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A new Quaternary record of regional tectonic, sedimentation and paleoclimate changes from drill core BDP-99 at Posolskaya Bank, Lake Baikal

BDP-99 Baikal Drilling Project Members

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Abstract

This contribution presents the most recent sedimentary drill core section (BDP-99) from Lake Baikal. We discuss lithological composition and general stratigraphy, the BDP-99 age model, and draw implications for past sediment deposition changes at Posolskaya Bank in relation to tectonics and regional climate change. The BDP-99 drill core penetrated several sedimentary sequences identified in prior seismic surveys of the Selenga Delta area and helps to better constrain the age of these sequences. Lithological studies were used to identify erosional intervals apparently correlative with sequence boundaries at Posolskaya Bank. Intensified tectonic activity between ca. 1.15 and 0.8 Ma as observed at a number of locations in continental interior Asia, resulted in deposition of a ca. 90-m unit of remarkably uniform fine silty clay during the Jaramillo subchron with accumulation rates exceeding 100–160 cm/ka. A disconformity occurs at the top of this unit, and as a result, the sedimentary interval equivalent to ca. 1.0–0.8 Ma is not present in the BDP-99 section. At ca. 710–660 ka a transition to rather quiet hemipelagic sedimentation takes place as seen from an overall decrease in sedimentation rates and from higher diatom abundance in interglacial sediments.

The new late Pleistocene palynological record from BDP-99 drill core shows repetitive landscape changes from steppe and forest-steppe environments during glacials and interstadials to coniferous taiga conditions during the present and last interglacial. Every glacial/interglacial transition of the past 130 ka is marked by an early peak of Siberian spruce (*Picea*) pollen abundance. The MIS 4 interval is clearly divided into two zones due to changes in moisture availability. The late MIS 6 interval stands in stark contrast with subsequent glacial periods due to extremely low pollen abundance. Palynological records in the vicinity of the Selenga Delta contain overprinting signals from different landscape types in the extensive Selenga catchment basin.

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1. Introduction

1.1. Geological setting

Posolskaya Bank is the pronounced underwater ridge at the boundary between Southern and Central basins of Lake Baikal. This structure is part of the Selenga Delta accommodation zone comprising the structural boundary between the South and Central Basins of Baikal rift (Fig. 1). Posolskaya Bank is an asymmetric horst, and the southern side of the Bank forms an underwater escarpment plunging to the depths of 800–900 m. Along this scarp formed by a south-dipping normal fault, 800–900 m of lacustrine strata are exposed (Bogdanov and Zonenshain, 1991). The tip of Posolskaya Bank is 50–60 m water depth, and on the NW side of the Bank (opposite to tectonic escarpment) a rather gentle slope is observed (Fig. 2). The sediment sequence of Posolskaya Bank preserved evidence of basin evolution since the mid-Miocene.

Previous multi-channel seismic profiles showed that a major acoustic reflection boundary R_1, dipping to the north at 5°, is exposed at the base of the Posolskaya Bank escarpment. 'Pisces' submersible dives were later used to observe and sample subaqueous exposures in the depth range of 650–800 m (Bogdanov and Zonenshain, 1991) (Fig. 2). These visual explorations found that the R_1 reflector corresponds to the boundary between a unit of gray lithified sandstones and an overlying unit of semi-compact gray, thin-bedded clays with a characteristic cavernous surface (the origin of these irregular caverns 1–2–10 cm in diameter is not known). The sandstones consist of rounded to sub-rounded grains of quartz and feldspar cemented by carbonates, and palynological analysis suggested that the age of this unit is early Miocene (Bogdanov and Zonenshain, 1991). The age of the overlying cavernous clay unit was determined as mid-late Miocene based on a rich pollen assemblage. This unit is thought to be of regional importance because similar clays have been observed during submersible dives along underwater escarpments of Academician Ridge and Ushkanie Islands (Fig. 1), and at the underwater southern extension of Svyatoi Nos Peninsula, where the thickness of the cavernous clay unit reaches 300 m (Zonenshain et al., 1991). These authors stressed the importance of the observation that cavernous clays overlay crystalline basement on tectonic blocks in the southern part of the North Basin and of Academician Ridge, thereby indicating that this unit marks the major stage of tectonically induced

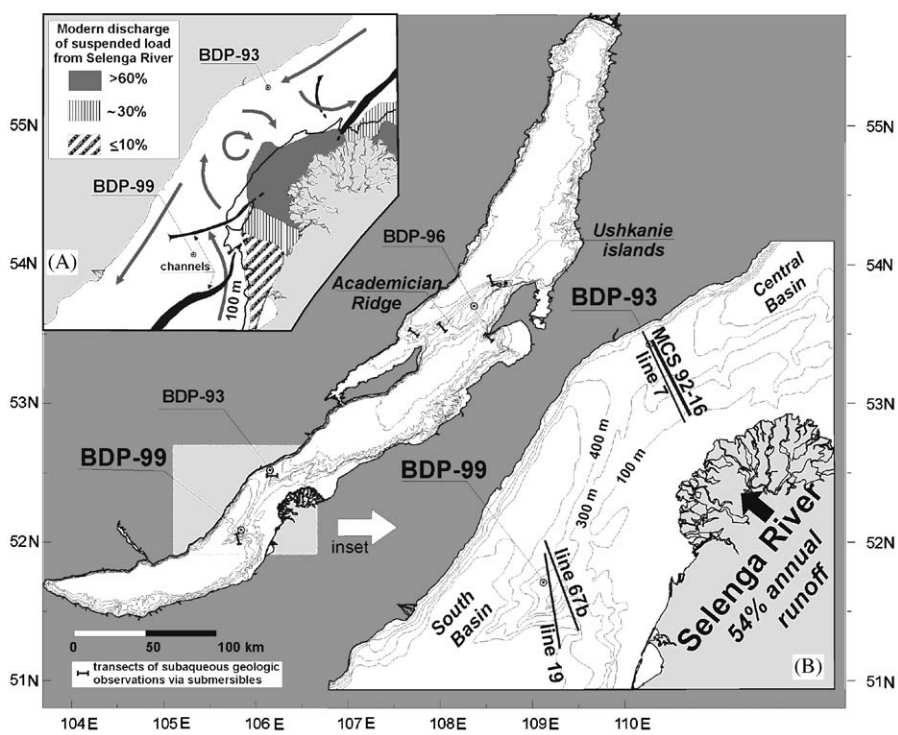


Fig. 1. Map of Lake Baikal showing locations of BDP drill sites and traverses of the subaqueous geological observations referred to in the text. Inset A shows the distribution of Selenga River suspended load in the vicinity of the delta (modified from Potemkina and Fialkov, 1993) in relation to surface currents shown by gray arrows (from Shimaraev et al., 1994). Black curved outlines show incised subaqueous channels and canyons (modified from Colman et al., 2003). Inset B: Enlarged portion of bathymetric map showing the location of drill cores and seismic profiles referred to in the text. Water-gun lines 19 (Fig. 2) and 67-B (Fig. 7) are from Colman et al. (1996). Water-gun line 7 (Fig. 7 in Colman et al., 2003) and multi-channel line 92-16 (Fig. 5 in Scholz and Hutchinson, 2000) were used by respective authors to discuss the morphology of the uppermost 'draped unit' and several deltaic progradational packages on Selenga Delta slope.

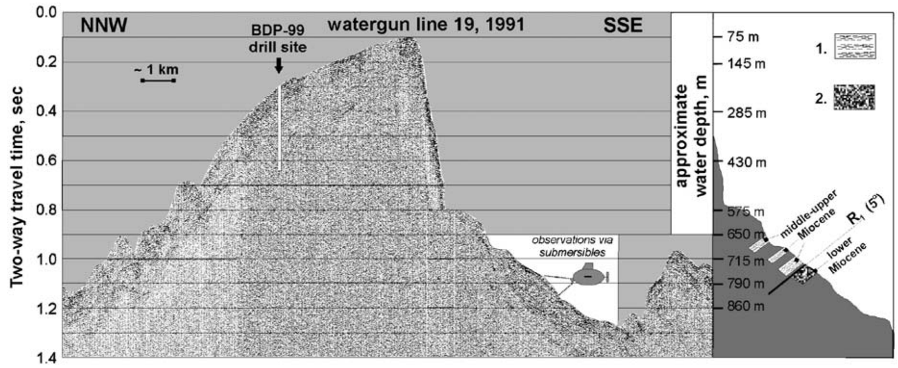


Fig. 2. Water-gun line 19 (Colman et al., 1996) showing the overall morphology of the tilted tectonic block of Posolskaya Bank and the projected location of the BDP-99 drill core. The results of observations via submersibles suggest that the major regional unconformity R_1 marking the increased subsidence throughout Baikal rift (Bogdanov and Zonenshain, 1991; Zonenshain et al., 1991, 1993) is observed at the base of Posolskaya Bank (see text). Lithology of the subaqueous exposures in the upper right: 1—cavernous clays; 2—carbonate-cemented sandstones.

transgression in the Baikal rift during the late Miocene (Zonenshain et al., 1991, 1993).

1.2. Quaternary deposition changes in the Selenga Delta area and at Posolskaya Bank

The Selenga Delta, possibly the largest freshwater delta in the world, is considered a dramatic example of tectonic control on deltaic sedimentation (Scholz and Hutchinson, 2000; Colman et al., 2003). The Delta is constructed atop several elevated tectonic blocks that form the accommodation zone between the Southern and Central Basins of the Baikal rift. Posolskaya Bank is one of these elevated blocks in the southwestern part of Selenga Delta area (Fig. 1). Previous interpretations of multichannel (Scholz and Hutchinson, 2000) and water-gun (Colman et al., 2003) seismic profiles have suggested that the present-day mode of sedimentation in the entire Selenga Delta area including Posolskaya Bank is a recent Quaternary development.

For example, Scholz and Hutchinson (2000) concluded that the interval of the past 2 Ma represents an active rifting stage with significant vertical movements on the order of hundreds of meters, representing a dramatic change in the depositional style of the Selenga area. Their preliminary age model has served as a reference frame for evaluating timing of Plio-Pleistocene tectonic events in the Selenga area. For instance, they estimated that initiation of increased relief of Posolskaya Bank and the associated thickening of the sedimentary strata in Selenga Basin could have occurred ca. 1.7–1.4 Ma, and estimated the age of the pronounced D2_b erosional surface as ca. 1.12 Ma.

Colman et al. (2003) concluded that deposition of fine hemipelagic mud of the uppermost 'draped unit' 100 ± 20 m thick (represented by a set of continuous high-amplitude reflectors throughout Selenga area) was initiated at ca. 650 ka. Since that time, Lake Baikal may be considered a hydrologically overfilled basin, even in the vicinity of this major delta. Underneath the 'draped unit' there are series of stacked delta clinoforms (Scholz and Hutchinson, 2000). Starting at ca. 650 ka, subsidence far outstripped sedimentation and as a result the present extreme depths of the South and Central Basins of the Baikal rift are rather unusual in the context of its history (Colman et al., 2003). In this contribution we use the new data from BDP-99 drill core section to shed new light on these prior observations.

1.3. Modern sedimentation in the Selenga Delta area and at Posolskaya Bank

The spatial pattern of the suspended load discharge from the Selenga River (% of the total) largely mimics the contour of the 100-m isobath and in addition to being affected by currents (Fig. 1, inset A). As much as 84% of annual total suspended load is discharged during April–May (Potemkina and Failkov, 1993). A system of troughs on the delta slope (Fig. 1, inset A) has formed along the upslope-facing tectonic scarps and presently channels coarse material to deep parts of the Central and Southern Basins (Colman et al., 2003). Presently, Posolskaya Bank is separated from the delta slope by a trough and located beyond the zone directly affected by Selenga riverine sediment load (Fig. 1 inset A). The Bank is characterized by quiet hemipelagic sedimentation as suggested by continuous high-amplitude reflectors of the 'draped unit' (Colman et al., 2003). Modern delta is distinctly 'offset' to the northeast relative to the contour of the 100-m isobath (Fig. 1). Consistent with this observation, sedimentation rate estimates from the BDP-99 drill core discussed below suggest that riverine suspended load was supplied at a much higher rate into the southwestern sector of the delta during the middle Pleistocene.

2. Investigations

2.1. BDP-99 drilling operations

The BDP-99 drill core was intended to penetrate the boundaries of several packages visible in the seismic profiles of Selenga area (Scholz and Hutchinson, 2000; Colman et al., 2003) and to provide new Pleistocene high-resolution paleoclimate proxy records from the sedimentary environment influenced by the major tributary of Lake Baikal. Previously, the first Lake Baikal 100-m drill core from the Selenga Delta area (BDP-93) fell short of penetrating the Brunhes/Matuyama paleomagnetic reversal boundary (BDP-Members, 1997). A much longer drill hole was therefore planned for Posolskaya Bank site. Drilling took place from 28/01/1999 to 8/03/1999 using the drilling complex "Nedra-Baikal-2000" mounted on a barge, which was frozen into the ice with the support ship *R/V Baikal* at 52°05′23″ N and 105°15′24″ E in 201 m water depth. Two continuous drill cores, BDP-99-1 (0–113.3 m subbottom) and BDP-99-2 (109–251.9 m subbottom) were retrieved at the site, and the drilling continued for test purposes to 350.5 m subbottom with discontinuous sampling (e.g., Fig. 4). Hydraulic piston coring was used down to borehole depths of 151.9 m, and rotary coring was used below. Core BDP-99-2 was drilled using a riser and untreated bentonite drilling mud. Core BDP-99-1 was drilled without a riser using lake water as a drilling fluid (Fig. 3).

2.2. Materials and methods

After being stored at 4 °C in the BDP core repository, cores were split longitudinally, described and sampled for water content and smear slide observations. Water content was measured on 3 cm^3 samples at 10-cm resolution as a weight loss after drying at 60 °C (total 2079 samples). Magnetic susceptibility was measured on 1223 samples at an average sampling step of 20 cm. Magnetic inclination measurements were performed on 656 samples using a JR-4 magnetometer after demagnetization at 5, 10 and 20 mT. The abundance of diatoms, clay, silt and sand particles was estimated semi-quantitatively in temporary smear-slides by comparing observations made by light microscopy with visual percentage comparison charts (Terry and Chilingar, 1955; Scholle, 1979). γ-ray logging was performed after the completion of the drilling in light-alloy drill pipe due to difficulties in passing the tool in open holes.

2.3. Lithologic composition

The BDP-99 drill cores recovered a section of fine hemipelagic sediments, composed mostly of clay (on average, 50–80% volume according to semi-quantitative observations in temporary smear slides) and 20–40% silt (Fig. 4A). In the upper 85 m, diatom frustules found in the intervals with elevated silt content also comprise a significant portion of sediment volume, up to 20–50% (Fig. 4A).

The elevated content of fine, usually poorly rounded sand is found either (1) in the form of flattened lenses (few mm to few cm long) along with scattered granules and pebbles (Fig. 4B), or (2) in the form of laminae (up to several cm thick) associated with lithological transitions (Fig. 4B). In the first case, observations of abundant lenses of poorly sorted silt-sand material may be attributed to ice- and iceberg-rafting modes of transport (BDP-Members, 1998; Karabanov et al., 1998). In the second case sand laminae usually have uneven lower boundaries and are associated with erosional contacts (discussed in Section 2.7).

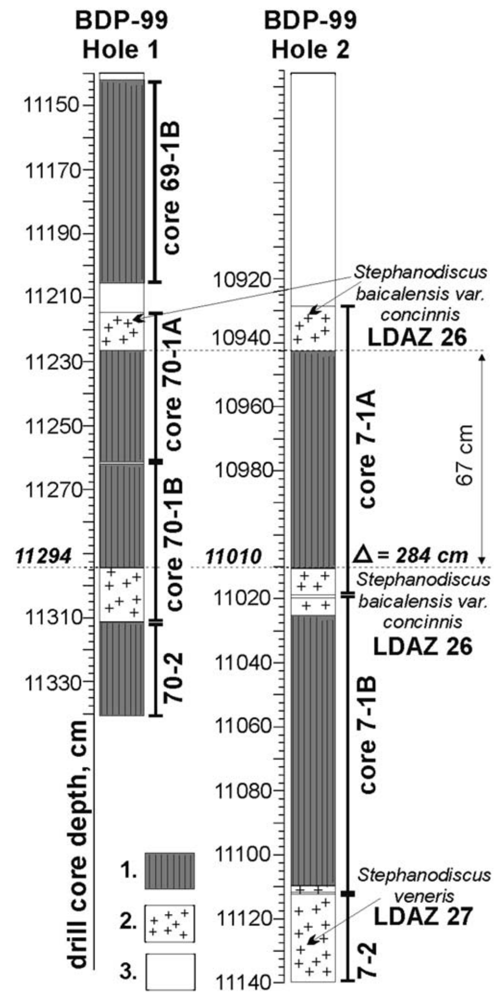


Fig. 3. Recognition of the equivalent diatom biostratigraphic (Khursevich et al., 2005) and lithologic intervals in BDP-99-1 and BDP-99-2 twin drill cores allows an accurate splicing of these cores into a composite record by adding 284 cm to the slurry-adjusted absolute depths of BDP-99-2 drill core. Legend: 1—diatom-barren silty clay; 2—silty clay with diatoms; 3—core gap.

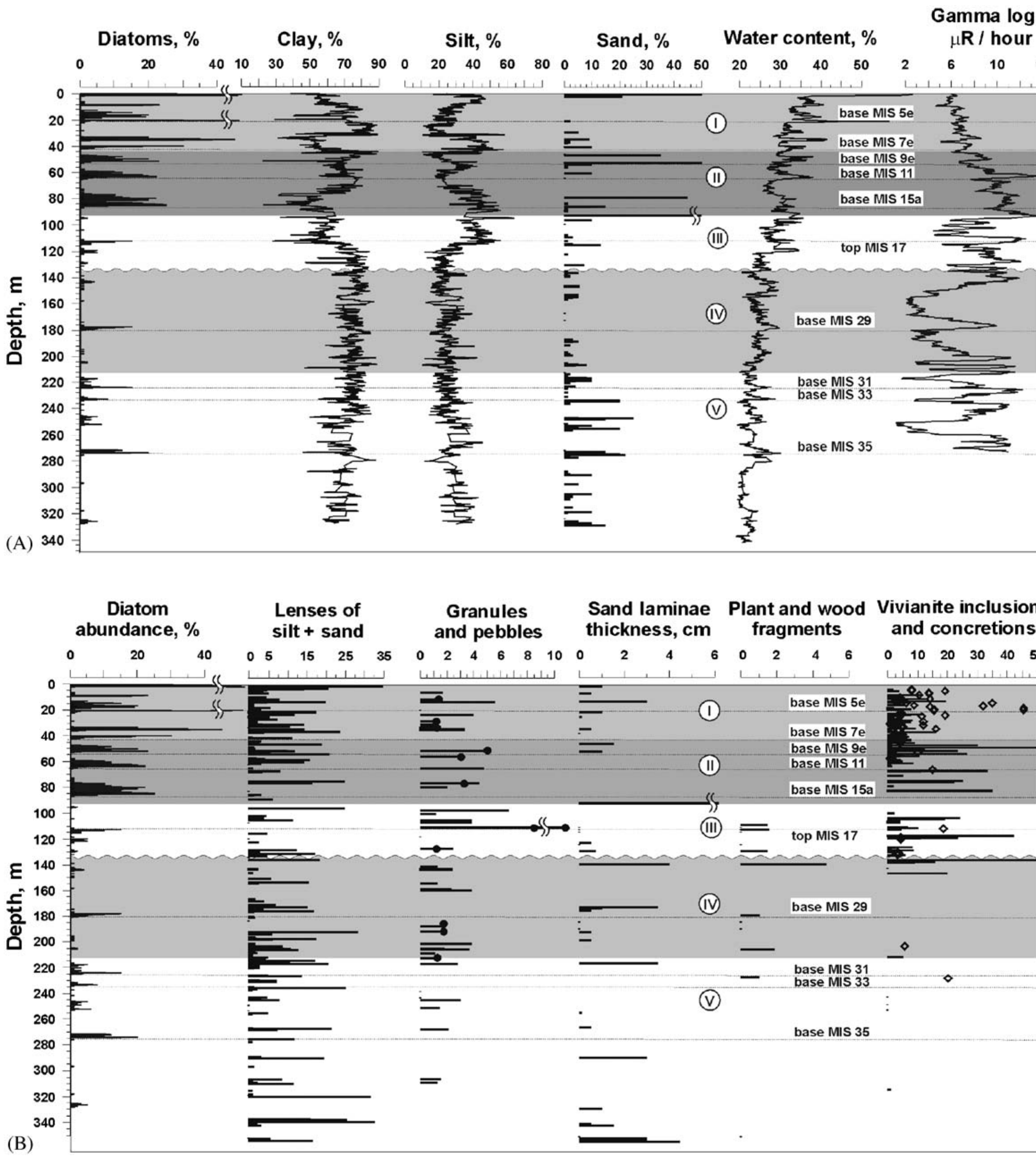


Fig. 4. (A,B) Lithological composition and physical properties of the BDP-99 composite section. Wavy line indicates a major disconformity at ca. 134 m core depth. Shading and Roman numerals correspond to a number of packages identified in Posolskaya Bank seismic profile (see Fig. 7 and text below). Also shown are the intervals equivalent to Marine Oxygen Isotope stages (MIS) based on Baikal diatom biostratigraphy.
Diatom abundance and clastic components are given as semi-quantitative estimates of volumetric percent from smear slide observations (% grains). The number of lenses and inclusions are given as semi-quantitative estimates based on the number of occurrences per 1 m-long section, as observed at the surface of the split core.

From the distribution of main clastic and biogenic components in Fig. 4, three broad intervals corresponding to specific types of sedimentation processes can be distinguished in the BDP-99 composite section. The upper 85-m interval is characterized by regular alternation of (a) layers of diatomaceous silty clay (at some intervals clayey silt) containing fragments of siliceous sponge spicules and (b) layers of diatom-barren silty clay containing silt-sand lenses and scattered granules and pebbles. This type of alternation of two characteristic lithologies represents respective changes of biogenic and clastic sediment fluxes in response to alternating glacial and interglacial periods during the Pleistocene, as previously observed in BDP-93, BDP-96, BDP-98 drill cores (BDP-Members, 1997, 1998, 2001[1]) and in multiple piston cores (e.g., Colman et al., 1994; Karabanov et

[1]Due to a typesetting error, this publication on behalf of the BDP-98 Baikal Drilling Project Members is often referred to as Antipin et al. (2001). The correct reference is BDP-Members, 2001.

al., 1998) from Lake Baikal. The peaks of water content are correlative with diatom abundance peaks reflecting higher porosity of layers containing diatom frustules. Below 85 m, diatoms are no longer a major component of sediments and diatomaceous intervals are few and rather thin (Fig. 4A). The opposite trends in average water content and in borehole γ-log values in the upper 85 m interval reflect sediment compaction (Fig. 4A). Similar to the Pleistocene sediments of previous BDP drill cores (BDP-Members, 1997, 1998, 2001[1]), the upper 85-m interval of BDP-99 contains abundant powdery inclusions of vivianite and vivianite concretions, most often found associated with burrows and other bioturbation structures (few mm to several cm long) (Fig. 4B).

The interval ca. 140–230 m underlying the major disconformity in BDP-99 section (BDP-Members, 2004; Khursevich et al., 2005) consists of remarkably uniform silty clay with the highest average clay content and the lowest average sand content (Fig. 4A), although the abundance of lenses of silt with sand remains essentially uniform throughout the BDP-99 section (Fig. 4B). Vivianite inclusions are virtually absent in this ca. 90-m interval (Fig. 4B). Water content shows little variation, whereas borehole γ-log exhibits dramatic changes, which apparently cannot be explained by changes in clastic component in this uniform interval (Fig. 4A). Most likely, the observed γ changes are reflective of changes in allochthonous organic matter content in sediments. Below ca. 230 m, the average content of the coarse fraction (both silt and sand) increases and the sediment is no longer as uniform as in the overlying interval (Fig. 4A).

The interval 140–85 m represents a transition from uniform fine silty clay to the typical variable glacial/interglacial Baikal lithologies of the upper 85–0 m interval. The average silt content (Fig. 4A), the amount of scattered ice-rafted coarse detritus and the amount of vivianite inclusions (Fig. 4B) all increase over this transitional interval.

2.4. Textures and sediment color

Throughout most of the BDP-99 section, the sediment is structureless, with the exception of intervals with faint lamination observed due to the distribution of hydrotroilite laminae and mottles. Laminated and sometimes finely laminated (e.g., Fig. 8) intervals on the order of tens of centimeters thick are occasionally found within longer (several meters thick) glacial diatom-barren intervals in the upper 100-m section of BDP-99. Intervals with a lens-like texture are quite rare, too. Usually, these intervals are several centimeters thick. Individual lenses few millimeter long are visible from slight color changes, but they are not associated with lithological contrasts and possibly reflect the effect of bioturbation. In the BDP-96 and BDP-98 drill cores from Academician Ridge (BDP-Members, 1998, 2001), intervals with faint lamination and lens texture were more abundant than in BDP-99. Only at the very bottom of the BDP-99 section around 350 m drill core depth does the typical massive texture change to bedded texture, evident from the readily seen color changes and from regular occurrences of laminae of fine poorly rounded sand 1–4 cm thick with even parallel boundaries (e.g., Fig. 5K).

On average, the BDP-99 sediments at Posolskaya Bank are darker and have a distinct olive hue as compared with sediments in the corresponding intervals of BDP-96 and BDP-98 at Academician Ridge (BDP-Members, 2001), where typical sediment colors are lighter greenish gray to olive gray (2.5–10 GY 4-5/1). In the upper 44 m of the BDP-99 section, the color usually varies from olive gray to olive black in diatomaceous layers (5Y-7.5Y 3/1) and from gray to olive black (10 Y 4/1-7.5 Y 3/1) in glacial layers. In the interval 44–94 m sediments with lighter gray to dark olive gray colors (10 Y 3-4/1) are no longer observed, with the exception of core 46-1B. At 94–109, 152–166, and 178–185 m drill core depth lighter gray colors reappear at certain intervals. This pattern is unlikely to be random, as suggested by comparison with other proxy signals in Section 2.6.

2.5. Age model and sedimentation rate estimates

The results of diatom biostratigraphic analysis of BDP-99 compared with preliminary paleomagnetic inclination measurements allow a reliable age model to be constructed for the BDP-99 composite section as discussed by Khursevich et al. (2005) (Fig. 6). Here we discuss changes in estimated sedimentation rates based on correlation of BDP-99 with the BDP-96 holostratotype section, for which an orbitally tuned age model is available (Prokopenko et al., 2001a). Sedimentation rate estimates for BDP-99 were calculated using the depths of recognized diatomaceous interglacial intervals in BDP-99 divided by the estimated age of the respective biostratigraphic boundaries in the BDP-96 holostratotype section (Khursevich et al., 2001, 2005), without adjustments for sediment compaction (Fig. 6).

Unlike in BDP-96 or in other sediment cores from Academician Ridge, there appears to be a clear difference between ‘glacial’ and ‘interglacial’ sedimentation rates in BDP-99 drill core due to the site’s proximity to the Selenga riverine sediment source. The interglacial (and interstadial, e.g., MIS 5a, 5c, etc.) rates remained quite similar at 5–14 cm/ka throughout the recovered section (Fig. 6). This observation is true for all interglacials of the Brunhes chron, and also for two interglacial intervals recognized in the lower part of the BDP-99 drill core, correlative with MIS 31 and MIS 33

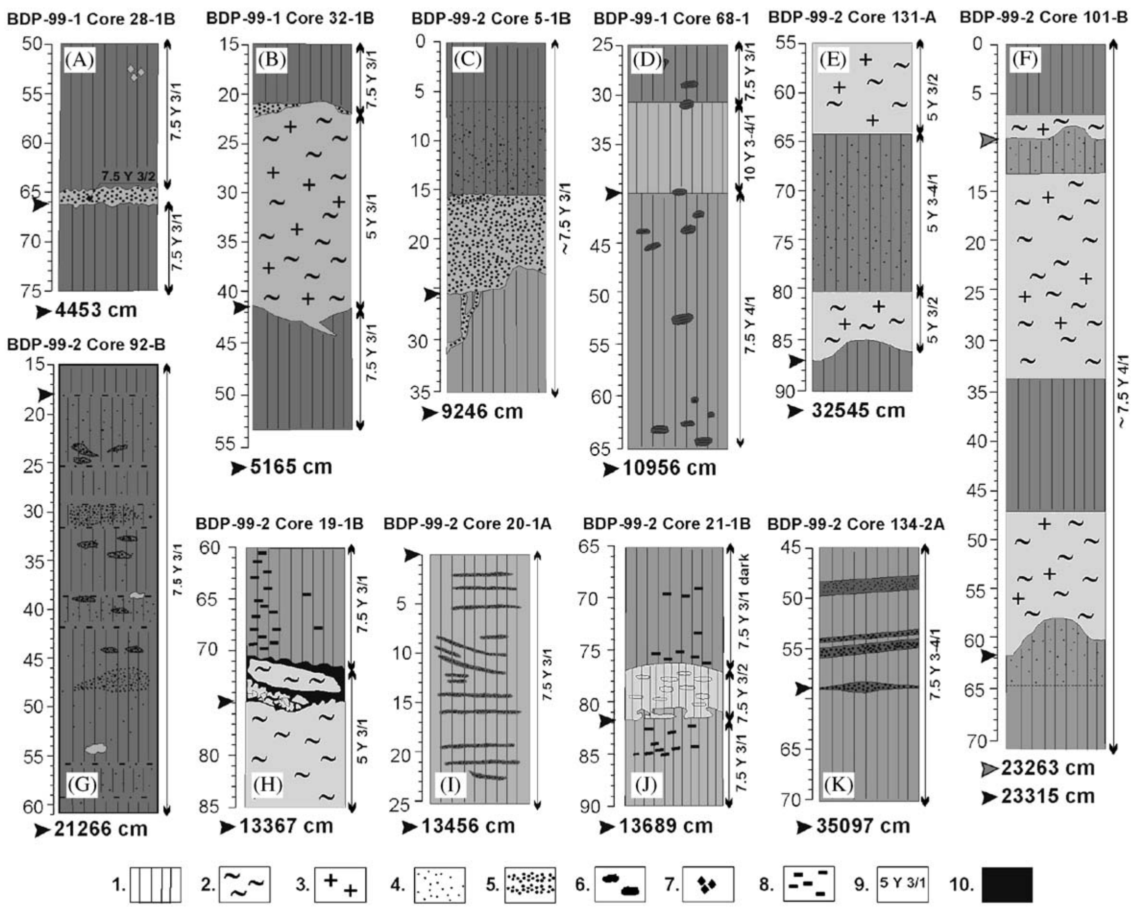


Fig. 5. (A–K) Erosional contacts and the most peculiar lithological changes observed in the BDP-99 section. Vertical scale gives relative depth in each of the sections; marked arrows correspond to absolute composite drill core depth for each of the selected horizons. Legend: 1—silty clay; 2—very silty clay/clayey silt; 3—diatom frustules; 4—dispersed medium to coarse silt; 5—sand; 6—sub-angular and sub-rounded fragments of pebble size; 7—vivianite inclusions; 8—hydrotroilite mottles; 9—sediment color; 10—core gaps.

(Khursevich et al., 2005). By contrast, glacial rates are higher by factors of at least 2–3 (Table 1).

Glacial (and therefore average) sedimentation rates grew progressively lower throughout the depositional history of the section penetrated by BDP-99 drill core on Posolskaya Bank (Table 1). During the period from 1.2 to 1.05 Ma, average glacial sedimentation rates increased from 40–44 cm/ka to 67 cm/ka (Fig. 6). The highest sedimentation rates are observed within the age interval 1.05–1.0 Ma during Jaramillo subchron, reaching as high as 170 cm/ka during MIS 30 interval and then decreasing slightly to 115 cm/ka during the interval equivalent to MIS 28 (Table 1 and Fig. 6).

During the Brunhes chron, glacial sedimentation rates at Posolskaya Bank reduced from 77 cm/ka at the base of the Brunhes chron to 33 cm/ka during MIS 16 interval, and further to 27–17 cm/ka during MIS 12, 10, 8 and MIS 2–4 (Fig. 6). One exception from this consistent trend is MIS 7d glacial substage: it appears that during this glaciation sedimentation rates could have been about 2 times higher than during MIS 2-4, MIS 6 and MIS 8 glacial periods (Table 1 and Fig. 6).

2.6. Rock-magnetic properties and drill hole γ-log

Previously in BDP-96 and BDP-98, a clear cyclic glacial/interglacial signal of dilution with biogenic silica was observed in magnetic susceptibility profiles throughout the Pleistocene sections (BDP-Members, 2001). In BDP-99, however, it is difficult to trace the equivalent pattern and recognize individual glacial and interglacial stages in the magnetic susceptibility profile. A first order comparison of the γ-log with magnetic susceptibility shows a general counter-phase relationship, consistent with the expectation of higher γ and lower susceptibility values in interglacial intervals, characterized by higher contents of sedimentary organic matter (Fig. 6). Within the Brunhes chron in BDP-99, this inverse relationship is particularly evident for the MIS 11 interval (Fig. 6). Below 90 m core depth in BDP-99, several intervals marked by broad lows in gamma are matched by

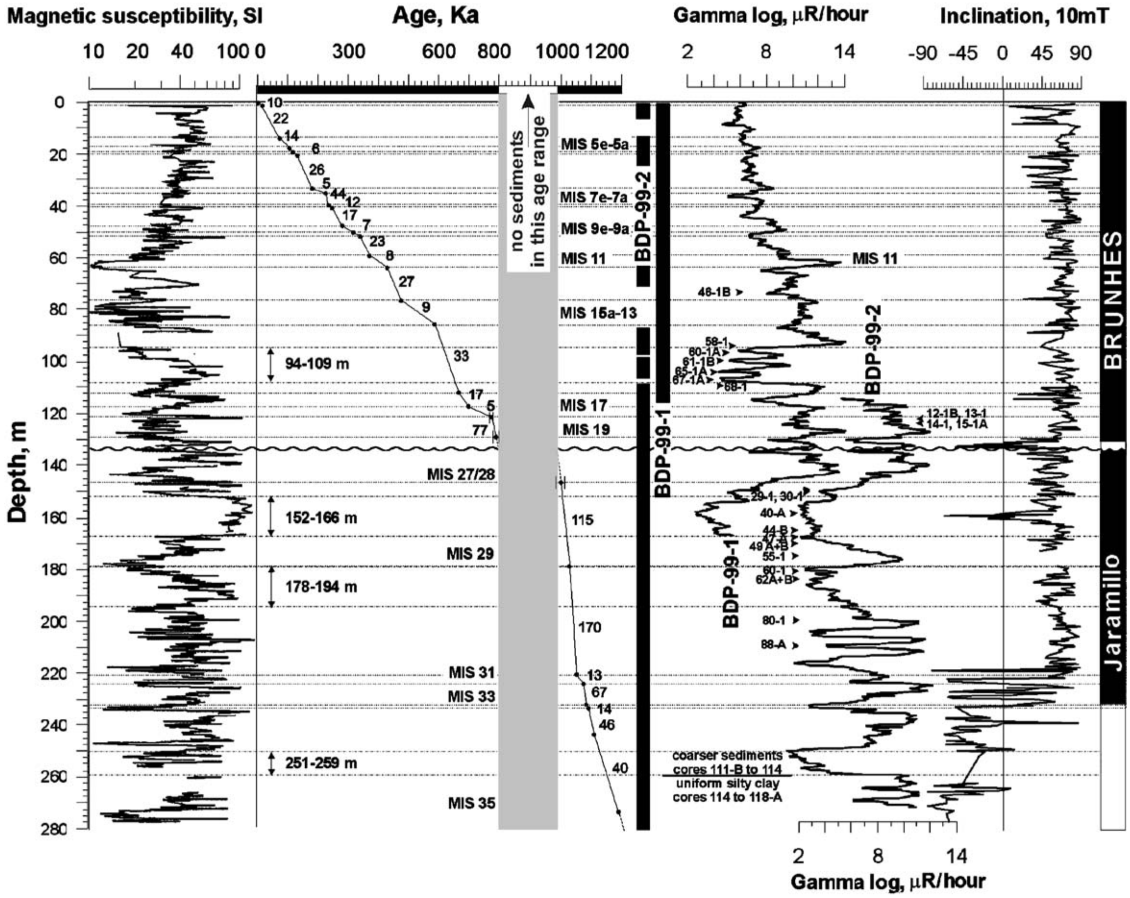


Fig. 6. The composite BDP-99 magnetic susceptibility profile and γ-log profiles of twin BDP-99 drill holes compared with the age–depth relationship based on diatom biostratigraphy (Khursevich et al., 2005) and preliminary paleomagnetic inclination record. The slope of the lines connecting the age/depth tie points (identified as intervals correlative with marine oxygen isotope stages, MIS 5–33) reflects changes in sedimentation rates given as cm/ka for each pair of tie points (Section 2.5 in the text).
Labeled arrow symbols next to γ-log profiles of BDP-99-1 and BDP-99-2 indicate core sections in respective drill holes in which distinctly lighter sediment color (10Y 3-4/1) was observed (Section 2.4 in the text).

sustained maxima in magnetic susceptibility, all corresponding to glacials. For instance, a broad low in gamma values matching high susceptibility is observed between 94 and 109 m core depth in BDP-99, correlative with the MIS 16 glacial interval. Similar γ lows concurrent with susceptibility peaks at 152–166 m and 178–194 m are correlative with parts of MIS 28 and MIS 30 glacial intervals (Fig. 6).

It is possible that the distinct signatures in the rock-magnetic and natural radioactivity signals in these three broad intervals are the result of interplay between the provenance of the clastic material and particularly rapid sedimentation at Posolskaya Bank. Although rather speculative, this assumption appears to be consistent with estimates of sedimentation rates based on transposing age-depth tie points onto the water-gun profile at the drill site (Figs. 6 and 7). Also, the observed relationship between the two lithological indices appears to match to a certain extent sediment color changes. For example, in the interval of ca. 94–190 m, where the average content of the coarse fraction (sand) is the lowest (Fig. 4A), lighter color appears to be associated with low γ values. Somewhat lighter-gray and therefore distinct intervals (10 Y 3-4/1) in several cores (58–68) between 94 and 119 m core depth also appears to match the lows in γ profiles (Fig. 6). Similar observations appear true for the interval 150–166 m, and 178–185 m (Fig. 6). Below 190 m core depth, this relationship is no longer evident, and intervals with lighter color hue (10 Y 3-4/1) are no longer found below core 88-A (Fig. 6).

Below 190 m core depth, dramatic oscillations in γ-log profile appear to be related to changes in lithology. For instance, γ low at 251–259 m corresponds to the interval with contrasting lithology is an elevated sand-silt content in cores 111-B to 114. High γ values just below this interval correspond to a more uniform interval of finer silty clay in cores 114 through 118-A (Fig. 6).

Table 1
BDP-99 composite section sedimentation rate estimates based on correlation of Lake Baikal diatom stratigraphy with marine oxygen isotope timescale (Khursevich et al., 2001, 2005)

Core #	interval (cm)	Absolute drill core depth (cm)	Stratigraphic boundary	Age (ka)	Sed. rate (cm/ka)
BDP-99-1					
Top		~−15	—	0	—
1-1B	58	125	~Bolling	14	*10*
10-1B	60	1361	Top MIS 5a	71	22
13-1A	60	1833	Base MIS 5c	104	*14*
14-1A	50	1934	Top MIS 5e	115	*9*
14-2	11	2024	Base MIS 5e	130	*6*
21-1B	32	3306	Top MIS 7a	179	26
22-1B	33	3533	Base MIS 7c	225	*5*
25-1A	85	3931	Top MIS 7e	234	44
25-2	26	4048	Base MIS 7e	244	*12*
29-1B	60	4658	Top MIS 9a	279	17
31-2	20	5001	Base MIS 9c	315	*10*
32-1B	43	5168	Base MIS 9e	338	*7*
36-1B	19	5887	Top MIS 11	369	23
38-2	23	6363	Base MIS 11	427	*8*
48-1B	19	7613	Top MIS 13	474	27
52-1C	20	8582	base MIS 15a	584	*9*
70-1A	10	11214	Top MIS 17	664	33
BDP-99-2					
10-1B	50	11806	Mid-MIS 17	698	17
12-1B	47	12163	Upper MIS 19	~770	5
16-1C	50	12936	Base MIS 19	~780	77
25-1A	0	14276	~Base MIS 27	~1000	6
58-1	71	17953	Base MIS 29	1032	115
95-C	33	22193	Top MIS 31	1057	170
96-B	95	22422	Base MIS 31	1075	*13*
101-A	40	23223	Top MIS 33	1087	67
101-C	10	23334	Base MIS 33	1095	*14*
108-C	20	24586	~Top MIS 35	1122	46
118-B	95	27450	~Base MIS 35	1194	40

The systematic difference between 'interglacial' (italicized) and 'glacial' rates is emphasized by alignment.

2.7. *Sedimentary structures and erosional boundaries*

A number of erosional contacts are observed in the BDP-99 section. Usually, erosional boundaries are found within diatom-barren glacial intervals (Fig. 5A,C and J), or at the transitions from diatom-barren clay to diatomaceous silt (Fig. 5B,E and F). This pattern suggests that higher and perhaps less steady supplies of suspended load during glacial intervals resulted in more active down slope movement of sediments on Posolskaya Bank. At the top of diatomaceous intervals, gradual transitions into overlying layers of silty clay are usually observed (Fig. 5E and F). One exception to this general rule is BDP-99-1 core 32-1B (Fig. 5B), where a diatomaceous layer equivalent to the MIS 9e interglacial interval (Khursevich et al., 2005) is capped by an erosional surface accentuated by lenses of silt with an admixture of poorly rounded sand. A somewhat similar uneven boundary is found in the upper part of the MIS 5e diatomaceous layer identified in BDP-99-1 core 14-1B.

Unlike in deep basins of Lake Baikal, where turbidites are abundant (Nelson et al., 1999; Colman et al., 2003), none of the most evident in erosional contacts in BDP-99 (Fig. 5) shows clear graded bedding indicative of turbidite deposition at Posolskaya Bank. The most distinct erosional contact associated with the thickest sand layer in the entire 350-m long drilled section is observed at 9246 cm in BDP-99-2 core 5-1B (Fig. 5C). The 10-cm thick layer of fine poorly rounded sand with sponge spicules is overlain by a 9-cm layer of silty clay with dispersed sand, yet it is not evident whether this lithological change represents gradational bedding of a turbidite.

A peculiar lithological signature was found in BDP-99-2 core 20-1A, where a series of slightly curved sub-parallel laminae enriched in silt is observed (Fig. 5 I). These structures resemble ripple marks produced by deep-water currents and are unlikely to have been produced by turbidity flows. These structures possibly indicate an interval of slowed down sediment deposition at Posolskaya Bank.

The BDP-99-2 core 92-B (Fig. 5G) is particularly enriched in coarse material (silt and sub-angular to poorly rounded sand) as lens-shaped pockets apparently too big to be produced by ice rafting. It is possible that erosion played a role in formation of these structures.

3. Discussion

3.1. *The structure of Quaternary sedimentary cover at Posolskaya Bank*

Located about 3 km NE from the BDP-99 drill site, the acoustic reflection data of water-gun line 67-B (Colman et al., 1996) allow the lithological and sedimentation changes at BDP-99 to be placed into the context of the depositional history of Selenga Delta area. The resolution of acoustic signal in this profile is better than in the nearby profile 19 (Fig. 1). Although not of a particularly high quality, line 67-B reveals the morphology of several stacked sediment packages gently sloping northwestward off the top of Posolskaya Bank (Fig. 7). In order to better show changes in the fabric of sedimentary strata at Posolskaya Bank, we traced individual reflectors to arrive at a rough interpretation of this seismic profile (Fig. 7).

The general morphology of the traced acoustic reflectors in Fig. 7 suggests at least five major sequences in line 67-B. On the mid- to lower slopes of the bank, the upper sequence I is characterized by strong, regular, parallel high-amplitude reflections, which appear to be

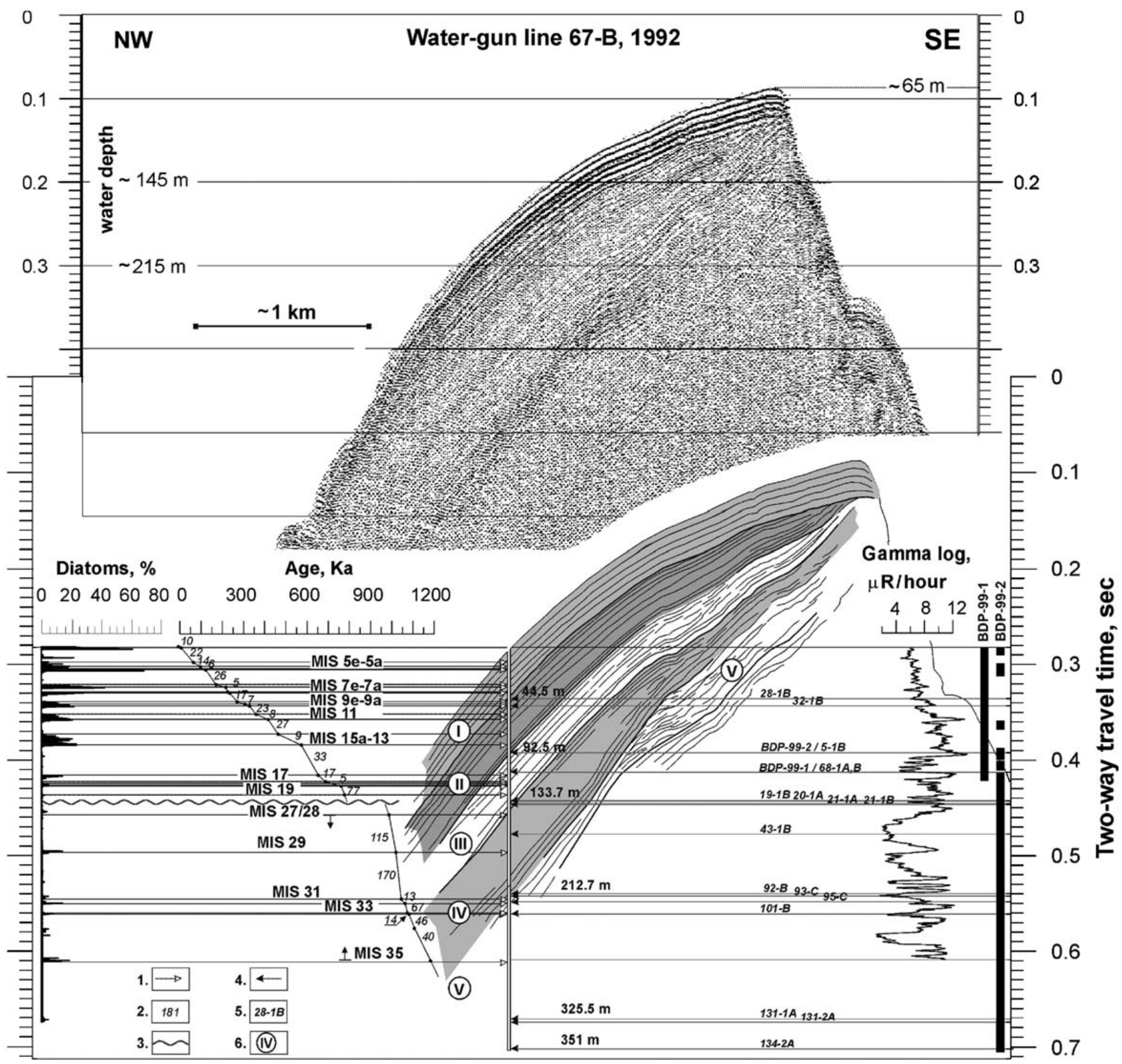


Fig. 7. Water-gun line 67-B (Colman et al., 1996) (top panel), and an interpretation of the sequence morphology of Posolskaya Bank based on tracing acoustic reflectors (bottom panel). Sequences I through V are identified from changing character of acoustic signal and from more or less evident erosional truncation boundaries. Projected onto the interpreted line 67-B are: the location of BDP-99 drill core; the age/depth tie points with respective estimates of sedimentation rates; erosional boundaries and other lithologic contrasts (Fig. 5 and section 2.6 in the text); composite BDP-99 γ-log; and vertical bars indicating approximate core recovery in each of the drill holes.
Combined sequences I and II and Posolskaya Bank correspond to the 'draped unit' of Colman et al. (2003), whereas sequences III and IV appear to correspond to packages D1 and D2 of Scholz and Hutchinson (2000) on Selenga Delta slope. The provisional boundary between sequences I and II is dated back to MIS 8.

conformable with those of the underlying sequence II. In the relatively shallow water near the top of the bank, reverberations from a strong bottom reflection mask the internal character of sequence I and its relation to sequence II. Therefore, the acoustic boundary between sequences I and II is tentative since it is not clear if overlapping acoustic reflections truly reveal erosional truncation towards the top of the Posolskaya Bank (Fig. 7).

Sequence II is also characterized by parallel reflectors, although not as distinct as in sequence I. The lower boundary of sequence II is provisionally traced along the reflector that appears to represent another erosional truncation boundary near the top of Posolskaya Bank (Fig. 7). This boundary also separates the overlying set of continuous high amplitude reflectors from the underlying interval with poorly resolved acoustic signals likely indicative of a rather uniform sediment composition. In the middle of this uniform interval, a pair of reflectors traceable almost to the top of Posolskaya Bank stands out in amplitude. This acoustic signal in line 67-B is chosen as a boundary between sequences III and IV (Fig. 7). It appears that reflectors at the top of sequence IV tend to 'pinch out' when traced down slope, suggesting possible erosional truncation and thereby reinforcing this choice of sequence boundary (Fig. 7).

Finally, a wedge-shaped set of strong discontinuous reflectors with a clear erosional truncation upper boundary can be distinguished as sequence V at 0.3–0.4 s two-way travel time (Fig. 7). Because of poor resolution of the acoustic signal below 0.4 s, however, it is difficult to trace this boundary down the slope of Posolskaya Bank and to observe the structure of this sequence (Fig. 7).

3.2. Sequence boundaries at Posolskaya Bank and erosional contacts in BDP-99

In this section we discuss the implications of BDP-99 depositional changes in the context of previous interpretations of acoustic reflection data in the Selenga Delta area (Scholz and Hutchinson, 2000; Colman et al., 2003). In order to do so, we project the BDP-99 location and approximate length of the drilled section onto the water-gun line 67-B (Colman et al., 1996) using the acoustic velocities measured at Academician Ridge in BDP-98 drill hole (Pevzner et al., 1999; BDP-Members, 2001).

In order to test how biostratigraphic boundaries and erosional contacts identified in BDP-99 compare with acoustic sequences, we also projected the composite absolute core depth horizons corresponding to these boundaries onto the same water-gun line 67-B (Colman et al., 1996). To calculate the corresponding two-way time, we used acoustic velocities previously measured in Lake Baikal (Pevzner et al., 1999; see Fig. 3 in BDP-Members, 2001). According to prior estimates, velocities vary between 1650 and 1680 m/s in the Pleistocene section of BDP-98. We used the average value of 1665 m/s for BDP-99 and took into account that at Posolskaya Bank above the drill site acoustic waves traveled through 201 m of the water column at measured 1430 m/s. The maximum potential error of such estimates is quite tolerable, increasing from ± 0.5 m at 30 m core depth and ± 1 m at 55 m, to ± 2.4 m at 130 m and ± 6 m at 325 m at the base of BDP-99 section. The projected diatom biostratigraphy boundaries correspond to open arrowhead symbols to the left of the profile, and erosional contacts (shown in Fig. 5) are marked by solid arrowheads on the right (Fig. 7). To avoid bias in our qualitative analysis, in addition to the most prominent erosional contacts and textural changes summarized in Fig. 5, we also projected the positions of other 'suspicious' intervals with significant lithological changes onto the same profile (e.g., transitions from uniform silty clay to intervals with a significantly higher silt content) (Fig. 7).

Because of poor resolution of acoustic signal below 0.4–0.5 s two-way travel time in line 67-B, it is difficult to clearly trace the provisional boundary between units IV and V all the way down slope to the projected drill core section. In cores 92-B (215.44–215.54 m composite depth) through 95-C (222.28 m), series of contrasting lithological transitions are observed (Fig. 7), of which the sandy portion of 92-B (Fig. 5G) particularly stands out, yet it is not clear whether lithological change in this core can be identified as the base of sequence IV. According to diatom biostratigraphy, the base of sequence IV in BDP-99 lies somewhere around the MIS 31 and MIS 33 intervals (1.05–1.12 Ma), near the base of Jaramillo subchron (Fig. 7).

The top of sequence IV corresponds to the major disconformity in BDP-99, just below the Brunhes/Matuyama boundary, ca. 790–800 ka (Khursevich et al., 2005). There are at least three intervals indicative of sediment bypassing or erosion (Fig. 5H–J) projecting onto line 67-B close to this boundary (Fig. 7). The most likely candidate for this major erosional boundary in BDP-99 is the 133.67-m horizon in core 19-1B (Fig. 5H). According to smear-slide observations, two adjacent intervals in this core are not dramatically different in terms of lithology, yet a break and crumbling at the lithologic boundary in the middle of the otherwise continuous core is quite unusual for BDP-99 section and suggests significant density contrasts across this boundary.

The acoustic signal of sequence III overlying this major disconformity is characterized by a quite poor resolution. The top of this sequence may be assigned to a higher-amplitude reflector representing a truncation boundary towards the top of Posolskaya Bank (Fig. 7). When traced down slope, this boundary appears to intersect with BDP-99 drill hole at ca. 0.39 s two-way travel time. The only significant erosional contact projecting close to this intersection is the thickest 10-cm sand layer at 92.48 m in BDP-99-2 core 5-1B (Fig. 5C), and it is therefore logical to assume that it represents the top of sequence III at BDP-99 site (Fig. 7). This sand layer unfortunately was not recovered in twin drill hole BDP-99-1, where significant gaps 89.85–92.42 m and 92.56–93.84 m exist between cores 56 and 58.

A provisional boundary separating sequences II and I at Posolskaya Bank in line 67-B (Fig. 7) corresponds to MIS 8 interval according to diatom stratigraphy (Fig. 7). There are no dramatic lithologic signatures associated with this boundary except for the sand layer at 44.53 m in core 28-1B (Fig. 5A) projecting close to the intersection of this reflector with BDP-99 (Fig. 7). The lack of readily identifiable sharp lithologic contrasts supports the assumption that sequences II and I at Posolskaya Bank are generally conformable.

It is also possible that additional erosional boundaries, not clearly seen in acoustic reflection pattern of line 67-B, and/or not represented as sharp lithologic contrasts in the recovered drill core occur within these broadly defined five sequences. For instance, within sequences III, in the interval of silty clay from 10940 to

11010 cm (core 68-1, BDP-99-1) abundant fragments of poorly lithified claystone were found (Fig. 5D). Although stratigraphically this interval corresponds to the early part of glacial period equivalent to MIS 16 (Khursevich et al., 2005), these fragments may actually derive from the material eroded on top of Posolskaya Bank and not from ice/iceberg rafted detritus.

Missing local diatom zones are another indicator of potential erosion. In addition to the most evident disconformity between MIS 19 and MIS 27 (missing LDAZ 35-32 according to Khursevich et al., 2005), there seems to be another missing diatom zone in BDP-99 within the Brunhes chron. In the continuous type section BDP-96 there is a very distinct interval recognized as MIS 15e with high biogenic silica content and a very peculiar diatom assemblage of LDAZ 24 (Khursevich et al., 2001). We were not able to find the equivalent interval in BDP-99. It is possible, however, that this short interval was not recovered due to a significant drill core gap between BDP-99-1 cores 54 and 57.

As noted by Khursevich et al. (2005), the successive diatom zones LDAZ 28–30 corresponding to the interval from top MIS 19 to the middle of MIS 17 are 'squeezed' into a 254-cm thick interval, thereby producing an unusually low apparent average sedimentation rate of ca. 3.6 cm/ka. There are no evident erosional boundaries within this interval in BDP-99-2 (cores 11–13), yet it is possible that low sedimentation rates could result from sediment bypassing and/or erosion during the period equivalent to MIS 18-17.

3.3. Correlation of acoustic facies of Selenga Delta slope with BDP-99 drill core section at Posolskaya Bank

The new BDP-99 drill core section, three times longer than the BDP-93 section (BDP-Members, 1997) allows ground-truthing prior reconstructions of depositional changes discussed in Section 1.2 and testing the age models previously proposed for sequence boundaries based on extrapolation of radiocarbon age models of the last glacial–interglacial transition (Scholz and Hutchinson, 2000; Colman et al., 2003). To make this comparison we rely on the above projection of BDP-99 onto line 67-B and on the series of age tie points derived from diatom biostratigraphic zonation coupled with paleomagnetic inclination record (Khursevich et al., 2005) (Fig. 7).

As discussed in the previous section, the thickness of sequence IV at Posolskaya Bank may be estimated as 82–89 m corresponding to the time interval from 1.12–1.05 to 0.8–0.79 Ma. These age estimates are quite close to the age range between 1.12 and 0.75 Ma for the ca. 57-m thick delta sequence D2 identified by Scholz and Hutchinson (2000) on Selenga Delta slope. It is therefore possible that sequence IV in line 67-B at Posolskaya Bank (Fig. 7) is equivalent to the D2 sequence.

The overlying sequence III on Posolskaya Bank bounded by erosional contacts at 133.67 m (Fig. 5(H)) and 92.46 m (Fig. 5C) is about 41 m thick in the BDP-99 section and corresponds to the time interval from about the base of the Brunhes chron 800–790 ka to the glacial diatom-barren interval slightly older than the distinct MIS 15a-13 warm interval (Prokopenko et al., 2002), presumably to the upper part of MIS 16 or to MIS 15d, i.e., 650–600 ka. Scholz and Hutchinson (2000) identified a 42-m thick progradational package D1 on the Selenga Delta slope and traced the toplap boundary of this sequence across several seismic profiles to the 82-m depth in core BDP-93. Above this boundary lies a set of continuous high-amplitude reflectors representing the 'draped unit' as discussed by Colman et al. (2003). Age estimates for this boundary, inferred to mark a substantial increase in regional subsidence rates, vary from 450 ka by Scholz and Hutchinson (2000) to 650 ka by Colman et al. (2003). It seems apparent that sequence III at Posolskaya Bank (Fig. 7) is equivalent to the Selenga D1 package and that the boundary between sequences III and II correspond both morphologically and stratigraphically to the base of the 'draped unit'. The transition to more quiet hemipelagic sedimentation at the BDP-99 site appears to have occurred during MIS 17 (710–660 ka), as seen from a major inflection in the profile of estimated sedimentation rates (Figs. 6 and 7). The changes in average sedimentation rates in BDP-99 are therefore consistent with the 650-ka estimate of the basal age of the 'draped unit' (Colman et al., 2003). The thickness of the 'draped unit' estimated seismically at 100 ± 20 m is also in good agreement with the 92-m combined thickness of sequences II and I in BDP-99. Sequence I, corresponding to the continuous section deposited since MIS 7e through the Holocene, thickens upslope towards the top of the Bank (Fig. 7). This observation suggests that down slope movement of sediment was not as important in shaping the morphology of sequence I as was proximity to the source of suspended load.

3.4. Regional correlations of tectonic events

Depositional changes throughout Selenga Delta area appear to have been quite uniform, as seen from the close convergence of the prior age estimates based on extrapolating radiocarbon-based sedimentation rates to deeper sections of Selenga Delta and Buguldeika Saddle (Scholz and Hutchinson, 2000; Colman et al., 2003) with new observations from the BDP-99 drill cores. It is therefore reasonable to assume regional character of these tectonic events (rather than localized) and to attempt drawing comparisons with evidence outside the subaqueous Selenga Delta area. In this section we therefore briefly mention other regional tectonic changes that may have relevance to the new observations from BDP-99.

Previous studies have shown that the Primorsky phase of tectonic activity resulted in rupturing the runoff channel of the Baikal drainage to the Lena River (Logatchev et al., 1974) and established a new drainage system to the Yenisei River system at ca. 0.8 Ma (Mats, 1993). The major disconformity boundary in BDP-99 has about the same estimated age (Fig. 6; also, Khursevich et al., 2005). The progressive change in sequence geometries throughout Selenga Delta area as a result of enhanced vertical movements (Scholz and Hutchinson, 2000; Colman et al., 2003), and the progressive changes in sedimentation rates at BDP-99 are consistent with the previous age estimates for the Primorsky tectonic phase.

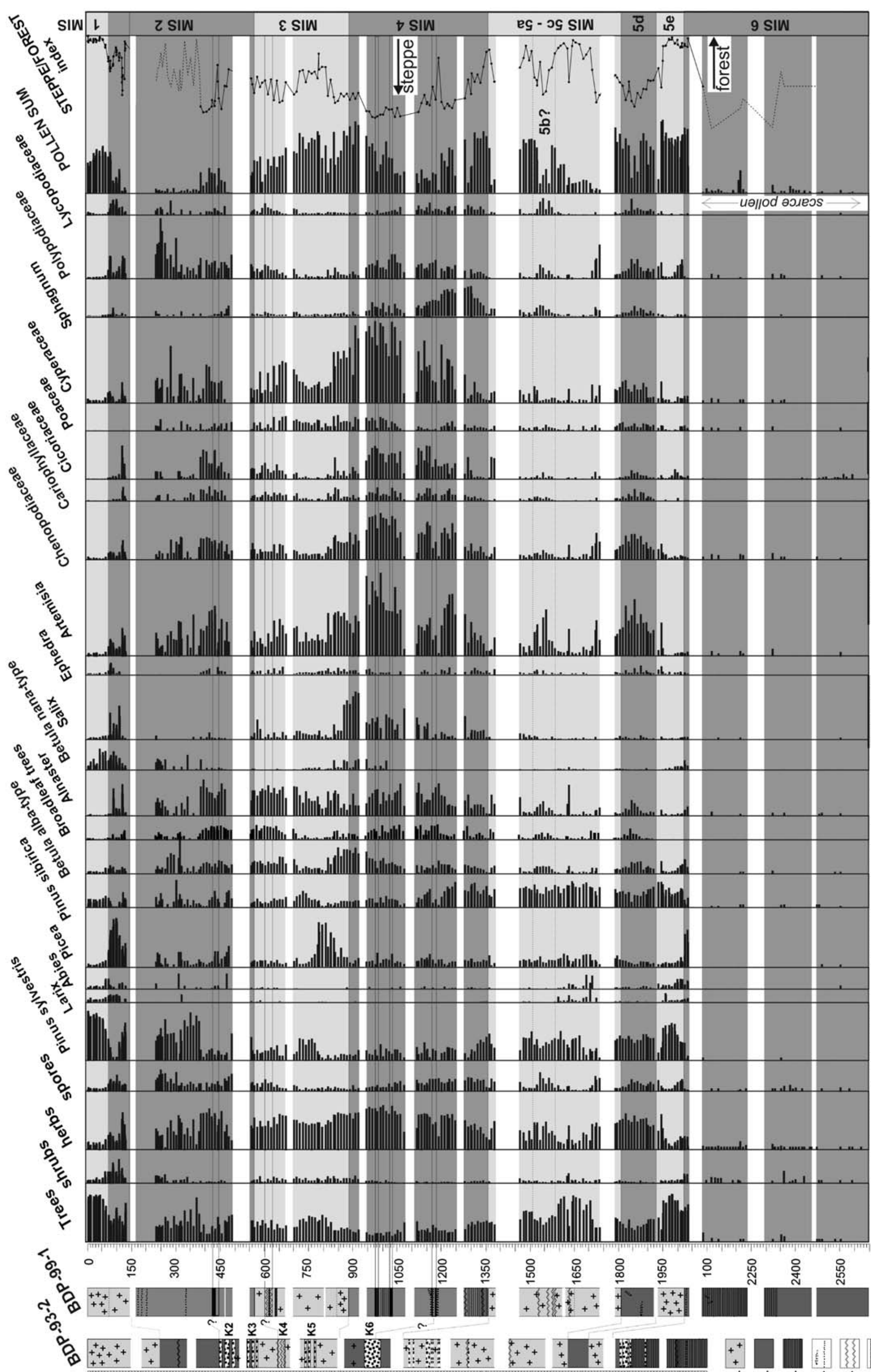
Another interesting comparison derives from the observations of the tectonic evolution in the north-eastern part of Tibetan Plateau, 35–40°N. In their recent review, Sun and Liu (2000) used several lines of evidence to suggest a middle-Pleistocene age for the uplift in this region. For instance, they argued that the distinct character of sandy loess intervals L15 and L9 (correlated with glacial stages MIS 32 and 22, 1.1–0.87 Ma) and anomalously high eolian mass accumulation rates during this interval are indicative of high abundance of locally derived clastic material, produced as a result of tectonically driven base level adjustment and river incision. Supportive of this tectonic change of drainage patterns is the disappearance of several paleo-lakes in Huang He catchment after 1.1 Ma, when these lakes were drained as a result of base level adjustment (Sun and Liu, 2000; Lemkuhl and Haselein, 2000). Anomalously high sedimentation rates in four drill cores from Qaidam basin between the Jaramillo and Brunhes/Matuyama boundary, as well as thick conglomerate and gravel sections with the age range of 1.2–0.9 Ma in the northeast margin of Tibetan Plateau, are also cited as evidence for intensified uplift at that time (Sun and Liu, 2000). Finally, according to the above authors, the Pulu basalts along the Kunlun, dated at ca. 1.2 Ma, may indicate the initiation of the uplift.

It is possible that the observations in the new BDP-99 drill core are directly related to the above tectonic activization. As discussed above, there is clear and plentiful evidence of intensified tectonic activity in the Baikal rift at 1.1–0.8 Ma associated with a major reorganization of sedimentation patterns in the Selenga Delta area and with large-scale changes in Baikal drainage. The interval 1.1–0.8 Ma in the BDP-99 section is in fact characterized by anomalously high sedimentation rates as compared with the younger and older intervals (Figs. 6 and 7). Based on a review of volcanic formations in the Baikal area (Kuzmin et al., 2003), it is not clear, however, if a distinct regional phase of intensified volcanic activity can be associated with tectonic events around 1.1–0.8 Ma.

3.5. Palynological record and climate response during the last climatic cycle

The visual comparison of BDP-93-2 and BDP-99-1 lithologies plotted to the same depth scale in Fig. 8 shows that corresponding glacial intervals in BDP-99 are thicker, whereas interglacial diatomaceous layers are either thinner or of thickness comparable with that in BDP-93. The systematic difference in thickness of glacial intervals points to the higher supply of suspended load to Posolskaya Bank as compared with Buguldeika Saddle (Fig. 1). In both drill cores the upper part of MIS 6 interval is finely laminated (Fig. 8), although detailed comparison of finer features has proven difficult because, unlike BDP-93, the BDP-99 sediments are generally structureless, with rather uniform dark olive gray to olive black color. The distinct brownish dolomite-bearing erosional layers K2, K3, K5 and K6 (Fig. 8) observed in both BDP-93 drill cores (Prokopenko et al., 2000, 2001b) and also in 339 PC-2 (Colman et al., 1994) from Buguldeika saddle are indicative of millennial-scale changes in sediment supply and appear correlative with the timing of Bond cycles/Heinrich events in North Atlantic (Prokopenko et al., 2000, 2001b). Although it was difficult to visually identify equivalent intervals in the BDP-99 section, it is possible that brownish layers at the base of core 3-1B (430–440 cm) and several faint relics of reduced Fe–Mn crusts in the interval 605–633 cm (core 5-1B) in BDP-99-1 are equivalent to K2 and K4 layers in BDP-93-2. The coarser layer 20–36 cm in BDP-99-1 section 9-1B, corresponding to mid-MIS 4 interval, appears correlative with a thick erosional layer K6 in BDP-93-2 (Fig. 8).

In Fig. 8 we make a general comparison of the lithologic record of BDP-99 and the pollen record with reference to marine oxygen isotope (MIS) stratigraphy of the past 130 ka. The intervals equivalent to individual MIS stages are distinguished based on the abundance of diatoms in sediments reinforced by diatom biostratigraphy (Khursevich et al., 2005, and references therein), which has proven to be a reliable approach in a number of previous Lake Baikal studies. The sediments of the glacial interval correlative with MIS 6 in BDP-99 contain little pollen. The transition to the last interglacial is marked by a dramatic increase of pollen concentration, tree pollen in particular (Fig. 8). The high abundance of *Pinus sibirica*, *P. sylvestris*, *Abies* and Polypodiaceae suggests that landscapes during the last interglacial were characterized by dark coniferous taiga with ferns, indicative of annual precipitation of 600–1000 mm by analogy with modern vegetation of the western Sayan region (Polikarpov, 1970) and the Khamar–Daban Range along the SE fringe of Lake


BDP-93-2
BDP-99-1
Trees
shrubs
herbs
spores
Pinus sylvestris
Larix
Abies
Picea
Pinus sibirica
Betula alba-type
Broadleaf trees
Alnaster
Betula nana-type
Salix
Ephedra
Artemisia
Chenopodiaceae
Cariophyllaceae
Cicoriaceae
Poaceae
Cyperaceae
Sphagnum
Polypodiaceae
Lycopodiaceae
POLLEN SUM
STEPPE/FOREST index
MIS
1
MIS 2
MIS 3
MIS 4
MIS 5c - 5a
5d
5e
MIS 6
5b?
steppe
forest
scarce pollen
K2
K3
K4
K5
K6
1.
2.
3.
4.
5.
6.

Baikal (Epova, 1961). A notable feature of the MIS 6/5e glacial/interglacial transition is a distinct early post-glacial peak of Siberian spruce (*Picea*) leading relative to pollen signals of other arboreal species (Fig. 8).

The diatom-barren interval equivalent to MIS 5d is characterized by a dramatic increase in non-arboreal pollen, especially that of xerophytic flora such as *Artemisia* and Chenopodiaceae suggestive of expansion of forest-steppe in the Baikal catchment basin and the onset of continental climate with hot and relatively dry summers and cold winters with little snow. However, the abundance of pine and birch (*Betula alba*-type) remained quite high and the peaks of *Sphagnum*, Polypodiaceae and Lycopodiaceae indicate the existence of poorly drained forest-tundra landscapes in parts of the watershed (Fig. 8). Although the palynological record of the following MIS 5c-5a interstadial interval is not completely resolved due to core gaps, the distinct *Artemisia* peak at ca. 1500–1630 cm and coeval peaks in fern and moss pollen apparently reflect a MIS 5b climatic deterioration, similar to that of the MIS 5d interval.

BDP-99 provides a quite detailed record of the glacial diatom-barren interval corresponding to MIS 4. This interval is clearly divided into two zones at ca. 1080 cm (Fig. 8). Early MIS 4 is characterized by cold and rather humid climate as seen from the maximum of *Sphagnum* pollen, typically indicative of excess moisture and stagnant waters. The second half of MIS 4 interval is characterized by the expansion of steppe vegetation (as seen from maximum abundance of *Artemisia* and Chenopodiaceae) and mire vegetation (as suggested by abundant Cyperaceae pollen). The increase in willow (*Salix*) and decrease in *Sphagnum* pollen in the second half of MIS 4 suggests a change to a more efficient drainage in Selenga River catchment. Low abundance of tree pollen likely indicates that the development of forest vegetation was limited by widespread permafrost during MIS 4.

The transition from the MIS 4 glacial to MIS 3 interstadial is marked by a maximum peak of *Salix* pollen abundance followed by another distinct peak of *Picea* (Fig. 8). This early climatic amelioration, marked by the expansion of Siberian spruce, was predictably followed by an increase in pollen abundance of other tree species. The significant presence of *Artemisia*, Chenopodiaceae, Cyperaceae and other non-arboreal pollen throughout the MIS 3 interval suggests that steppe landscapes remained widespread during this interstadial. In addition, shrub associations, particularly *Alnaster* (Fig. 8) appear to have expanded on slopes and along river valleys in response to higher moisture availability during MIS 3.

The MIS 2 glacial interval was characterized by another expansion of xerophytic steppe flora. Furthermore, low abundance of moss and fern pollen suggests that MIS 2 interval was likely more arid as compared with prior late Pleistocene glacials. At the MIS 2/1 transition again the distinct postglacial peak of *Picea* is observed in the interval where pollen abundance of other arboreal species is low (Fig. 8). This type of vegetation, dominated by Siberian spruce, birch and larch, suggests cold relatively humid climate with widespread permafrost, and is therefore consistent with reconstructions of the late glacial climate in the middle latitudes of Eurasia (for detailed discussion please refer to Bezrukova et al., 2005). The transition to the Holocene modern-type forest vegetation dominated by *Pinus sylvestris*, *P. sibirica*, and *Larix* is observed at ca. 70 cm core depth in BDP-99 (Fig. 8). Prior to this transition, however, a short interval of aridization occurred as seen from coeval peaks of *Ephedra* and *Artemisia*, possibly correlative with climate reversal associated with the Younger Dryas cooling.

It may therefore be concluded that the new BDP-99-1 sediment section provides robust and representative pollen records of both interglacial/interstadial and glacial intervals alike. The latter is of particular importance for Baikal because glacial sediments at Academician Ridge usually contain too little pollen to produce representative spectra. The co-occurrence of pollen of steppe vegetation and that of dark coniferous taiga at a number of intervals suggests that palynological signals in BDP-99 are derived from different types of landscapes occurring in the vast Selenga River catchment. The variation of pollen abundance of certain index-species, however, allows clear identification of recurring periods of glacial, interglacial, and interstadial climatic conditions. One of the systematic features of MIS 6/5e, MIS 4/3 and MIS 2/1 transitions is the lead of *Picea* pollen signal relative to pollen signals of other arboreal species (MIS 2/1 is discussed in detail by Bezrukova et al., 2005). A notable presence of pollen of broadleaf trees in BDP-99 sediments is consistently observed in glacial and interstadial, but not in the interglacial intervals (Fig. 8). Broadleaf taxa in BDP-99 include *Ulmus*, *Quercus*, *Tilia*, *Corylus*, *Juglans*, *Fagus*,

Fig. 8. Pollen diagram of the last climatic cycle in BDP-99-1 drill core compared with lithological composition of BDP-99-1 and the corresponding interval of BDP-93-2 (E. Karabanov, E. Stolbova, E. Kornakova, unpublished BDP-93 core description). Glacial (dark shading) and interglacial (lighter shading) intervals approximately equivalent to MIS 1–6 are distinguished based on correlation with respective diatomaceous intervals (see text). Note the reversed axis for the SFI index. The dashed portions of the SFI profile are not reliable because of sparse pollen.

Legend: 1—diatomaceous mud; 2—silty clay; 3—finely laminated silty clay; 4—laminae and lenses of coarse silt with sand; 5—dense greenish granular laminae, relics of buried and reduced Fe–Mn crusts; 6—brownish erosional layers at Buguldeika saddle; layers K2, K3, K5 and K6 contain detrital dolomite (Prokopenko et al., 2001b).

Carpinus, *Carya*, *Tsuga*, and *Taxodium*. Most of these taxa are typical for Pliocene and Oligocene–Miocene flora of Baikal region (Belova, 1985). Pollen of these taxa is apparently redeposited, most likely due to active erosion associated with permafrost processes.

The steppe/forest index (SFI) profile serves to illustrate a generalized vegetation response (Fig. 8). We use a modified version of the SFI index proposed by Traverse (1988) by adding *Ephedra* and Caryophyllaceae as typical members of steppe association in the Lake Baikal area. We therefore calculate SFI as a ratio of the pollen sum of *Artemisia*, Chenopodiaceae, *Ephedra* and Caryophyllaceae to the pollen sum of the above group with tree pollen sum, multiplied by 100. The SFI clearly reflects glacial/interglacial cyclicity of the last climatic cycle in the Lake Baikal region (Fig. 8), consistent with diatom abundance lake paleoproductivity indices. A dramatic reversal in the SFI profile during MIS 5d reveals a rapid decline of forest vegetation in the Lake Baikal watershed. A similar, although less dramatic, SFI reversal is observed in the MIS 5b interval. For the MIS 2 interval, SFI profile in BDP-99 is not reliable: because of scarce pollen, even an insignificant admixture of redeposited tree pollen skews the SFI index towards a 'forest' association. Interestingly, both BDP-99-1 intervals correlative with K2 and K6 layers in BDP-93-2 are associated with spikes in the SFI index (Fig. 8).

4. Conclusions

The latest BDP-99 drill cores provide a unique sedimentary archive demonstrating the dramatic interplay of how tectonics and climate affected sedimentation in Lake Baikal during the past ca. 1.2 Ma. Although the pattern of changes in diatom productivity and deposition of biogenic silica, as well as the succession of dominant planktonic species, are similar throughout Lake Baikal as shown by the good agreement between diatom biostratigraphic records at BDP-99 site at Posolskaya Bank and the BDP-96 drill core from Academician Ridge (Khursevich et al., 2005), the pattern of changes in the deposition of clastic material is markedly different and includes: (1) a general trend of lowering sedimentation rates towards the top of the strata cored by BDP-99, (2) evidence for erosion and disconformities, and (3) dramatic changes in sedimentation rates brought about by alternating glacial and interglacial periods. These significant depositional changes at Posolskaya Bank can be linked with regional climatic and tectonic events. For instance, the BDP-99 archive confirms that a major tectonic reorganization occurred between 1.1 and 0.8 Ma, consistent with interpretations of past changes in Baikal drainage patterns and with conclusions from prior seismic reflection surveys. The BDP-99 drill core penetrated several acoustic packages previously identified in seismic-reflection profiles in Selenga Delta area helping to constrain their age. The new BDP-99 estimates show good overall agreement with prior estimates derived from extrapolation of a radiocarbon-based chronology into older sequences.

One of the major advantages of the BDP-99 sedimentary section relative to longer but lower-resolution records in BDP-96 (BDP-Members, 1998) and BDP-98 (BDP-Members, 2001) is the presence of abundant pollen. Interpretations of palynological records in vicinity of the Selenga Delta are complicated by overprinting signals of both the mountainous terrain surrounding the Baikal rift basin and the steppe environment of the extensive catchment basin of the lake in Transbaikalia and northern Mongolia. Despite this overprinting, using BDP-99 core material it is now possible to generate relatively high-resolution palynological records of climatic changes in Lake Baikal watershed over several key intervals of early and middle Brunhes chron. The thickness of identified individual interglacials (e.g., 9.4 m of MIS 15a-13 and 4.7 m of MIS 11 intervals) approaches those of the corresponding intervals in the classical Chinese loess/soil sequences, whereas potential climate proxy indicators in BDP-99 are much more diverse.

We therefore conclude that the BDP-99 archive may become the key section to link the Lake Baikal 'paleoclimate' response (known mostly from lacustrine proxy records such as diatom productivity from drill cores BDP-96 and BDP-98) with the processes in the watershed including environmental changes and sediment supply/lake-level changes (inferred from regional palynological records and the records of subaerial sedimentation). By helping to bridge the current gap in understanding the relationships and interplay between lacustrine and terrigenous processes on a regional scale, the new BDP-99 sedimentary archive will greatly contribute to developing a coherent picture of the climatic evolution in continental interior Asia throughout the middle-late Pleistocene.

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