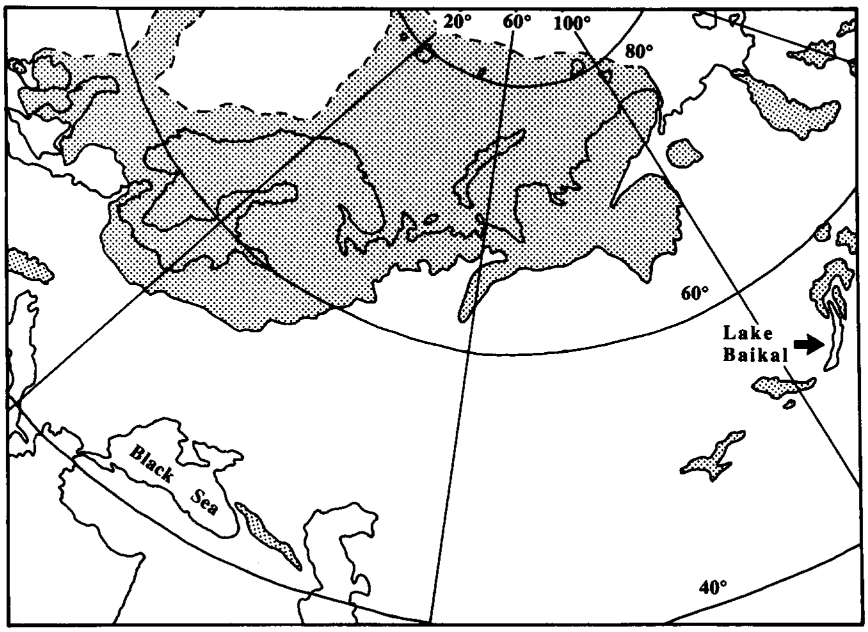

Fig. 1. The location of Lake Baikal in southeastern Siberia. Extent of Eurasian ice sheet and mountain glaciers at last glacial maximum are shown as shaded regions. Eurasian ice sheet boundary dashed where it joined ice shelves [6].

Lake Baikal lies at an elevation of 468 m above sea level and comprises three basins separated by two structural highs (Fig. 2). Within the Baikal depression more than 7500 m of lacustrine sediment have accumulated since the Miocene [4,8]. Modern sedimentation rates are estimated at 0.1–1 mm/yr based on ^{137}Cs and ^{210}Pb inventories [9]. Net sedimentation rates for the Holocene vary from 0.03 to 0.3 mm/yr, as determined by AMS radiocarbon dating [10]. Academician Ridge, a structural and bathymetric high, is isolated from direct fluvial and downslope sedimentation and thus has a low rate of sedimentation of about 0.03 mm/yr during the Holocene. In contrast, basin floors experience turbidite sedimentation and have a correspondingly high sedimentation rate of 0.3 mm/yr [10].

At present the climate near Lake Baikal is characterized by long, cold (−17° to −25°C) and dry winters and summers which are short, relatively hot (19°–20°C) and wet, reflecting the continental nature of the region [7]. The drainage

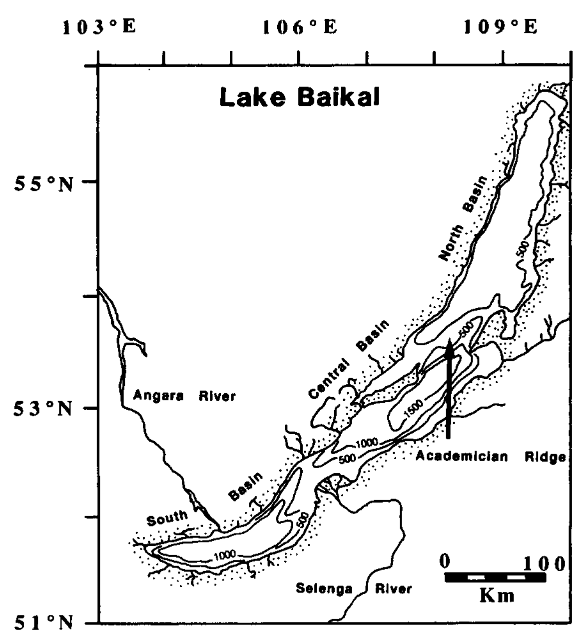

Fig. 2. Bathymetric map of Lake Baikal. Isobath interval = 500 m.

basin covers 540,000 km^2 with over 300 rivers delivering 60 km^3/yr of water to the lake, 72% of which is delivered by just three rivers [7]. During modern times, lake-level fluctuations of 120–140 cm have been recorded due to variations in precipitation [7].

Lake Baikal sediments are well suited for paleoclimatic study because (i) the lake contains a long, continuous stratigraphic record and (ii) it lies in a high-latitude, continental-interior setting. Initial lake sedimentation began during the middle Miocene approximately 15 m.y. ago, with a major change in the nature of sediment deposition occurring in the early Pliocene as rifting rates changed from slow to fast [4,11]. Although the drainage basin was glaciated, the lake was not (Fig. 1), so sediments from previous glacial/interglacial cycles may be preserved within the lake [6]. As one of the world's oldest existing lakes, Lake Baikal provides an unusual opportunity for studying a long, continuous record of extreme continental climate change.

The high northern latitude (51°–56°N) location of the lake makes it sensitive to orbitally induced variations in solar insolation in the obliquity band. The lake is located in the mid-continent region dominated by the Asiatic high in winter and the region is characterized by a high degree of continentality [12]. This high degree of continentality (seasonality) is an important component in the study of paleoclimate. Temperature modeling efforts suggest that precessional (seasonal) forcing yields the greatest change in summer maximum temperatures over the central Asian continent [13]. These modeling efforts for the Baikal region show that the orbital signal is translated linearly into a large seasonal temperature response. An 800 k.y. modeled temperature record "has the look of an eccentricity-modulated precessional cycle, so familiar in Milankovitch curves" [13]. For these reasons we expect to find all three orbital periodicities in climate proxy data from the sediment record of Lake Baikal.

Paleomagnetic investigations of Lake Baikal sediments were initiated by the late A.Ya. Kravchinsky. Baikal sediments were shown to be

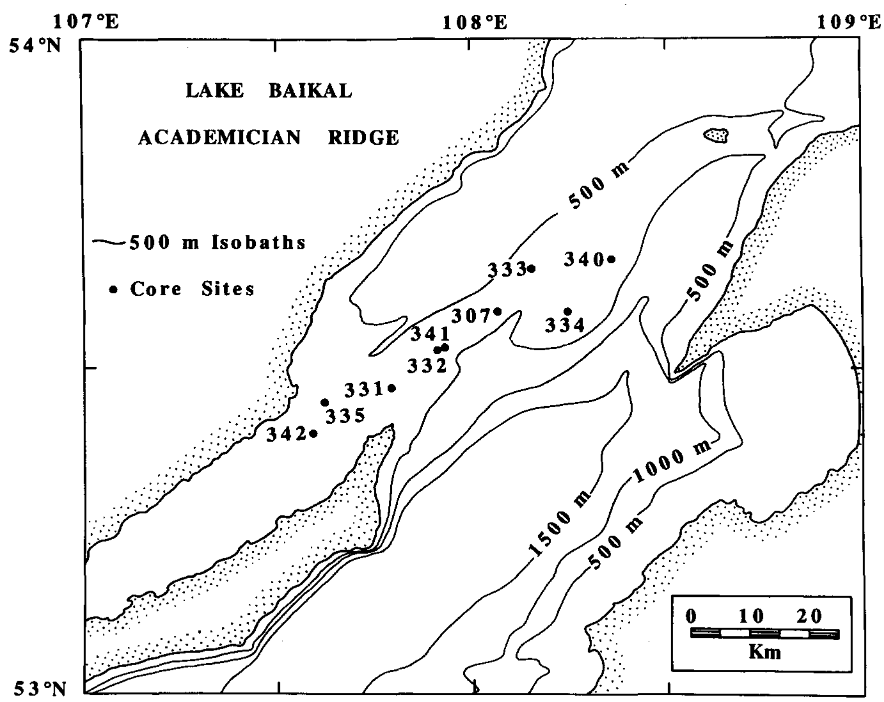

Fig. 3. Core site locations on Academician Ridge. See Fig. 2 for location of Academician Ridge within Lake Baikal. At each core site multiple cores were obtained.

suitable for paleomagnetic study and good core correlations were obtained using magnetic susceptibility and the intensity of remanent magnetization [14].

Rock-magnetic and paleomagnetic measurements are an important component of an ongoing, multidisicplinary study of the paleolimnology of Lake Baikal conducted by a large Russian–American team [15]. In this paper we present rock-magnetic measurements of sediment cores obtained from the Academician Ridge region of Lake Baikal. Whole-core magnetic susceptibility measurements are used to correlate sediment cores on a variety of scales. Variations in rock-magnetic properties are interpreted as indicators of past climatic and limnologic change and used to construct a conceptual model for the last glacial–interglacial cycle dated by radiocarbon methods. The conceptual model is used to identify older glacial–interglacial cycles in a long core. Correlation of magnetic concentration and mineralogy to the SPECMAP marine oxygen-isotope record of global ice volume provides further support to the conceptual model and a method of dating Baikal sediment beyond the limit of the radiocarbon method.

2. Methods

2.1. Analytical methods

As part of the joint Russian–American paleolimnologic study of Lake Baikal, field programs to gather sediment cores and seismic-reflection profiles were undertaken from 1990 to 1992 [15]. During these three field seasons, a total of 41 sediment cores were obtained from the Academician Ridge region of Lake Baikal using a variety of corer types, including gravity, modified Kuhlenberg piston and box corers (Fig. 3). Core locations were selected based on analyses of seismic reflection profiles, so that areas of faulting and onlap/offlap reflectors could be avoided. Areas of parallel draped reflectors were targeted with the goal of coring undisturbed sediment.

Magnetic measurements were made on both the whole core and on oriented subsamples. Onboard the ship, low-field magnetic susceptibility (K) of all cores was measured at 3 cm intervals with a Bartington Instruments susceptibility meter generating an alternating field (AF) of 8 μT. A pass through loop sensor operating at a low frequency (0.565 kHz) allowed entire sections of core to be measured rapidly and nondestructively. Cores of differing diameter were normalized to a diameter of 10 cm using a calibration graph provided by the manufacturer. Selected cores were returned to the United States for further study by U.S. participants in the study.

Oriented paleomagnetic subsamples in 5 cm^3 plastic boxes were taken and measured for low and high frequency (0.43 and 4.3 kHz) magnetic susceptibility with a Bartington Instruments single-sample sensor operating at a peak AF field of 8 μT. Anhysteric remanent magnetization (ARM) was induced in the samples with a Schonstedt GSD-1 demagnetizer operating at a peak AF field of 0.1 T and a steady field of 0.1 mT and measured on a SCT cryogenic magnetometer. The ARM was normalized to the steady field and expressed as K_{ARM}. Saturation isothermal remanent magnetization (SIRM) was induced in the samples by an electromagnet using a field of 1.2 T and measured on the cryogenic magnetometer. Several strongly magnetized samples were measured on a Molspin spinner magnetometer. An induced back IRM (bIRM) was imparted to the samples by subjecting them to a reversed field of 0.3 T generated by the electromagnet and measured on the cryogenic magnetometer. An alternating force magnetometer was used to measure the hystersis parameters saturation magnetization (M_s), saturation remanence (M_{rs}), coercive force (H_c) and coercivity of remanence (H_{cr}) on a subset of samples.

In addition to measuring the rock-magnetic properties of the sediment, gamma-ray attenuation was measured with a GeoTek multisensor core logger. Whole cores returned to the U.S. from the 1992 field season were measured at 1 cm intervals. Gamma-ray attenuation is primarily due to Compton scattering, a measure of electron density, and therefore can be used to estimate the wet bulk density of the sediment [16]. Several new AMS radiocarbon ages have been determined for Academician Ridge cores using the method described by [10].

2.2. Interpretation of rock-magnetic parameters

Measurement of the magnetic parameters described above yields information useful in the study of the sediment deposits of Lake Baikal. The rock-magnetic parameters (K, K_{ARM}, SIRM, bIRM) and the ratios derived from them are used to identify variations in the concentration, grain size and mineralogy of the magnetic material downcore. We use the terms 'magnetic material' and 'magnetic minerals' to refer to substances which can carry a remanent magnetization or remanence.

Rock-magnetic parameters that indicate variations primarily in magnetic mineral concentration are K, K_{ARM}, SIRM and M_s [17–20]. These parameters increase in value as the concentration of magnetic material in the sediment increases. Both K_{ARM} and SIRM are grain-size dependent and increase in value with an increase in concentration of fine magnetic grain sizes (single domain). K is also grain-size dependent, with higher values at both larger magnetic grain sizes (multidomain) and very fine magnetic grain sizes (superparamagnetic). M_s is independent of grain-size variation and dominated by the concentration of low coercivity minerals (i.e., magnetite and maghemite) when these minerals are present in a sample. SIRM is also dependent on magnetic mineralogy, with minerals having a high magnetization (e.g., magnetite) contributing to a larger SIRM value. Unlike K_{ARM} and SIRM which measure magnetic remanences only, K is measured in a weak magnetic field so that non-remanent (diamagnetic and paramagnetic) sediment components contribute to it. When remanence-bearing minerals occur in low concentration, the diamagnetic and paramagnetic components can significantly influence K.

The interparametric ratios K_{ARM}/K and $K_{ARM}/SIRM$ indicate variations primarily in magnetic grain size. These ratios vary inversely with magnetic grain size [17,20–22]. Both ratios primarily reflect the presence of finer magnetic grain sizes (single domain) and can be used to assess the relative change in concentration of finer magnetic grain sizes [23].

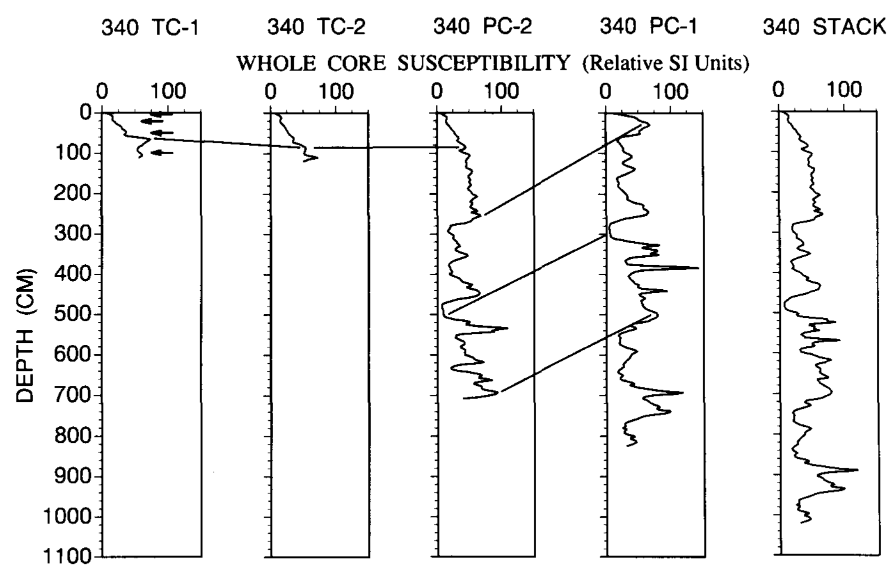

Fig. 4. Whole-core magnetic susceptibility profiles for piston (PC) and trigger (TC) cores obtained at site 340 on the Academician Ridge. Core correlation indicated that core PC1 failed to recover the upper 2 m of sediment. CORPAC, an inverse correlation method, was used to correlate and stack cores PC1 and PC2 to yield the stacked profile shown. Depths of radiocarbon-dated samples are identifed by arrows (refer to Table 1 for ages).

The interparametric ratios S (−bIRM/SIRM) and HIRM [(bIRM + SIRM)/2] reflect variations in the coercivity spectrum of the magnetic mineral assemblage and therefore in the mineralogy. The S ratio is the ratio of higher coercivity minerals (i.e., hematite and goethite) to lower coercivity magnetic minerals (i.e., magnetite and maghemite). Values of S of about 1.0 indicate a high proportion of magnetite, whereas lower values indicate an increasing proportion of hematite and goethite [17–19]. The HIRM parameter is a measure of the concentration of high coercivity magnetic minerals (i.e., hematite and goethite) and the parameter varies directly with the concentration of high coercivity minerals [17–19].

The interpretation of rock-magnetic parameters is complicated because sediments contain a complex mixture of grain sizes, shapes, mineralogy and concentrations of magnetic grains. However, rock-magnetic studies have been used successfully in a wide range of depositional environments to provide insight into past climatic changes in deep-sea [18,24], loess [25,26] and lake [27] sediments. The basis for interpreting the sediment-magnetic variations in terms of past climatic, limnologic and tectonic processes is the inference that climatic, limnologic and tectonic processes change components of the Lake Baikal hydrologic system. These components include sediment sources, sediment transport paths, sediment influx rates, lake productivity, weathering/pedogenic phases, reduction diagensis and lake level. These components, in turn, influence the type of sediment accumulating in the lake and therefore the magnetic properties of the sediment.

3. Results

3.1. Core correlation

The magnetic susceptibility profiles clearly demonstrate their utility for core correlation on a variety of scales (Figs. 4 and 5). First, different types of cores from a single site can be correlated. Box cores and trigger cores often recover an undisturbed sediment surface, so that correlation of K profiles allows the extent of either core disturbance or surface sediment loss by the piston corer to be determined. For example, piston core 340 (PC1) failed to recover the upper 2 m of sediment, possibly due to a faulty trigger arm causing a delay in the release of the piston in the

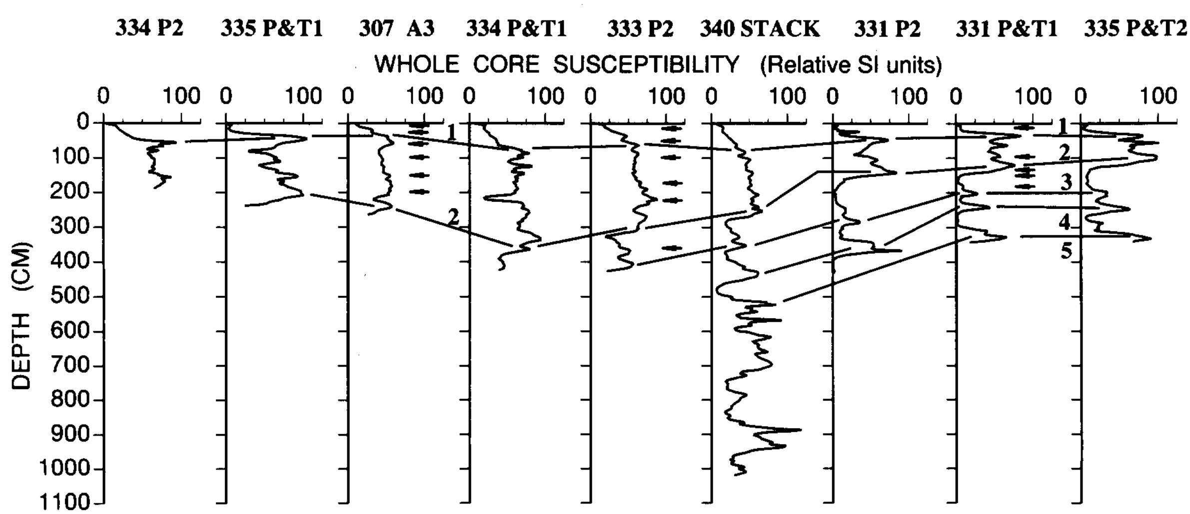

Fig. 5. Correlation of whole-core magnetic susceptibility profiles for cores obtained from Academician Ridge. At several sites the piston core and trigger core have been correlated and combined into a composite profile using the method illustrated in Fig. 4. The overall good correlation between six different core sites indicates a high degree of lateral continuity to the sedimentation on Academician Ridge. Depths of radiocarbon dated samples are identified by arrows (refer to Table 1 for ages).

piston corer (Fig. 4). CORPAC, an inverse correlation program [28], was used to correlate and stack the whole-core K records of the two piston cores from site 340. Stacking involves averaging the two K profiles at a common depth scale. This analysis enabled a stacked record which represents the entire sediment sequence to a depth of 10.2 m to be constructed (Fig. 4). A composite core was constructed for the remaining magnetic parameters measured in the cores from site 340 (PC1 and PC2) by joining the two piston cores at a depth of 480 cm in PC2 and the equivalent depth in core PC1 (section 3.2). Second, magnetic susceptibility profiles can be correlated on a larger scale by correlating between sites on Academician Ridge. Correlation between sites allows measurements made at one site (e.g., radiocarbon dating) to be applied to cores from other sites (Fig. 5).

When the K profiles are used in conjunction with lithology logs, the lateral extent of sediment facies on Academician Ridge can be determined (Fig. 5). The latest Quaternary interglacial sediment is characterized by low concentrations of magnetic minerals. An age of about 13 ka has been assigned to tieline 1 based upon AMS radiocarbon ages from cores 307 (A3) and 333 (PC2). The subsurface unit characterized by high concentrations of magnetic material (between tielines 1 and 2) represents sediment deposited during the last glacial interval, based on AMS ages. The overall good correlation between six different core sites indicates a high degree of lateral continuity to the sedimentation on Academician Ridge. Both the interglacial and glacial sediments vary in thickness between sites on Academician Ridge, indicating a lateral variation in the sedimentation rate and/or the presence of unconformities. In the deeper cores, alternating intervals of low and high K values suggest the presence of earlier interglacial and glacial sediments (Fig. 5).

3.2. Rock-magnetic results

Cores from sites 307, 333 and 340 on the Academician Ridge (Fig. 3) were subsampled and measured for a standard set of rock-magnetic parameters. A total of nine cores was measured; one representative core from each site is presented in this paper. Although cores 307 (A3) and 333 (PC2) are short they have good radiocarbon age control during the last glacial to interglacial transition (Table 1) and therefore are used to develop the conceptual model presented in section 4.1. Core 340 (composite) is the longest and oldest record from Academician Ridge and is used for correlation to the SPECMAP record.

The results of rock-magnetic studies of core 307 (A3) reveal two distinct magnetic mineral assemblages (Fig. 6 and Table 2). Above the 13,550 yr dated horizon, interglacial sediment is characterized by low magnetic concentration and

Table 1
AMS radiocarbon ages on total organic carbon for Academician Ridge cores

Core	Sample Depth (cm)	Laboratory No.	Age (yr)	Error (1 SD)
307 A3 [a]	4	OS-00105	1830 [c]	120
307 A3 [a]	34	OS-00106	13550 [c]	140
307 A3 [a]	64	OS-00107	17450 [c]	150
307 A3	101	OS-00811	29100 [c]	190
307 A3	149	OS-00805	35800	300
307 A3	201	OS-00810	30000	390
331 PC1 [a]	96 [b]	OS-00457	22000	100
331 PC1 [a]	128 [b]	OS-00456	21800	170
331 PC1	131 [b]	OS-00813	23300	140
331 PC1	148 [b]	OS-00812	26600	640
331 PC1	148 [b]	OS-01338	22000	110
331 PC1 [a]	170 [b]	OS-00455	30500	160
331 TC1 [a]	2	OS-00459	1090 [c]	40
331 TC1 [a]	18	OS-00458	5440 [c]	45
333 PC2 [a]	22	OS-00453	6270 [c]	45
333 PC2 [a]	56	OS-00452	12650 [c]	95
333 PC2	98	OS-00815	22300 [c]	95
333 PC2 [a]	182	OS-00451	30200	180
333 PC2	222	OS-00816	33200	500
333 PC2 [a]	362	OS-00450	33400	210
340 TC1	2	CAMS-7585	1600 [c]	100
340 TC1	21	CAMS-7588	5790 [c]	80
340 TC1	51	CAMS-8893	11030 [c]	140
340 TC1	101	CAMS-8890	13720 [c]	200

[a] Published radiocarbon age [10].
[b] Sample depth corrected for the thickness of sediment missing from the top of the core.
[c] Samples used to calculate the radiocarbon age model, other samples are likely contaminated by modern carbon.

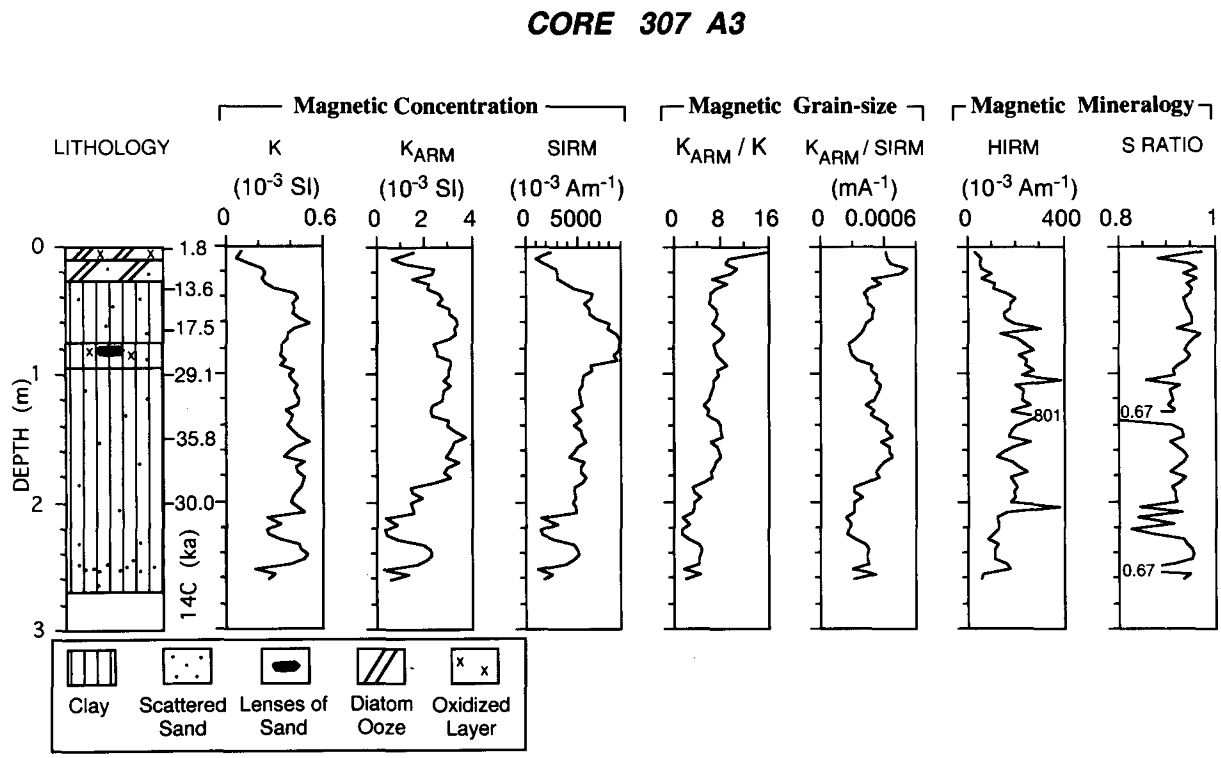

Fig. 6. Core description and analytic data for core 307 (A3) located on Academician Ridge (see Fig. 3). Radiocarbon ages from [10]. See section 2.2 for detailed explaination of rock-magnetic parameters.

a composition that is predominantly low coercivity minerals (i.e., magnetite/maghemite) (Fig. 6). Late Pleistocene glacial sediment is characterized by a higher magnetic concentration and increased amounts of high coercivity minerals (i.e., hematite and goethite) (Fig. 6). The interglacial sediment assemblage present at the top of the core corresponds to a diatomaceous lithology. Low mag-

Table 2
Generalized characteristics of the two broadly defined sediment assemblages for the present interglacial and previous glacial intervals

PARAMETER	INTERGLACIAL ASSEMBLAGE	GLACIAL ASSEMBLAGE
MAGNETIC CONCENTRATION (K,KARM,SIRM)	Low	High
MAGNETIC MINERALOGY (HIRM)	Lower concentration of high coercivity minerals	Higher concentration of high coercivity minerals
(S ratio)	Lower proportion of high coercivity minerals	Higher proportion of high coercivity minerals
SEDIMENT DENSITY (Gamma-ray attenuation)	Low	High
LITHOLOGY	Diatomaceous	Clay
ACCUMULATION RATES	Higher biogenic Lower terrigenous	Lower biogenic Higher terrigenous

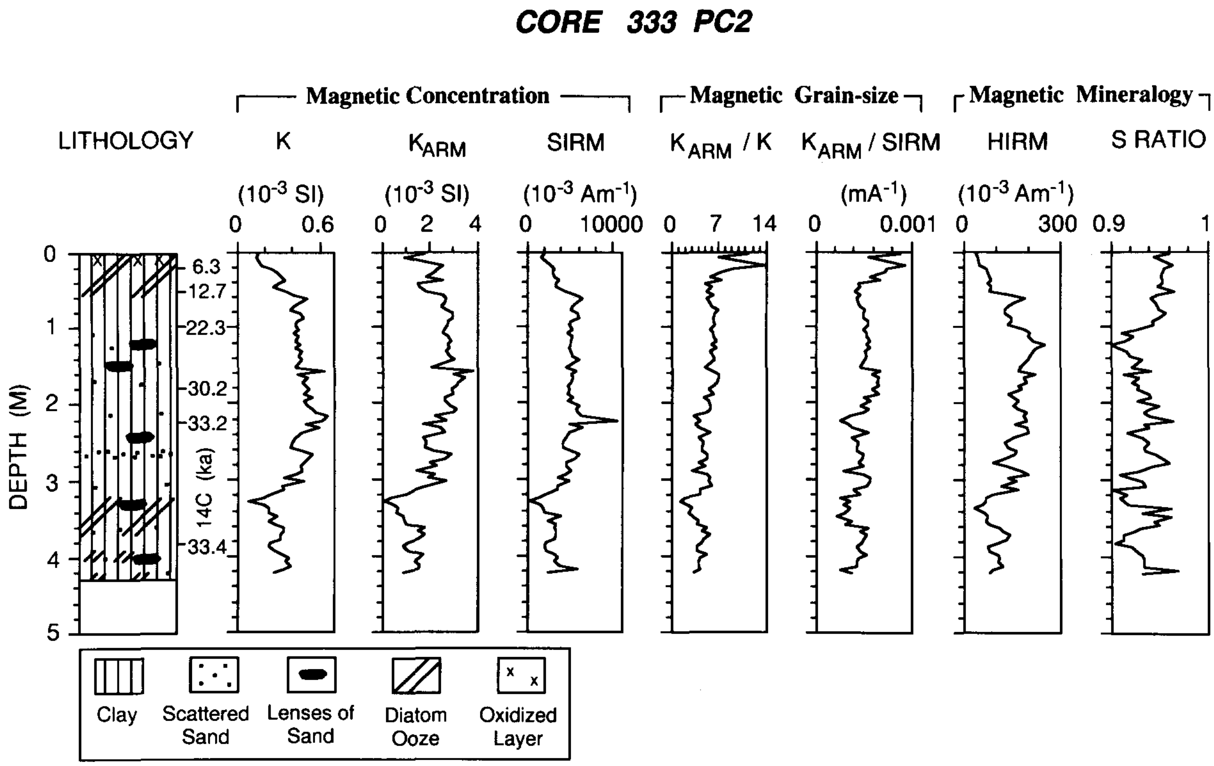

Fig. 7. Core description and analytic data for core 333 (PC2) located on Academician Ridge (see Fig. 3). Radiocarbon ages from [10]. See section 2.2 for detailed explaination of rock-magnetic parameters.

netic concentrations at depth (210–230 cm) correspond to an interval of increased proportions of high coercivity minerals and coarse magnetic particle size (Fig. 6). The finest magnetic particle size is found in the uppermost interglacial sediment (Fig. 6). The *S* ratio indicates a change to a significant proportion of high coercivity minerals at about 90 cm which corresponds to a change in lithology. The change in magnetic mineral proportions occurs about 50 cm deeper than the major change in the concentration and HIRM parameters.

The results of rock-magnetic studies of core 333 (PC2) also reveal two different magnetic mineral assemblages for the last glacial–interglacial transition, similar to the pattern observed in core 307 (A3) (Table 2). Above the 12,650 yr dated horizon the interglacial sediment-magnetic assemblage is present, corresponding to a diatom-rich lithology (Fig. 7 and Table 2). Late Pleistocene time is characterized by the glacial sediment-magnetic assemblage (Fig. 7 and Table 2). The finest magnetic particle size is found in the uppermost interglacial sediment (Fig. 7). The *S*

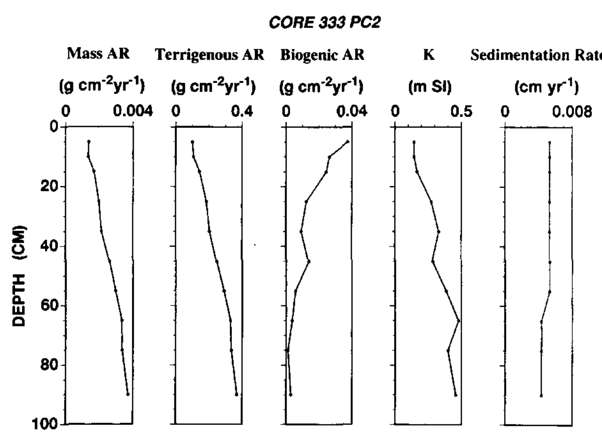

Fig. 8. Downcore profiles of mass AR, terrigenous AR, biogenic AR, K and sedimentation rate for the uppermost meter of core 333 (PC2) spanning the last glacial–interglacial transition.

ratio indicates a change to a significant proportion of high coercivity minerals at about 100 cm. The change in magnetic mineral proportions occurs about 50 cm deeper than the changes in concentration and HIRM parameters. Below the 320 cm depth, the magnetic-mineral assemblage is similar to the interglacial assemblage present at the top of the core, suggesting the presence of previous interglacial sediments. However, magnetic grain-size parameters do not show a return to fine particle size (Fig. 7).

Sediment flux was calculated following the method of [29] for the upper 1 m of core 333 (PC2) in an effort to determine if the K variations are dominated by terrigenous or biogenic influx variations during the well-dated glacial–interglacial transition. Dry bulk density (DBD) was measured approximately every 10 cm. Sedimentation rates were calculated for each point based upon the AMS radiocarbon ages (Table 1). K and biogenic silica, measured every 5 cm, were linearly interpolated to the DBD sample depths. The biogenic component is largely diatom opal because total organic carbon attains only a few percent and carbonate is nearly zero percent in Academician Ridge sediments [15]. The equations used to calculate the terrigenous and biogenic fluxes are:

Mass accumulation rate (AR)
= DBD · sedimentation rate

Biogenic AR = biogenic silica fraction · mass AR

Terrigenous AR
= (1 – biogenic fraction) · mass AR

The mass AR, terrigenous AR, biogenic AR, K and sedimentation rate data are shown in Fig. 8. The importance of biogenic dilution is indicated by a subtle change in the K profile at 45 cm that also occurs in the biogenic AR profile but which does not occur in the terrigenous AR profile. Following the method of [29] crossplots of AR and fraction data are used to determine if

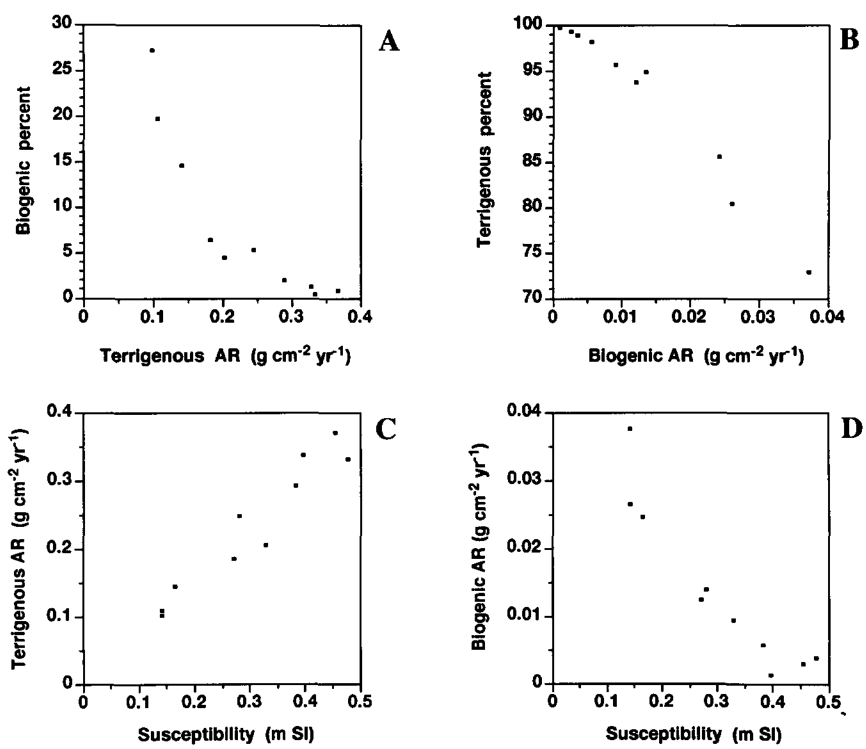

Fig. 9. Crossplots of terrigenous AR versus biogenic fraction (A) and biogenic AR versus terrigenous fraction (B). Crossplots of K versus terrigenous AR (C) and K versus biogenic AR (D) for core 333 (PC2).

variations in K are the result of terrigenous or biogenic flux variations (Fig. 9). In the Arabian Sea it has been demonstrated that variations in terrigenous supply overwhelm any influence biogenic dilution has on K [29]. The relationship between terrigenous AR (biogenic AR) and biogenic fraction (terrigenous fraction) are equally strong, indicating that the Academician Ridge K record is influenced by both biogenic dilution and terrigenous influx (Fig. 9). Although biogenic and terrigenous supply vary inversely they produce a similar effect on K. During the present interglacial the biogenic supply increases, thereby diluting K, whereas the terrigenous supply decreases, also decreasing K. Conversely, during the last glaciation the biogenic supply decreases, thereby increasing K, whereas the terrigenous supply increases, also increasing K. It is the interplay of biogenic and terrigenous supply that produces an overall sedimentation rate that does not vary greatly between interglacial and glacial periods. In developing the conceptual model (section 4.1) which accounts for variations in the sediment magnetic properties both biogenic dilution and terrigenous supply are considered as the dominant sedimentary processes.

Core 340 (composite) is the longest core from Academician Ridge and extends well beyond the limit of radiocarbon dating. In addition to new radiocarbon ages (Table 1), radiocarbon ages from cores 307 (A3) and 333 (PC2) have been tied to core 340 (composite) via correlation of the whole-core K profiles (Figs. 4 and 5). Core 340 (composite) also shows a magnetic assemblage for the present interglacial and last glacial period similar to cores 307 (A3) and 333 (PC2). Above the 13 ka dated horizon (tieline 1, Fig. 5), the interglacial sediment assemblage is present (Fig. 10 and Table 2). Gamma-ray attenuation indicates low wet bulk density for this interval (Fig.

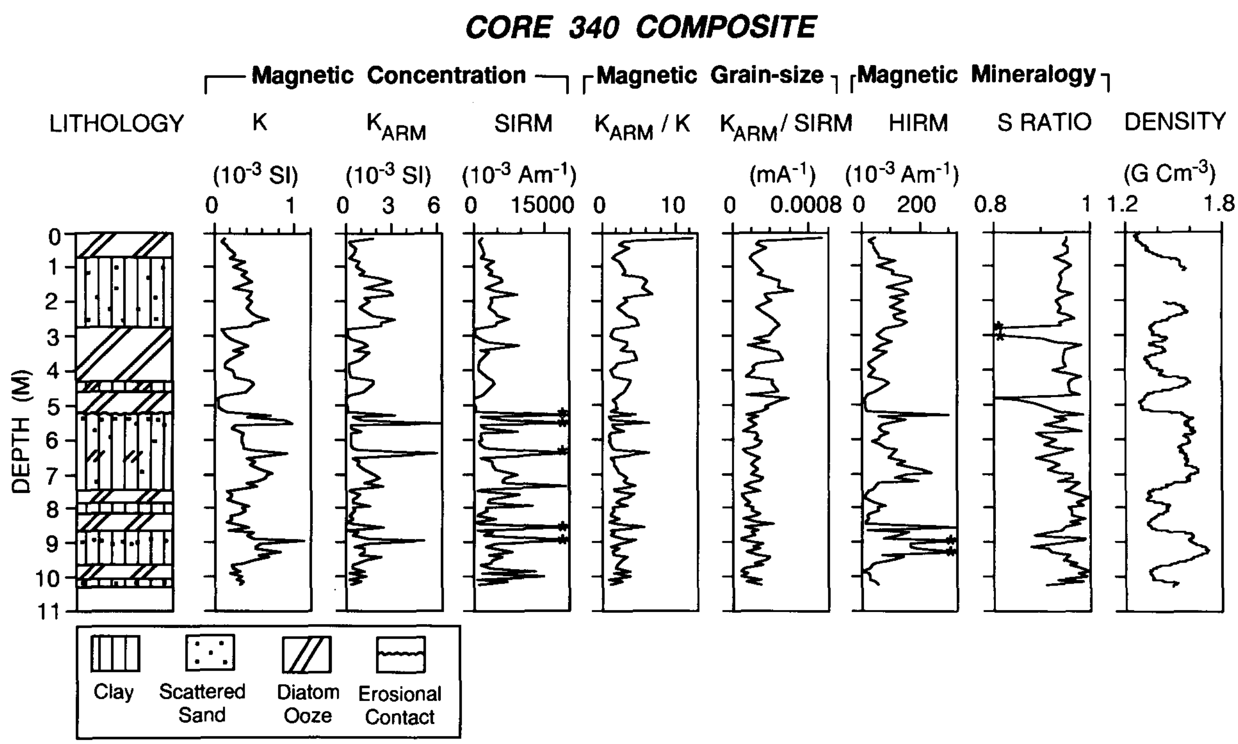

Fig. 10. Core description and analytic data for core 340 (composite) located on Academician Ridge (see Fig. 3). Approximate sediment density estimated by gamma-ray attenuation for cores 340 TC1 (0–1 m) and 340 PC1 (2–10 m). Asterisk indicates sample value beyond plotted range.

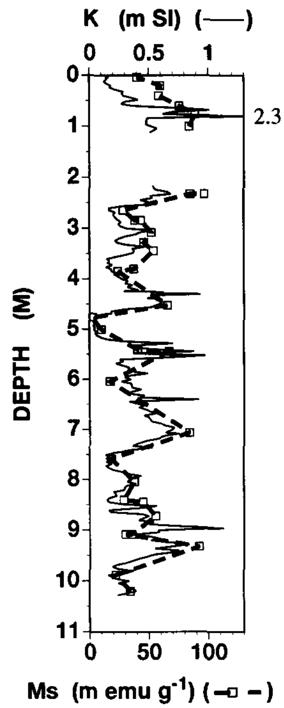

Fig. 11. Downcore susceptibility (K) and saturation magnetization (M_s) for cores 340 TC1 (0–1 m) and 340 PC1 (2–10 m). Core 340 PC1 has been shifted downwards by 2 m to account for missing surface sediment (see Fig. 4).

10). This interglacial magnetic assemblage and low sediment bulk density correspond to a diatomaceous lithology (Fig. 10). The interval between 80 and 280 cm is characterized by the glacial sediment assemblage (Fig. 10 and Table 2). This glacial sediment assemblage corresponds to a clay lithology and increased wet bulk density (Fig. 10). In core 340 (composite), magnetic particle size does not vary between the interglacial and glacial assemblages, although the finest magnetic particle size is found in the uppermost interglacial sediment (Fig. 10). Deeper in core 340 (composite), intervals with characteristics similar to the present interglacial sediment assemblage occur at depths of 280–520, 730–870 and 950–1023 cm (Fig. 10 and Table 2). Intervals with characteristics similar to the last-glacial sediment assemblage also occur at 520–730 and 870–950 cm (Fig. 10 and Table 2).

Variations in M_s and K are in close agreement throughout cores 340 (TC1) and 340 (PC1) (Fig. 11). Because M_s is independent of grain-size variation the close agreement between M_s and K indicates that variations in K are responding largely to changes in magnetic concentration and not to changes in grain size. In the uppermost sediment, K and M_s co-vary although the values of K are consistently less than those of M_s. This variation may indicate the presence of fine-grained (single domain) magnetic particles which are removed by reduction diagensis at depth. The first-order coarsening trend in the grain-size parameter K_{ARM}/K (Figs. 6, 7 and 10) would support this inference although changes in the grain size of sediment transported to the lake may also be important.

The major feature of the magnetic particle-size records is the presence of the finest magnetic grain sizes in the uppermost portion of the present interglacial sediment (Figs. 6, 7 and 10). Magnetic grain size is not as clearly related to glacial–interglacial change and therefore is not used as a proxy indicator for climatic/limnologic change. The origin of the finest magnetic particles in the surficial sediment is under continued investigation.

4. Discussion

4.1. Conceptual model

A conceptual model for the Academician Ridge region of Lake Baikal can account for variations in the rock-magnetic concentration and mineralogy parameters during the last glacial–interglacial cycle (marine oxygen-isotope stages 1 and 2). Deglaciation in Siberia dates to about 13 ka [30], with major changes in the drainage of large Siberian proglacial lakes occurring at about 13.5 ka [6]. We consider the 13 ka tieline 1 horizon (Fig. 5), calculated from AMS radiocarbon ages in cores 307 (A3), 333 (PC2) and 340 (TC1), to approximately mark the transition from glacial to interglacial conditions. Rock-magnetic results from the three cores described in this paper and the remaining six cores that were measured all show similar changes between glacial and interglacial conditions. Interglacial sediments, considered to be younger than 13 ka, are characterized as a diatomaceous lithology with low bulk density, low magnetic concentrations and relatively high proportions of low coercivity minerals (i.e., magnetite and maghemite) (Figs. 6, 7 and 10 and Table 2). To develop the conceptual model we consider glacial sediments as the interval between 13 ka and the 29,100 yr (core 307 A3) and 30,200 yr (core 333 PC2) dates and the correlative interval in core 340 (composite) (Fig. 5). Glacial sediments extend below this approximately 30 ka horizon probably to the depth marked by sediments with properties similar to those from the present interglacial. Glacial sediments are characterized by a clayey lithology with relatively high bulk density, high magnetic mineral concentrations, and high proportions of high coercivity minerals (i.e., hematite and goethite) (Figs. 6, 7 and 10 and Table 2).

Of the many processes that control sedimentation on Academician Ridge and produce the observed sediment assemblages (Table 2) two are considered to be the dominant processes and are described in the following conceptual model:

The first process involves increased biogenic sedimentation during the warmer, more productive interglacial periods. The concentration of biogenic silica is relatively high during the interglacial, attaining as much as 25, 33 and 50% in cores 333 (PC2), 307 (A3) and 340 (TC1) respectively [15]. During the last glacial interval biogenic silica averages about 4% in core 307 (A3) and at or near 0% in both cores 333 (PC2) and 340 (TC1) [15]. In addition to increased concentrations of biogenic silica during the present interglacial there is also an increase in biogenic accumulation rate (Fig. 8). In the north basin of Lake Baikal, limnologic productivity increased as climatic conditions changed from the last glacial to the present interglacial [31]. The increase in biogenic sedimentation yields a diatomaceous lithology and because diatom opal is diamagnetic it will slightly decrease the susceptibility values. In addition, diatom opal retains no magnetization and therefore has a diluting effect on the remanence parameters that reflect magnetic concentration (K_{ARM}, SIRM). Increased amounts of porous diatom frustules also result in a lower bulk density for the interglacial sediments, whereas the more tightly packed, clayey, glacial sediments have higher bulk density values (Fig. 10).

The second dominant process controlling sedimentation on Academician Ridge is the influx of terrigenous sediment. Academician Ridge is a structural and bathymetric high in central Lake Baikal and thus is isolated from the direct influence of fluvial and downslope depositional processes (Fig. 2). In this type of depositional environment, sedimentation rates are low. The lowest sediment accumulation rates measured in Lake Baikal are for Academician Ridge sediments [9,10,15]. In low sedimentation areas, the influence of eolian transport and sedimentation would be expected to be more significant. Sediment flux calculations for core 333 (PC2) indicate an increase in terrigenous flux during the glacial interval (Fig. 8). In addition, an increased contribution of eolian sediment is likely during the colder, windier, and more arid glacial conditions when extensive loess deposits were formed throughout Asia, including in the vicinity of Lake Baikal [32]. Previous studies [18,33,34] have shown that measures of the concentration of high coercivity minerals are an excellent proxy indicator of eolian sedimentation in the marine environment. The high coercivity magnetic minerals (i.e., hematite and goethite) are commonly present as staining on eolian grains [32]. The increased concentrations and proportions of high coercivity magnetic minerals during the last glacial interval (Table 2) suggests the importance of eolian sedimentation on Academician Ridge. The change in the proportions of magnetic minerals occurs 10 k.y. prior to the change in magnetic concentration (Figs. 6, 7 and 10). The difference in timing reveals the differing responses of mineralogy and concentration proxy indicators to climatic/limnologic change.

4.2. Correlation to the marine oxygen-isotope record

Using the conceptual model, which relates changes in the concentration and composition of magnetic minerals, as well as sediment bulk density, to a well-dated glacial–interglacial cycle we ask the following question: Do variations in rock-magnetic and density parameters found deeper in core 340 (composite) represent earlier glacial–interglacial stages? Sedimentary cycles of diatomitic ooze and glacial–lacustrine clay deposited on Academician Ridge have been interpreted by others to represent interglacial and glacial intervals [35]. Visual inspection reveals that downcore variations in the properties of core 340 (composite) resemble those of the standard oceanic oxygen-isotope record of global ice volume (SPECMAP) [36] (Fig. 10).

We have developed a simple age model to quantitatively compare the Baikal record with the SPECMAP record. An average sedimentation rate of 5.12 cm/k.y. has been determined by obtaining the median of average interglacial (3.66 cm/k.y.) and glacial (6.57 cm/k.y.) sedimentation rates. The average interglacial and glacial sedimentation rates were determined by linear regression for several AMS radiocarbon dated cores [10]. This rate was applied linearly down core 340 (stack) resulting in a basal age of approximately 200 ka. This application of a constant sedimentation rate makes no assumption that variations in rock-magnetic parameters are related to climatic and limnologic change. Although constant sedimentation rates are unlikely in detail, the average rate weights interglacial and glacial sedimentation rates equally. This average rate provides a starting point for identifying earlier glacial and interglacial sediments and for testing the conceptual model. Using the linear age model, we correlated the concentration of magnetic grains (whole-core susceptibility) from core 340 (stack) to SPECMAP, a record of global ice volume. Signal correlation is achieved using CORPAC, an

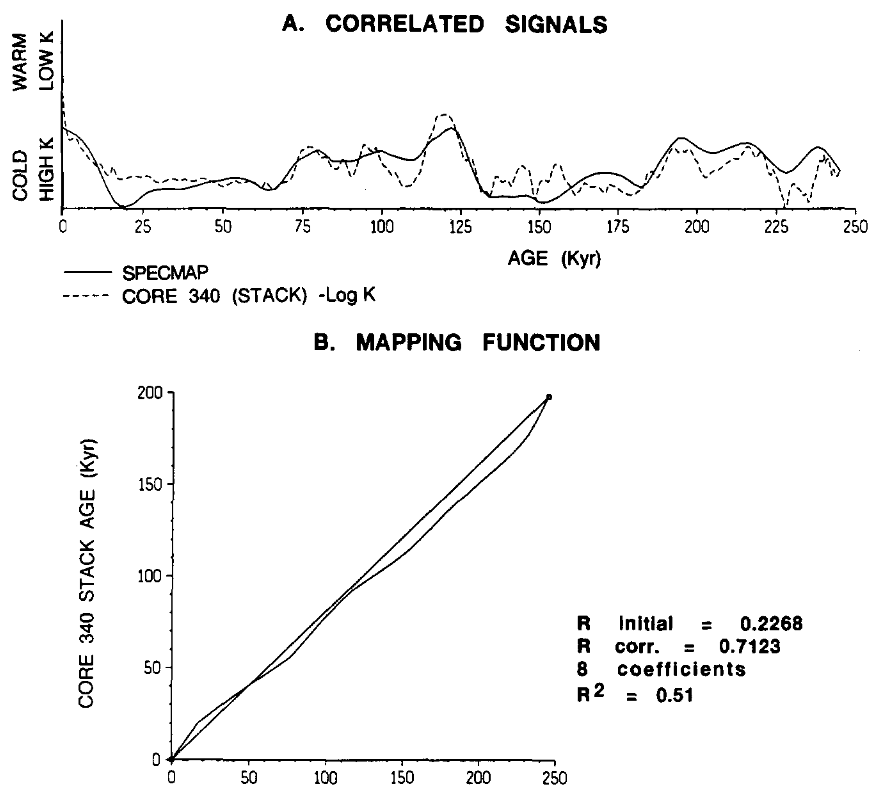

Fig. 12. (A) Logarithm of whole-core susceptibility (K) for core 340 (stack) correlated to SPECMAP [35] (arbitrary ordinate). (B) The mapping function, a one-to-one relationship between the K and SPECMAP records, results from the correlation shown in (A). This mapping function provides a nonlinear age model beyond the limit of the radiocarbon method.

inverse correlation method [28] (Fig. 12). The logarithm of susceptibility was used because the susceptibility of natural materials is log-normally distributed [17]. The log of susceptibility reduces the high frequency variability in the K record that is not recorded by the oxygen isotope data. The high frequency variability in magnetic concentration during glacial intervals may be the result of ice-rafted sedimentation. The conceptual model indicates that the logK record is inversely related to SPECMAP; therefore the negative logK was used for correlation purposes so that the two records would be directly related. The correlation results in a high degree of coherence (0.71) and 51% shared variance between the K and SPECMAP records (Fig. 12). Shared variance is calculated using the method described by [37]. Throughout the record, during interglacial stages (1, 5, 7) defined by SPECMAP magnetic concentration is low, whereas during glacial stages (2–4, 6) magnetic concentration is high (Fig. 12). In addition, during cold interglacial substages (e.g., 5b, 5d) the K record displays a 'colder' signal than SPECMAP. This correlation suggests that Baikal sediments are responsive to global climate change, supports our conceptual model of magnetic concentration as a climate/limnology proxy, and shows that the model can be used to identify earlier undated glacial–interglacial cycles (Fig. 12). A smooth mapping function representing a one-to-one relationship between the K and SPECMAP records does not show signs of either excessive compression or stretching during correlation, or major hiatuses in the Baikal sediment

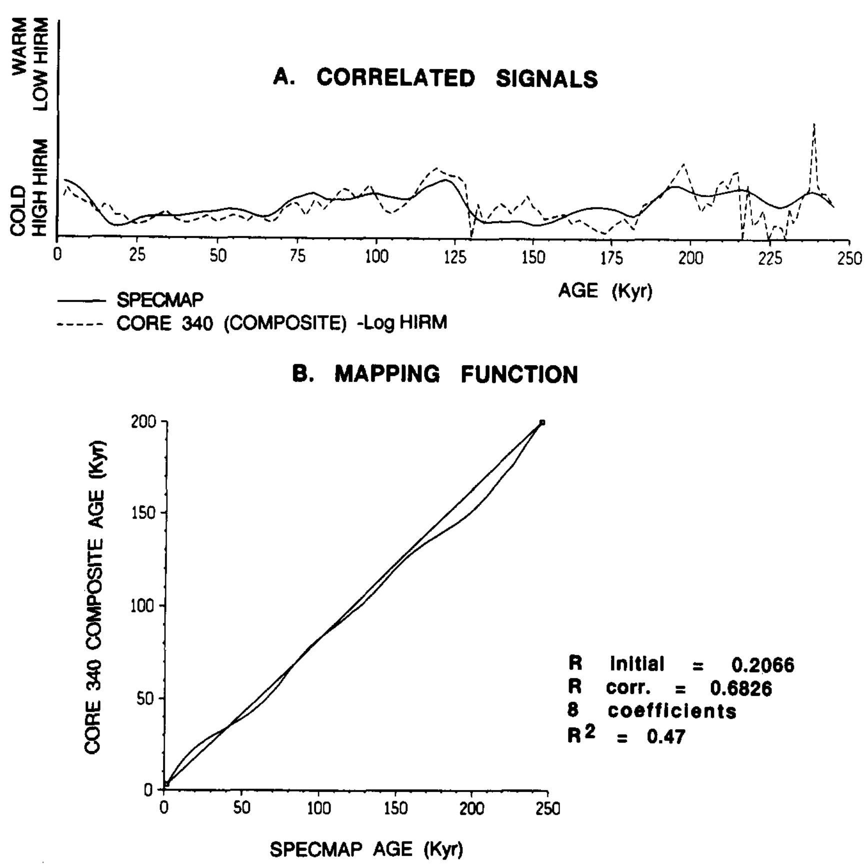

Fig. 13. (A) The HIRM parameter for core 340 (stack) correlated to SPECMAP [35] (arbitrary ordinate). (B) The mapping function, a one-to-one relationship between the HIRM and SPECMAP records, results from the correlation shown in (A). This mapping function provides a nonlinear age model beyond the limit of the radiocarbon method.

record (Fig. 12B). However, the lithology descriptions of cores 340 (PC1 and 2) indicates an erosional contact between the clay and diatomaceous lithologies at the 520 cm depth (Fig. 10). In addition the variable thickness of the sedimentary unit bounded by tielines 1 and 2 across Academician Ridge (Fig. 5) suggests that additional unconformities or changes in the sedimentation rate may be present. The mapping function is used to modify the linear age model by correlation of the K record to the SPECMAP age model, thereby providing a means of dating the Baikal sediment beyond the range of the radiocarbon method. It is important to recognize that the presence of potential unconformities mentioned above will limit the accuracy of this age model.

A similar CORPAC correlation exercise was completed for the HIRM magnetic mineralogy parameter and SPECMAP. The resulting correlation indicates 47% shared variance between the two records (Fig. 13). During interglacial stages (1, 5, 7) defined by SPECMAP there are low concentrations of high coercivity minerals. Conversely, during glacial stages (2–4, 6) higher concentrations of high coercivity minerals are present. Although the HIRM and K parameters are measures of different magnetic properties, the correlations to SPECMAP yield similar modified age models (Figs. 12 and 13).

Correlation of the Baikal record to SPECMAP allows us to provide first-order age estimates of the Baikal sediment beyond the limit of the radiocarbon method. If our correlation is correct, the oldest radiocarbon ages in cores 307 (A3), 333 (PC2) and 331 (PC1) are approximately 20–50 k.y. too young (Fig. 5). These ages are greater than 30 ka, approaching the limit of reliable radiocarbon dating. Radiocarbon ages older than 30 ka for cores 307 (A3) and 333 (PC2) and all ages for core 331 (PC1) yield inconsistent results, with stratigraphic reversals and unusually high sedimentation rates in comparison to the remaining glacial sediments from Academician Ridge. The correlation of the K profiles for these dated cores provides a relative time framework to compare the AMS ages (Fig. 5). This comparison shows that the older AMS ages are inconsistent between the three dated cores for the same relative time interval. In addition, these ages are from sediments of extremely low organic carbon content, and therefore slight modern carbon contamination from any source will yield finite ages [10,38].

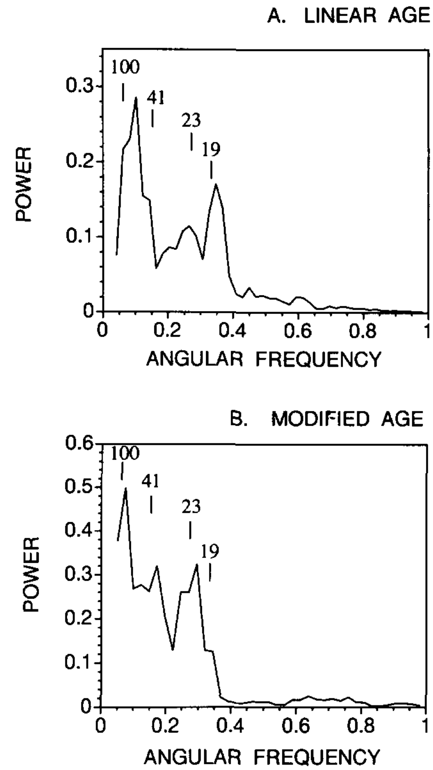

Fig. 14. (A) Spectrum of core 340 (stack) whole-core susceptibility using the linear age model consisting of a linear sedimentation rate of 0.0051 cm/yr. (B) Spectrum of core 340 (stack) whole-core susceptibility using the modified nonlinear age model resulting from the mapping function. Also shown are the orbital periodicities (k.y.).

The spectrum of core 340 (stack) magnetic concentration as a function of the linear age suggests the presence of orbital periodicities. Hence we infer that the Baikal sediments are responsive to orbital forcing (Fig. 14A). Based on the suggestion of orbital periodicities in the Baikal record and the conceptual model for the present interglacial and previous glacial, correlation of the Baikal and SPECMAP records to improve the age model is justified. The modified age model resulting from the correlation yields an improved spectrum showing all three orbital periodicities

(Fig. 14B). This improved spectrum does not validate our initial inference that the Baikal sediments are responsive to orbital forcing; rather an improved spectrum is an expected result according to the initial inference. Because an improved spectrum is obtained, it reveals a consistency to our method of correlating the Baikal and SPECMAP records. The spectral analysis results are at present limited because core 340 appears to be only about 250 k.y. old and does not have an independent age model older than the ^{14}C limit. However, the correlation and spectral results suggest that the Lake Baikal sediment record is responsive to orbital forcing and global climate change.

5. Conclusions

(1) Whole-core magnetic susceptibility is a rapid, nondestructive measurement which allows sediment cores from the Academician Ridge region of Lake Baikal to be readily correlated. This correlation allows surficial sediment not recovered in some piston cores to be identified and, using CORPAC, a stacked sediment sequence can be constructed. Also, AMS radiocarbon ages obtained from one core can be transferred to other cores.

(2) Rock-magnetic parameters are shown to be useful proxies of paleoclimatic and paleolimnologic conditions. Magnetic concentration parameters (K, K_{ARM}, SIRM) are all influenced by the combined effects of biogenic dilution during the interglacials and increased terrigenous (eolian) flux during the glacial periods.

(3) The rock-magnetic mineralogy parameters S and HIRM are also useful proxies of paleoclimate, indicating an increased flux of high coercivity minerals during the glacial intervals which we infer to be hematite stained eolian grains. This relationship suggests a more arid climate during the glacial periods in southeastern Siberia.

(4) The magnetic concentration and mineralogy profiles for a long, weakly dated core from Academician Ridge correlate well with the SPECMAP record of global ice volume. This correlation suggests that Lake Baikal sediments preserve a record of climate change for the last 250 k.y. and provides a method for dating Baikal sediment beyond the limit of the radiocarbon method.

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Erratum

A rock-magnetic record from Lake Baikal, Siberia: Evidence for Late Quaternary climate change

Earth Planet. Sci. Lett. 122, 221–238, 1994

J.A. Peck, J.W. King, S.M. Colman, V.A. Kravchinsky

The following errata pertain to this paper:
(1) Fig. 8 axis label 'Terrigenous AR (g cm^{-2} yr^{-1})' should read 'Terrigenous AR (10^{-2} g cm^{-2} yr^{-1})'.
(2) Fig. 8 axis label 'Biogenic AR (g cm^{-2} yr^{-1})' should read 'Biogenic AR (10^{-2} g cm^{-2} yr^{-1})'.
(3) Fig. 9A axis label 'Terrigenous AR (g cm^{-2} yr^{-1})' should read 'Terrigenous AR (10^{-2} g cm^{-2} yr^{-1})'.
(4) Fig. 9B axis label 'Biogenic AR (g cm^{-2} yr^{-1})' should read 'Biogenic AR (10^{-2} g cm^{-2} yr^{-1})'.
(5) Fig. 9C axis label 'Terrigenous AR (g cm^{-2} yr^{-1})' should read 'Terrigenous AR (10^{-2} g cm^{-2} yr^{-1})'.
(6) Fig. 9D axis label 'Biogenic AR (g cm^{-2} yr^{-1})' should read 'Biogenic AR (10^{-2} g cm^{-2} yr^{-1})'.

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