PERGAMON

Quaternary International 80–81 (2001) 19–36

The new BDP-98 600-m drill core from Lake Baikal: a key late Cenozoic sedimentary section in continental Asia☆

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Abstract

The new 600-m drill core BDP-98 from the Academician Ridge of Lake Baikal recovered a continuous sedimentary record of the past 10 Ma. The entire section is represented by lacustrine sediments, which gradually change from distal deltaic facies at the bottom of the section to fine undisturbed hemipelagic sediments of the upper 300-m interval. The entire 10-Ma lacustrine section contains abundant diatoms, thus allowing extension of Plio-Pleistocene diatom and biogenic silica records into the Miocene. Above the Matuyama/Gauss paleomagnetic reversal boundary, the BDP-98 record contains clearly delineated glacial/interglacial lithologic cycles. Below this boundary the diatom signal is quite different: average diatom contents are higher and variations are of lower amplitude. Although most likely paleoclimatic in origin, these variation presumably reflect past changes in the moisture regime of southeast Siberia under conditions of warm subtropical climate during the Miocene and Early–Middle Pliocene. The continuous BDP-98 drill core, which covers the hiati present in the composite continental sections of the Baikal region, is a key section for reconstructing the Neogene–Quaternary climatic evolution of continental Asia.

The BDP-98 section also places several important time constraints on the rifting history of Lake Baikal by providing reliable correlation of lithological and physical properties of the drill core sediments with calculated positions of the acoustic reflection boundaries interpreted from multichannel seismic studies. The lithologic composition indicates that, on the stable block of Academician Ridge where the BDP-96 and BDP-98 drill sites are located, acoustic reflection boundaries are not associated with major erosional events, but instead result from changes in sediment density and composition. Several lithologic indices further

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☆ BDP-98 Members (in alphabetical order).

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PII: S1040-6182(01)00016-7

suggest that significant changes have occurred in the physics and chemistry of Lake Baikal waters, affecting the carbonate equilibrium and oxygen regime of Baikal. © 2001 Published by Elsevier Science Ltd.

1. Introduction: drill site location and geological setting

The new Baikal Drilling Project borehole BDP-98 was drilled at the Academician Ridge of Lake Baikal at 53°44′48″ N and 108°24′34″ E in a water depth of 333 m (Fig. 1). The borehole penetrated to a depth of 670 m. Sediments were continuously cored down to 600 m with an average recovery of 95%. Previous drilling on the Academician Ridge in the winter of 1995–1996 resulted in recovery of two cores with the bottom age of 5 Ma and an exceptional regional paleoclimate record based on biogenic silica and diatom responses (BDP-Members, 1997, 1998; Williams et al., 1997; Kuzmin et al., 2000). The aim of the new BDP-98 drilling was to extend the Baikal drill core sections deeper into Miocene sediments. The new site had thicker sediments in the middle part of the cross-section as compared with the BDP-96 drill site and thus had the potential for a higher temporal resolution record (Fig. 2). The site's distant location from coarse delta deposits, which were identified in seismic profiles in the southeastern part of the Academician Ridge (Fig. 2), was an important factor for selecting the new BDP-98 drill site.

Academician Ridge is the bathymetric high in Lake Baikal separating the North and Central basins (Fig. 1). Academician Ridge is an asymmetrical horst, bounded by the Ushkanie fault on the northwest and the Ol'khon fault to the southeast. The ridge crest has an average depth from 300 to 350 m and rises to a height of 500 m over the lake bottom on the northwest and more than 1000 m on the southeast. The crystalline basement of the ridge is overlapped by a sedimentary sequence of 1000–1500 m thick (Hutchinson et al., 1992; Zonenshain et al., 1993). At the terminations of the Academician

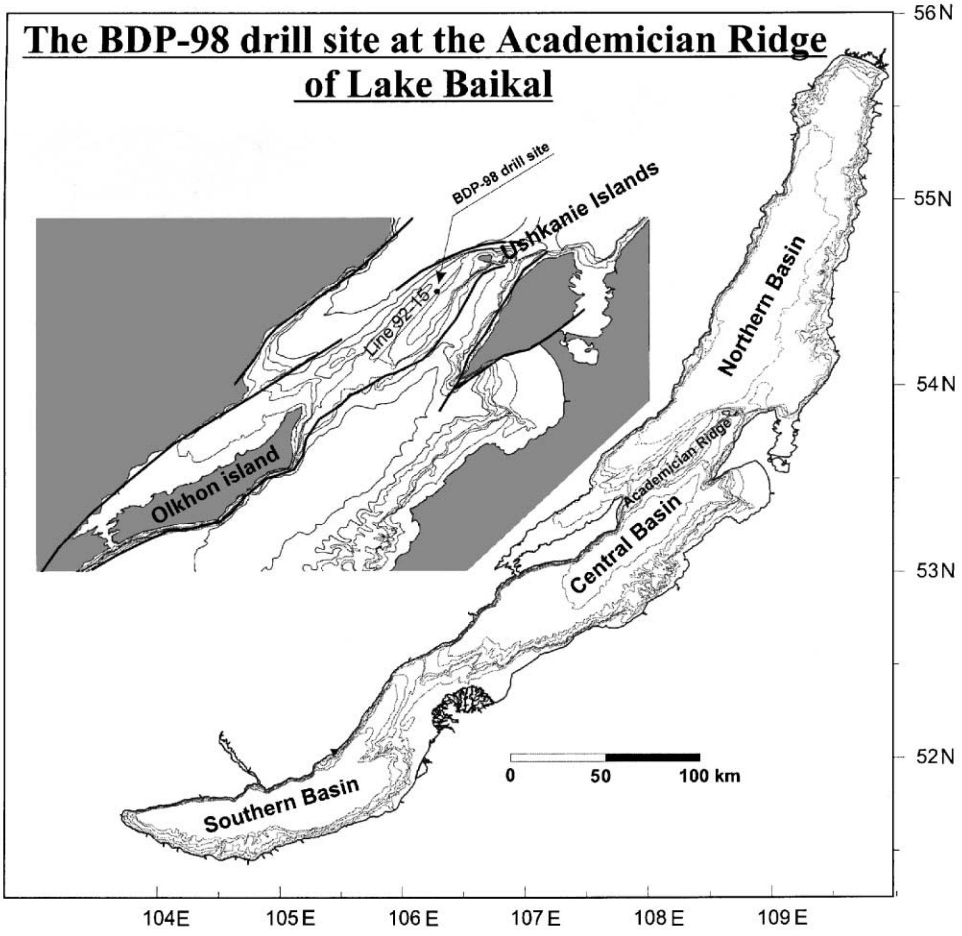

Fig. 1. Map of Lake Baikal, showing the principal bathymetric features and indicating the location of the BDP-98 drill site at the Academician Ridge (inset). Major tectonic faults are indicated by heavy solid lines. Dashed line indicates the multichannel seismic profile 92–15 (D. Hutchinson, USGS).

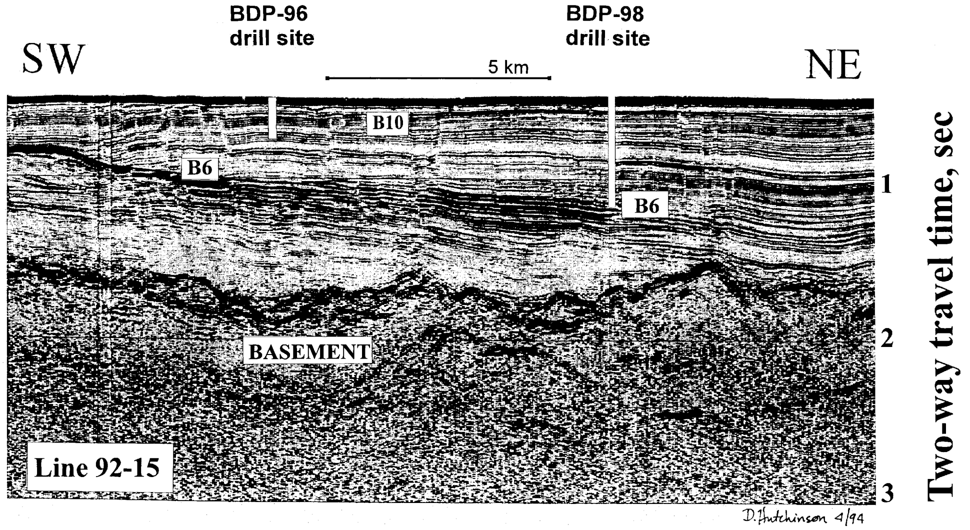

Fig. 2. The position of the BDP-96 and BDP-98 drill sites on seismic profile 92–15 (D. Hutchinson, USGS) and the total length of the section penetrated by the drill cores. B10 is the major acoustic boundary between the overlying A and underlying B sequences (Moore et al., 1997). The B6 acoustic boundary divides the B sequence set into two members: the overlying fine hemipelagic section and the underlying deltaic sequences of Paleo-Barguzin River. The buried delta is located in the southwestern part of the profile. The lowermost strata of the B sequence consist of deformed sediments with a discontinuous acoustic pattern filling in depressions in the crystalline basement.

Ridge (Ol'khon Island to the southwest and Ushkanie Islands to the northeast), the thickness of sediments sharply decreases to only few meters and in some places crystalline basement is exposed.

The multichannel seismic investigations of the sedimentary sequence of Academician Ridge (Hutchinson et al., 1992; Zonenshain et al., 1993; Kazmin et al., 1995; Moore et al., 1997) have revealed two main seismic–stratigraphic complexes, named by Moore et al. (1997) as "A" (Angara) and "B" (Barguzin) sequence sets. The formation of A and B sequence sets reflects different phases of the Baikal rift development. The thickness of the upper fine-layered A complex is less than 200 m at the Academician Ridge, whereas the lower B complex is over 1000 m thick. These sequence sets are separated by a pervasive acoustic boundary B10, which is associated with an angular erosional unconformity in the Northern Basin of Lake Baikal (Moore et al., 1997; Kuzmin et al., 2000). The lower sequence set "B" includes two members with different seismic characteristics bounded by the B6 acoustic reflector (Fig. 2). The upper fine-layered member of the B-sequence occurs between acoustic boundaries B10 and B6 and appears to consist of fine lacustrine sediments. The lower member below the B6 acoustic boundary is characterized by clinoforms, characteristic of a deltaic environment. Prior interpretation of the seismic pattern has suggested that this member of the B sequence set is composed of fluvial sediments carried westward by the Paleo-Barguzin River (Moore et al., 1997). The lowermost part of the B sequence set is composed of deformed sediments with discontinuous patterns of acoustic reflection signals. The sediments from this sequence fill in the depressions of the crystalline basement, and in some cases they are found on bedrock slopes.

The average sedimentation rate on the Academician Ridge for the last 5 Ma has been documented to be approximately 4 cm per 1000 years at the BDP-96 drill site (BDP-Members, 1997, 1998). By projecting this rate to the BDP-98 site and accounting for a thicker B sequences at the new drill site, a rough age estimate of about 10–12 Ma was inferred for the bottom of 600-m drill core at BDP-98 site. This depth/age estimate set the target for the BDP-98 drilling campaign.

2. Drilling technology

The drilling complex "Nedra-Baikal" was mounted on a 1300-ton barge and tugged to the drill site by the R/V *Baikal*. The complex included the drilling rig SKB-8, derrick B26/50, drilling pumps, electric station GD-390 and a system for preparation and circulation of drilling mud. The drill string was based on light alloy drill pipes LBT-147 × 11-D16T.

Three boreholes were drilled at the site during the winter season of 1997–1998. The first hole penetrated to a depth of 201 m using a drill string without a riser. The second hole was drilled using a 245-mm riser cemented at a depth of 180 m below the lake bottom. This riser, the first ever used on Lake Baikal, allowed the washing of the well by drilling mud, circulated in a closed circuit. A riser also prevented the collapse of well walls and increased the efficiency of slurry removal. As a result, a

674-m borehole was drilled with continuous coring taking place to a depth of 600 m. A third well was drilled to a depth of 100 m, and six cores sampled to overlap the gaps in the first drill core.

In order to obtain a continuous 600-m core from the BDP 98 holes, coring in the second well was started from a depth of 191 m. This provided a 10-m overlap between the cores of the first and second boreholes. Preliminary biogenic silica content data for the first and second cores showed a high comparability of the cross-sections. It was also found that the second core is shifted upward by 30.5 cm relative to the first core. This factor was taken into account while making a common BDP-98 depth scale. The hydraulic piston coring method was used to a depth of 270 m. Below, a rotary drilling was applied. The average core recovery was 95%, whereas for some intervals it exceeded 98%.

In order to insure that the uppermost layer of sediments was sampled, a number of piston cores were obtained before the drill string was lowered. The cores recovered an oxidized sediment layer (11 cm thick) containing the iron–manganese crust, typical of the uppermost sediment layer at Academician Ridge.

3. BDP-98 borehole logging

After drilling had been completed, logging was performed in the borehole, including gamma-logging, acoustic logging, spontaneous polarization potential, induction, resistivity logging, thermometry, inclinometry, and cavernometry. The logging details have been reported previously (Pevzner et al., 1999), so in this report we cite gamma and acoustic logging data only.

Gamma-logging of the BDP-98 borehole indicates significant variations in gamma-activity in the borehole due to changes in lithological composition. As shown below, the closest correlation with lithology is observed from the inverse relation of gamma-activity to diatom content in the sediments (refer to Fig. 5). The upper 100-m section, which corresponds to the interval with strong glacial/interglacial cyclic lithologic pattern, is characterized by the highest gamma-activity values. In the middle part of the core from 170 to 470 m, and especially from 170 to 270 m core depth, the values are low. Below 470 m, gamma-activity increased again apparently due to the higher content of coarse-grained material.

The acoustic logging in BDP-98 borehole was performed using the apparatus SPARK-6. The kinematic and dynamic characteristics of longitudinal acoustic waves were measured within the range of 180–671 m. Due to the difficult technical conditions data were obtained only for the 483–671 m interval, which corresponds to compacted sediments in the lower part of the BDP-98 section (Fig. 3). As the information on kinematic characteristics of sediments from the upper part is of practical importance, the data of acoustic logging were processed for the range from 481 to 671 m and compared with the results of density measurements to obtain the following statistical dependence between the interval time of longitudinal acoustic wave run (Δt) and the sediment density (ρ):

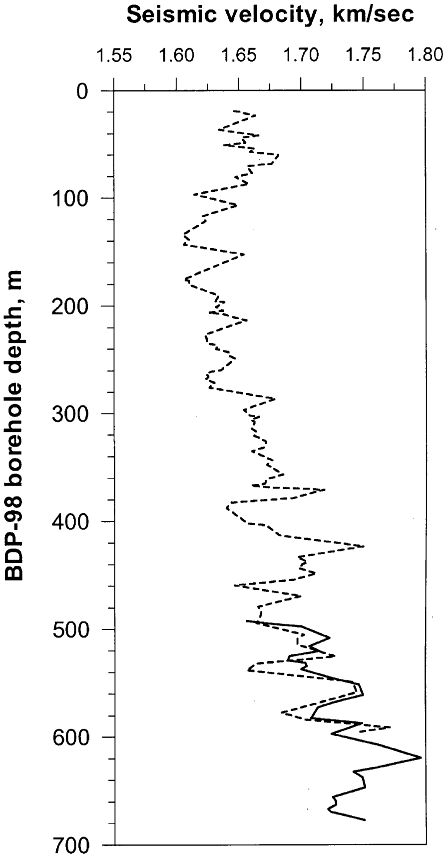

Fig. 3. Longitudinal acoustic wave velocity (km/s) in the Baikal sedimentary strata at the Academician Ridge. Solid line—results of acoustic logging in the BDP-98 borehole, dashed line—seismic velocity calculated from sediment density measurements (see text).

$$\Delta t = 770.563 - 113.638 \times \rho \quad (r = -0.96).$$

Using this equation and the density measurements, the acoustic velocities were calculated for the interval from 20 to 595 m. The velocities of longitudinal acoustic waves from acoustic logging fall within the range of 1.6–1.8 km/s. A low sound velocity in water (1430 m/s) was determined by direct measurements in the water body at the drill site using the logging probe SPARK-6. The average velocity of elastic waves was then calculated accounting for the water column thickness. These estimates permitted the recalculation of the travel time in the seismic profile into meters below lake bottom and thus to groundtruth previous interpretations of seismic results.

4. Groundtruthing interpretations of Academician Ridge seismic data

The depths of acoustic reflection boundaries separating the sequence sets at the Academician Ridge were calculated from the new data on seismic wave velocities (Figs. 3 and 4) and travel times recorded during multichannel seismic surveys (Figs. 2 and 4). The results are summarized in Table 1. The calculated position of the B10 boundary is about 104 m. The location of B6 boundary at the BDP-98 drill site is estimated at a depth of approximately 565 m in sediments. Thus, with the core depth of 600 m, the B10 boundary between A and B sequence sets and the B6 boundary between the two members of the B sequence set were penetrated by the BDP-98 drill core. The depths of the other acoustic reflection boundaries B9, B8, and B7 are estimated approximately at 197, 257, and 353 m core depth, respectively.

The major sequence boundaries B10 and B6 were interpreted from multichannel seismic data to be associated with past erosional surfaces and thus to represent major unconformities at the Academician Ridge (Kazmin et al., 1995; Moore et al., 1997). In the discussion below we explore the responses of the BDP-98 lithologic proxies at these intervals by plotting the approximate positions of the main acoustic boundaries on graphs showing lithological composition and physical properties in the BDP-98 drill core.

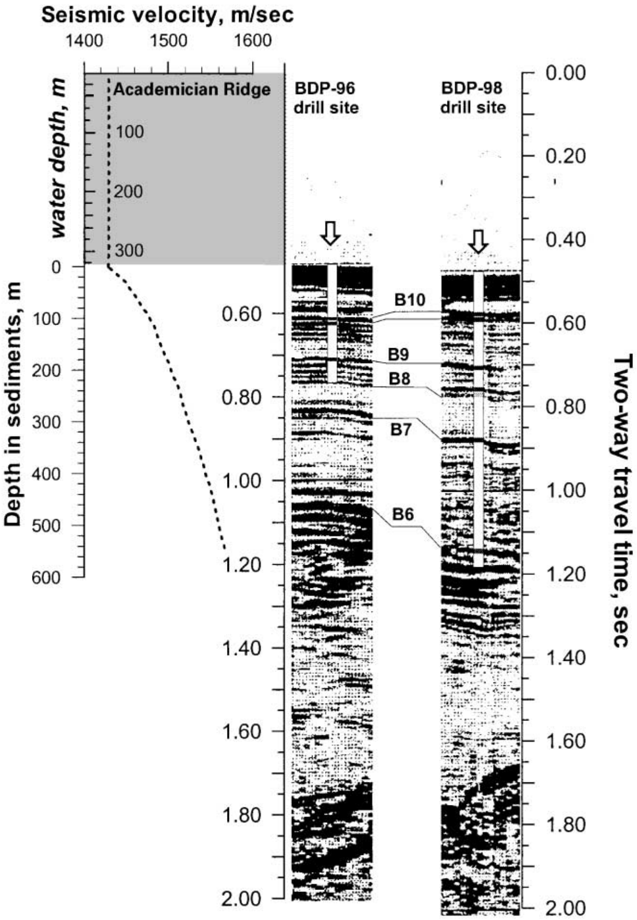

Fig. 4. Correlation of the seismic reflections length of the section penetrated by the drill cores BDP-96 and BDP-98 (refer to Fig. 2) and the average two-way seismic velocity accounting for the water column. The calculated positions of acoustic reflections in sediments are given in Table 1.

5. Sediment composition in the BDP-98 drill core

The sediments consist of silty clay and diatomaceous mud. In the lower part of the core silt content is significantly higher and the sediments are very dense. From semi-quantitative counting in smear-slides based on comparing observations made by light microscopy with visual percentage comparison charts (Scholle, 1979; Terry and Chilingar, 1955), the diatom content was found to vary from 0% to 90% grains. In the upper 100 m and in the lower 490–600 m core the diatom content dropped to 0–5% at some intervals, whereas in the middle part of the core (100–370 m) the minimum concentrations rarely fell below 10–15%. Several relatively homogenous intervals on diatom distribution profiles can be distinguished: 0–110, 110–270, 270–480, and 480–600 m (Fig. 5).

The alternation of clay layers with diatom-enriched layers is observed in the upper 100-m section of the core. The intervals with the highest clay content are found from 0 to 120 m core depth. Below 120 m, the average clay concentrations are relatively stable, but they are markedly lower than in the upper section (Fig. 5). The total concentration of the sand–silt fraction fluctuates significantly. The frequency and amplitude of these fluctuations are the highest at the interval of 0–60 m. A deep minimum in the content of the coarse-grained fraction is observed at core depth of 170–190 m (Fig. 5). The average concentration of the sand–silt fraction

Table 1
Acoustic reflection boundaries

Acoustic reflection	Two-way travel time (s)	Seismic velocity (m/s)	Approximate depth in sediments (m)
Sediment surface	0.44–0.49	1430	0.5 ± 18
B10	0.58–0.604	1475–1480	104.4 ± 9
B9	0.7–0.71	1500–1505	196.6 ± 5
B8	0.77–0.79	1510–1517	257.3 ± 9
B7	0.88–0.91	1531–1536	353.2 ± 12
B6	1.14–1.16	1560–1565	565.7 ± 9
Bottom of cored section	1.185	1575	600

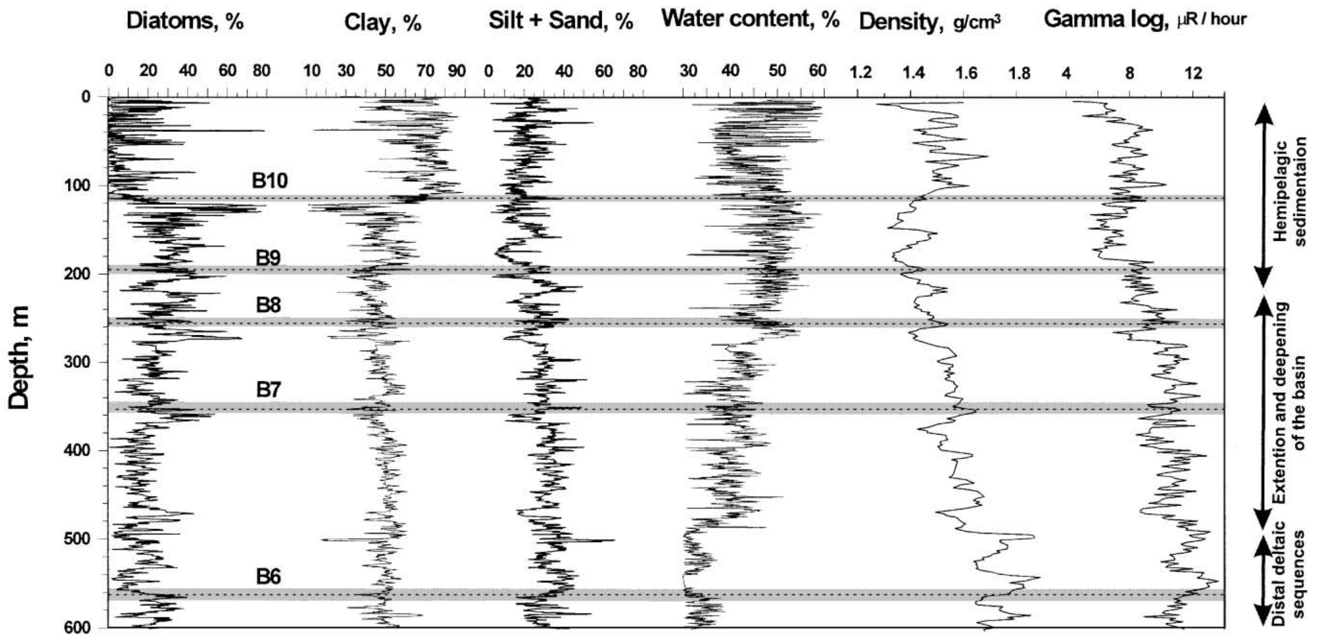

Fig. 5. Lithological composition and physical properties of the 600-m drill core section BDP-98. Diatom abundance, clay, silt, and sand are given in percent grains from smear slide observation data (see text). Lithological composition and water content are plotted as 3-point running average profiles. Shading indicates the approximate positions of acoustic reflection boundaries (refer to Fig. 4). Please refer to Figs. 11 and 13 for an explanation of the inferred sedimentary environments displayed to the right.

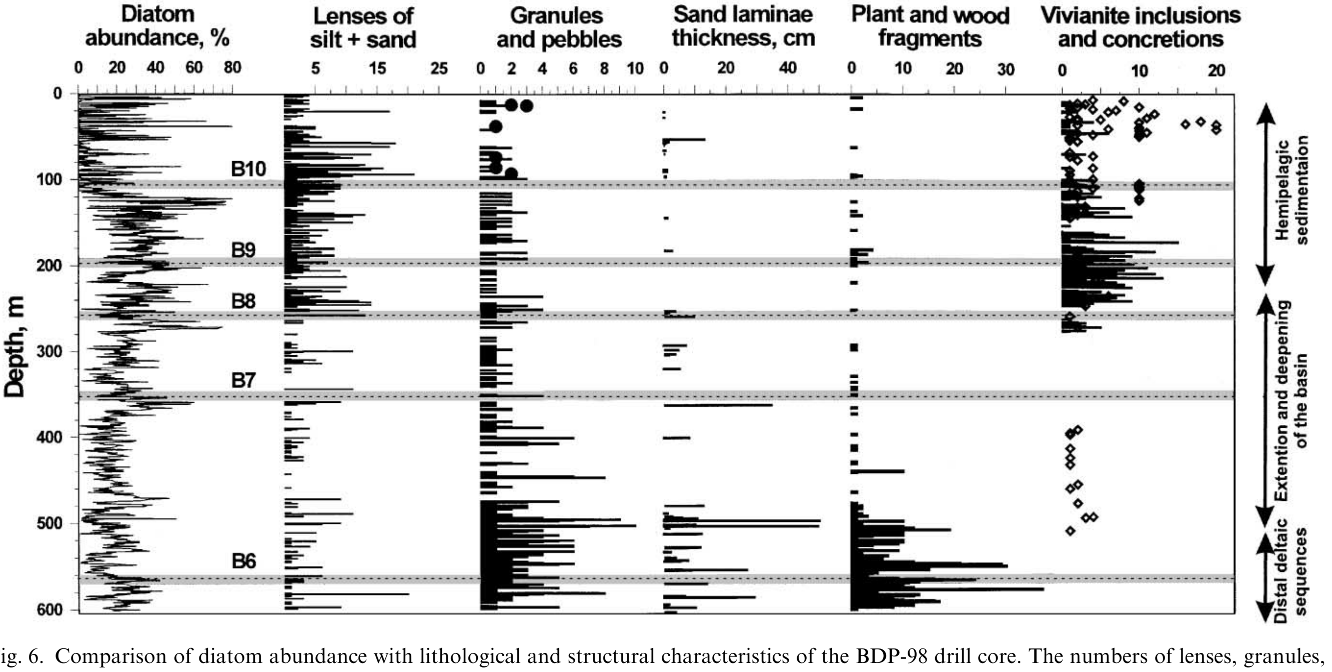

Fig. 6. Comparison of diatom abundance with lithological and structural characteristics of the BDP-98 drill core. The numbers of lenses, granules, wood fragments, etc., are given per 1-m section of split core. For sand laminae, the position in the section and the relative thickness are indicated. Shading indicates the approximate positions of acoustic reflection boundaries (refer to Fig. 4). Please refer to Figs. 11 and 13 for an explanation of the inferred sedimentary environments displayed to the right.

gradually increases from 200 to 600 m core depth. The abundance of sand particles is considerably lower than that of silt particles and amounts to 0–5%. Only in some layers does the sand content increase to 10–40%. Such layers are found in the lower part of the section (Fig. 6). In addition, the sandy–silty material occurs as small lens-like inclusions, which are found throughout the core (Fig. 6).

Gravel grains are abundant in the lower part of the BDP-98 section; in particular, in the lower 100 m, where gravel is well rounded. Some sections of this interval contain 10 granules per 1 m of split core (Fig. 6). In the upper part granules are scarce and poorly rounded or angular. Individual pebbles are found in the upper 100 m (Fig. 6). The size of the pebbles reaches 2–5 cm in diameter. Such pebbles, as well as the angular granules, are most likely the product of iceberg rafting.

Vivianite concretions and inclusions ($Fe_3(H_2O)_8[P_2O_4]_2$) are typical of BDP-98 sediments. The concretions are small spherical granules (fractions of a millimeter in diameter) and their aggregates. The concretions are irregularly distributed in the BDP-98 core. Abundant vivianite inclusions are found in the upper 270 m but individual concretions can be observed to a depth of 490 m. However, the maximum amount of concretions is found in the upper 50 m (Fig. 6), mainly in intervals of clay.

Bands and pockets of hydrotroilite ($FeS \cdot nH_2O$), as well as individual pyrite crystals, are abundant in the BDP-98 sediments. Hydrotroilite is readily visible in freshly opened cores due to its color, occurring in pockets as a black powdered substance. X-ray diffraction analysis indicates that small cylindrical inclusions (10–20 μm) of carbonate material found below 200 m core depth consist of siderite. Such concretions are also observed in consolidated silt layers. A 20-cm thick layer containing abundant microconcretions of carbonates and fragments of rhombic crystals (up to 0.2 mm in size) is found at a core depth of 455.5 m.

6. Sediment structures in the BDP-98 drill core section

The deposits in BDP-98 include laminated, finely laminated, structureless, and lens-like sedimentary structures. The lamination of sediments results mainly from the alternation of diatomaceous mud with terrigenous clay. The fine lamination is produced by the variations in diatom concentration and by the presence of thin black hydrotroilite-rich laminae and dense greenish laminae, which are the reduced relics of ferro-manganese crusts oxidized on the surface. Previous work has shown that preservation of these crusts is associated with changes in sedimentation rates (Granina et al., 1993; BDP-Members, 1998). The finely laminated structures are evident in the upper 0–200 m interval. In the middle part of the BDP-98 section the lamination is weaker. In the lower part, the layering is determined mainly by changes in grain-size and by the presence of coarse-grained beds.

Bioturbation structures are irregularly distributed. In the upper part of the section (0–100 m core depth) bioturbation is insignificant, and is mostly evident as small horizontal lenses in diatom-rich laminae. In silty laminae, bioturbation shows up as breaks in the continuity of lamination. In clay layers bioturbation is not evident. Bioturbation is most intense in the middle part of the BDP-98 section (150–300 m), which is also marked by relatively high concentrations of diatoms. In the lower part of the section bioturbation is weak. In no cases does it result in a complete disappearance of lamination, which suggests that bioturbation played a minor role in shaping the structure of lacustrine sediments at the Academician Ridge.

Small sand–silt lenses (from a fraction of a millimeter to a centimeter in thickness) are found throughout the section, but differ significantly in quantity, size, morphology, and the degree of rounding of sand grains, and hence, in genesis. Such lenses are abundant from 0 to 250 m core depth (Fig. 6). In the upper 130 m lenses are generally elongated and randomly oriented and contain angular to poorly rounded sand grains. The lenses in this interval were produced by ice or iceberg transport. In the interval of 130–300 m the number of lenses decreases and the degree of rounding of sand increases. The lenses in this interval may also have been formed in part by transport with seasonal ice. Very few lenses are found in the interval from 250 to 500 m core depth (Fig. 6). The number of lenses, mainly horizontal, slightly increases again in the lower 100 m of the BDP-98 section. The coarse-grained material of these lenses contains fine gravel and sand. The granules are well rounded. The origin of these lenses might be related to transport of coarse material trapped in roots of terrestrial plants washed out into the open waters of Baikal.

Turbidite beds are abundant below 250 m core depth. Two silt beds enriched in sand are found at depths of 251.80 and 258.60 m, close to the B8 acoustic boundary. The thickness of each bed is about 4 cm. The lower boundary is sharp, with traces of erosion. The sand in these beds is found as horizontal flat lenses, resulting from breaks in continuity of sand laminae due to bioturbation. The sand size in these lenses decreases towards the tops of the beds, indicating typical turbidite gradational structure. A clear turbidite bed 8 cm thick found at a depth of 297.32 m was deposited on an uneven winnowed surface. Its lower part contains medium-grained sand, which changes upward to fine-grained sand and silt. The upper boundary is transitional to diatomaceous mud. The sand includes remnants of coalified vegetation. The upper part consists of silt and clay and contains abundant fine mica particles. The turbidite beds also markedly differ from the surrounding diatomaceous mud by their low diatom contents.

Other distinct turbidite beds, which in addition to the coarse-grained material include carbonate concretions and abundant sponge spicules, are observed at 475 and 492 m. Fine mica particles are typical of the upper parts of these turbidite beds. Below 500 m the core contains beds of sandy silt with thicknesses ranging from 1.5 to 1.8 m. The boundaries of these beds with overlying and underlying sediments are transitional. These beds have an obscure layering, associated with changes in the content of fine sand, which can reach as high as 40%. Abundant plant remnants found in these beds are composed of coalificated leaves. "Plant-laminae" (up to 1–5 mm thick) are characteristic of the lower 550–600 m interval of the core, commonly with fine sand and current ripples. In the interval of 400–500 m, plant remnants occur as coalified wood fragments. In the upper 370 m, plant remnants are scarce, and are found as small (0.1–1.0 mm) inclusions in the sediment matrix, mostly in diatomaceous mud.

7. Physical properties of the BDP-98 drill core sediments

The sediment density was measured in samples collected from the bottoms of cores upon their shipboard recovery. A total of 277 samples (about 300–400 mg), collected regularly downcore, were weighed in air and in kerosene using a TV-500 microbalance. The measurements were performed at the drill site and corrections for the temperature were made later. The sediment density ranges from 1.27 to 1.87 g/cm^3 and on average increases downcore. However, the density profile is characterized by regular fluctuations, which correlate closely with changes in diatom content (Fig. 5). In diatomaceous intervals the density is significantly lower. For instance, at a depth of 120–140 m, where a sharp increase of diatom content is observed, the density decreases considerably. Below this interval there is a monotonous increase of the mean density, resulting from compaction and dewatering. Interestingly, the mean density of sediments in the upper 100-m section is significantly higher than in the middle part due to the presence of dense glacial clay. Maximum densities are observed in the lower 100-m interval, due both to compaction and to higher proportions of coarse-grained material.

The water content of 1 cm^3 sediment samples was determined immediately after the cores were opened. Collected with an open-end syringe at 10 cm intervals, the 5530 samples were weighed, dried at 60°C, and weighed again. The water contents ranged from 17.12% to 73.93%, decreasing downcore. The 0–60 m interval is characterized by frequent and dramatic variations in the water content. In the 60–270 m interval the amplitude of these variations decreases and the average content progressively decreases downcore. The lowermost interval of 470–600 m core depth is marked by significantly lower water content with little variation.

8. Lithology, physical properties and acoustic reflection boundaries

A comparison of density, water content, diatom abundance, and clay and sand contents reveals a close correspondence among these parameters, mainly defined by the content of the low-density porous diatom frustules. In addition, the calculated positions of acoustic reflection boundaries (Table 1) appear to reflect significant lithological changes (Figs. 5 and 6). For instance, the B6 boundary corresponds to the sharp drop in diatom and water contents, coincident with the abrupt increase in sediment density and in coarse fraction content (also registered in gamma-log) (Fig. 5). The calculated position of the B7 acoustic boundary also corresponds to a drop in diatom and water contents, coeval with increases in clay and coarse fraction contents, in gamma-activity, and with a peak in sediment density (Fig. 5). This boundary also confines the underlying interval where abundant granules and sand laminae are found (Fig. 6). The amount of fossilized plant material decreased much earlier, at the 450–500 m interval (Fig. 6). These changes indicate the gradual decrease in the direct fluvial input of coarse terrestrial clastic material, suggesting that by the B7 time, fluvial input had lost its primary significance as a sediment source at the BDP-98 site.

The B8, B9, and B10 boundaries are all associated with similar lithologic responses: decreases in diatom abundance, and increases in clay and coarse fractions, paralleled by increases in gamma-activity and sediment density (Fig. 5). The similarities observed between the BDP-98 core lithology and all the acoustic reflection intervals further convince us that we have interpreted this association correctly. Further corroboration is found in the nature of the lithological and acoustic signals. For instance, the interval 270–370 m core depth between acoustic boundaries B8 and B7 is characterized by weak fluctuations of sediment density (Fig. 5). Remarkably, this interval is shown on the seismic profile as a uniform, non-layered, acoustically transparent horizon (Fig. 4). Also interestingly, around the B8 boundary, abundant vivianite inclusions and rafted lenses of coarse material start to appear in the BDP-98 section thus indicating changes in sedimentation process at the Academician Ridge site. The lithologic changes in the drill core BDP-98 at 100 m core depth associated with the B10 acoustic reflection boundary corroborate prior interpretations for an early glaciation in the Baikal area during this time based on the drill core BDP-96 (Karabanov et al., 2000; also see Prokopenko et al., this issue).

Comparison of lithological composition and physical properties corroborates that the newly estimated positions for the major B10–B6 acoustic boundaries in the BDP-98 section at Academician Ridge are closely related to significant changes in lithological signals. Importantly, the BDP-98 section reveals that there is no clear sedimentological evidence for major erosional episodes associated with these acoustic boundaries, even with the major B10 and B6 boundaries. Sedimentation at the Academician Ridge was mostly continuous, and the strong reflections resulted from changes in sediment composition and density, not tectonically-driven erosional unconformities as suggested previously by Moore et al. (1997).

9. Fracturing and dislocations in the BDP-98 drill core section

Macroscopic investigations of the BDP-98 drill core revealed structural elements which can be considered tectonic fractures not caused by coring. This represents that for the first time this type of observation has been made for the Baikal sediments. The morphological features of these dislocations in the BDP-98 drill core section are of two main types (Fig. 7). Type I fractures are extension joints, usually 5–10 cm long (rarely up to 40–50 cm long), mostly vertical and often having curved shapes (Fig. 7). These fractures are completely sealed by fine-grained material, suggesting that they are inactive. The fractures are the most abundant in the BDP-98 section, appearing in significant numbers below 140 m core depth (Fig. 8). Type II fractures, 20–30 cm long, do not contain filling material and appear as straight lines. However, they are usually traced by black hydrotroilite inclusions and therefore are readily visible on the split core surface (Fig. 7). Type II fractures frequently displace sedimentary structures by as much as 20 mm and appear as miniature normal faults, which suggests that these fractures are shear joints. Shear joints are mostly found below 260 m core depth in the BDP-98 drill core section, sometimes displacing Type I extension joints, but never vice versa.

The distribution of density of fractures indicates that the BDP-98 drill core penetrates several fracturing zones (numbered in Fig. 8) in the interval of 300–500 m core

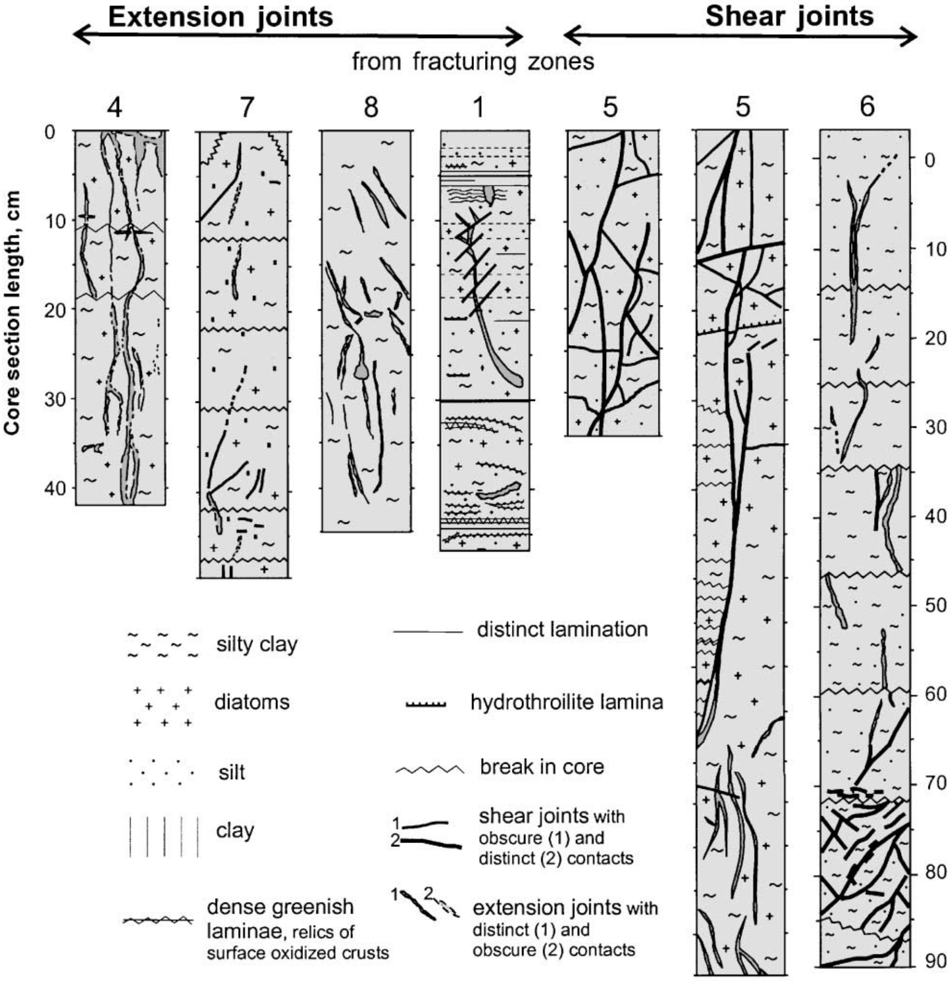

Fig. 7. Cores displaying Types I and II fractures, extension and shear joints corresponding to different fracturing zones in the middle interval of the BDP-98 drill core. For core depth positions of the numbered fracturing zones please refer to Fig. 8.

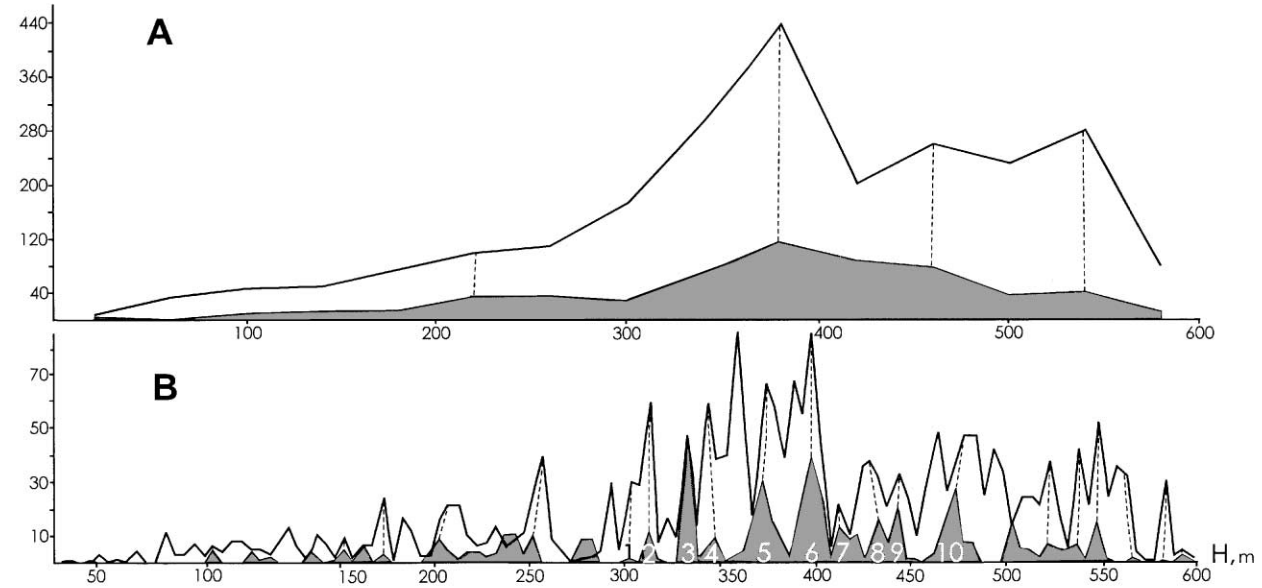

Fig. 8. The density of extension joints (heavy line) and shear joints (shading) in the BDP-98 section: A—number of joints per 40-m interval; B—number of joints per 5-m interval. The numbers indicate fracturing zones with the highest density of extension and shear joints.

depth. The formation of these fracturing zones is associated with lateral extension of sedimentary strata and suggests that the drill core penetrated a disjunctive structure in the early stages of development. In general, the observed fractures cause little effect on lithological composition and the continuity of the sedimentary section due to the insignificant amplitudes of displacement.

10. Age model based on sediment paleomagnetic and rock–magnetic properties

A preliminary age model for BDP-98 is presented here based on identification of paleomagnetic event/reversal boundaries (Fig. 9). To determine the inclination record, the natural remanent magnetization of the subsamples after AF magnetization at the optimum blanket field of 10 mT was measured with a cryogenic magnetometer. For the Brunhes chron, a graphic correlation of the BDP-98 magnetic susceptibility signals with the marine oxygen isotope chronology was used (Fig. 10). The whole-core, low-field magnetic susceptibility (K) was measured at 3 cm interval with a pass-through loop sensor. For the Brunhes chron, the magnetic susceptibility record provides reliable correlation of BDP-98 and BDP-96 with each other and with marine oxygen isotope record at the level of individual stages and substages (Fig. 10).

For the time interval where the cores of BDP-96 and BDP-98 overlap, they demonstrate a close correlation of inclination profiles (Fig. 9). The age model for the BDP-98 section is based on the preliminary correlation of event/reversal boundaries with the reference polarity time scale (Cande and Kent, 1995; Champion et al., 1988; Clement and Kent, 1987). According to this age model the cored section of the BDP-98 borehole spans over 9 Ma. The age versus depth plot (Fig. 11) reveals changes in sedimentation rates at the BDP-98 drill site. In the lower section of BDP-98 in the interval 7–9 Ma BP, sedimenation rates reach 12–17 cm/Ka, whereas the rates in the 0–6 Ma BP interval do not exceed 4–6 cm/Ka. This dramatic but not unexpected inflection in the profile of sedimentation rates occurs above the B8 acoustic boundary in the interval 230–240 m core depth. Dating between 6 and 7 Ma BP, this interval corresponds to the Messinian. Presently, it is difficult to judge the importance of this correspondence since the available lithologic data (Figs. 5 and 6) do not reveal evidence for an unconformity or breaks in sedimentation. The observed pattern and the timing of changes in sedimentation rates are intriguing and warrant future detailed studies and refinement of the BDP-98 age scale.

11. Correlation of BDP-98 with onshore sections and paleoclimate reconstructions

Prior to BDP, investigations of the Late Cenozoic onshore sedimentary strata around Lake Baikal (Fig. 12) have provided an important means of reconstructing the regional pattern of paleoclimate change (BDP-Members, 1998; Belova, 1985; Vorobyova et al., 1995). These and other studies have shown that the paleoclimates of the Early Miocene in South Siberia were similar to

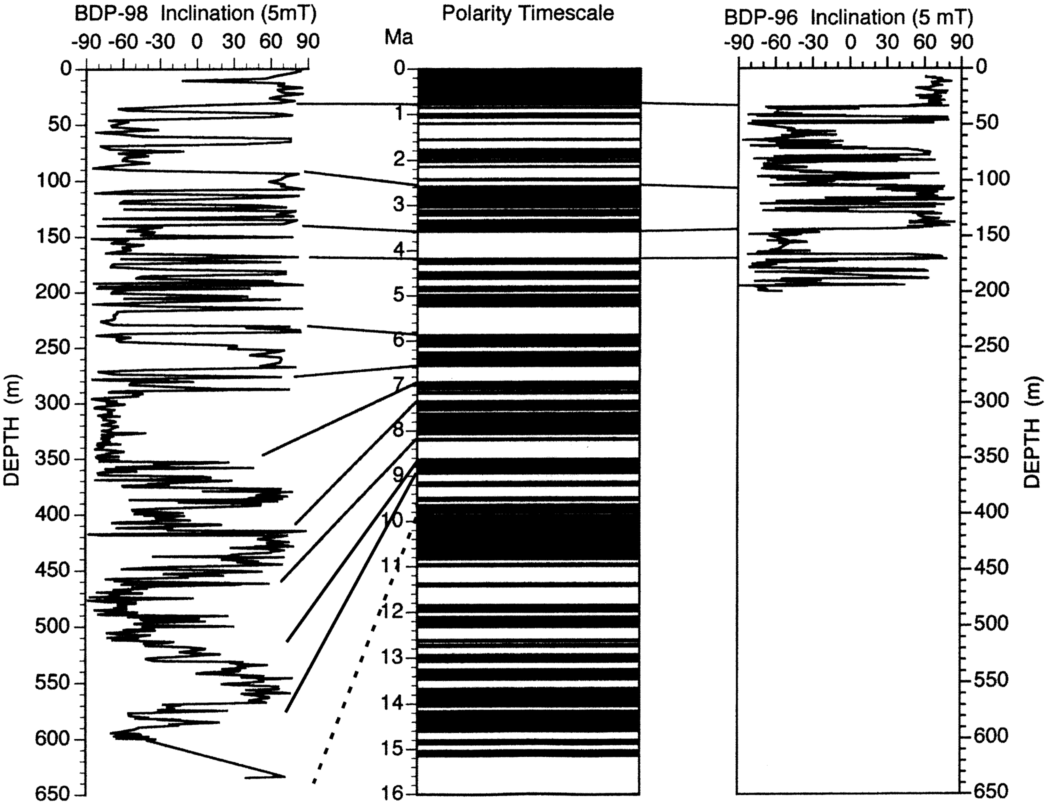

Fig. 9. Correlation of the BDP-96 and BDP-98 inclination profiles with the reference polarity time scale (Cande and Kent, 1995; Champion et al., 1988; Clement and Kent, 1987). The preliminary age model indicates that the cored section of the BDP-98 borehhole spans over 9 Ma.

climates in southern subtropics, with mean temperatures in January above 0°C and in June above 28°C, and with annual precipitation of about 1500 mm/yr. A slight cooling and decrease in humidity in the Baikal region occurred in the Middle Miocene. The mean January temperature then ranged from 0°C to –6°C, while the summer temperature had little variation. The ancient vegetation of the southeast Siberia in the Middle Miocene appears analogous to modern forests in South China at 35°–42°N (Belova, 1985). The climate of the late Miocene is marked by a further decrease in winter temperatures (down to –10°C) as well as by a decrease in precipitation (to 1000 mm/yr). This climate change resulted in the disappearance of many thermophilic plant species that also require humid conditions (magnolia, tulip tree, chestnut, bog cypress, beech, etc.) (Belova, 1985). The availability of moisture during the Early Pliocene was variable, as suggested by regular alternation of arid and semi-arid phases documented in the sedimentary record (Vorobyova et al., 1995). The climate of the Early Pliocene was close to the climate of the arid subtropics—the southern part of the temperate climate belt. By the end of the Pliocene in southeast Siberia, a strong cooling trend had developed, associated with an increase in humidity. This change is also associated with dramatic changes in faunal complexes (Vorobyova et al., 1995). By the end of the Pliocene the climatic conditions in the Baikal region were similar to those of the Quaternary (Belova, 1985; Vorobyova et al., 1995).

Using the preliminary paleomagnetic age model, we may now attempt to place the continuous sedimentary section at the BDP-98 drill site in the context of regional stratigraphy from the Miocene to the Quaternary (Fig. 12). Of particular importance are the Ol'khon Island strata, which are directly adjacent to Academician Ridge (Fig. 1). The Upper Miocene–Lower Pliocene Sasinsky Formation overlies the oldest Olkhon deposits of the Tagai Formation, which fill in small synrift depressions, formed on the surfaces of tilted tectonic blocks. In places, Sasinsky deposits lay directly on crystalline basement. Stratigraphically, Sasinsky deposits therefore correspond to the lower member of the B seismic–stratigraphic sequence at the Academician Ridge, whereas the deformed sediments with discontinuous acoustic patterns filling in the depressions of crystalline basement at the bottom of the B sequence apparently correspond to the Tagai unit, which is faunistically dated as Middle–Upper Miocene (BDP-Members, 1998; Vorobyova et al., 1995).

The thickness of Late Miocene–Early Pliocene deposits of the Sasinskaya and Saraiskaya/Odonim

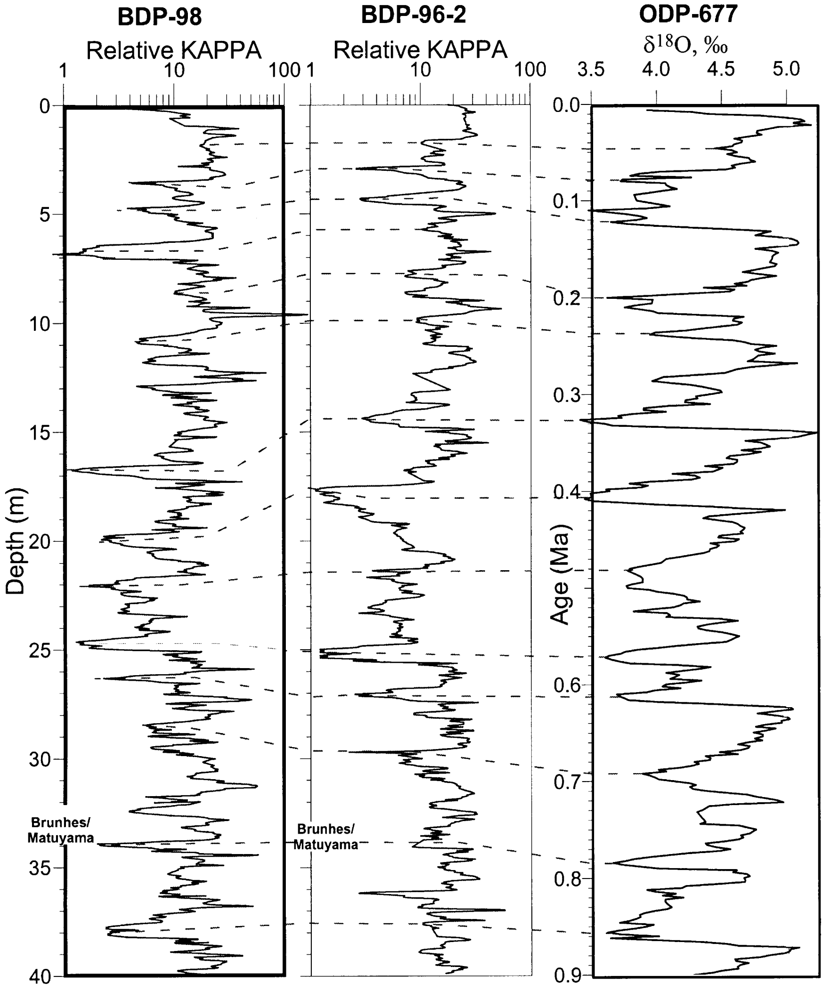

Fig. 10. BDP-96 and BDP-98 magnetic susceptibility records during the Brunhes chron demonstrate reliable correlation with each other and with the ODP 677 oxygen isotope record (Shackleton et al., 1990). Note the reversed scale of the marine isotopic record.

Formations at Olkhon do not exceed 10–60 m (Fig. 12). In contrast, in the new BDP-98 drill core the thickness of strata corresponding to this time interval exceeds 440 m, thus greatly expanding the sedimentary section available for studying paleoclimate cyclicity and variability during this time interval. On shore, the Early/Late Pliocene boundary corresponds to erosion associated with a major Neobaikalian tectonic phase (Logatchev et al., 1974; Logatchev, 1998; Mats, 1993) and with formation of a weathering crust (Fig. 12). This interval in the BDP-98 section corresponds to 130–140 m core depth and is characterized by continuous sediment accumulation (Fig. 11). The BDP-98 section provides an opportunity for detailed study of the paleoclimate response at this important boundary in the Baikal region. The interpretations based on terrestrial sections from Olkhon and from the southern part of the Lake Baikal depression agree that this period was indeed warm, although they contradict each other in interpreting the humidity conditions (Vorobyova et al., 1995). In the BDP-98 record this boundary is associated with a transition to the most diatom-rich deposits for the entire 600-m section, with low proportions of clay and coarse fractions.

The new BDP-98 section also provides important evidence for the onset of glacial conditions in Siberia. Based on terrestrial Plio–Pleistocene sections of the Kharantzi and Nyurgan Formations, the first evidence for cold climate corresponds to the lower Olduvai subchron at the top of the Kharantzi Formation, where a pedocomplex is observed with six cryoturbated tundra-type gleyed soils. However, the earliest glaciations were believed to have occurred about 1–1.2 Ma BP, corresponding to the deposits of the Zagli Formation (Fig. 12). The BDP-98 section, however, with its robust paleomagnetic scale, presents sound evidence for initiation of glacial periods in the region as early as the Matuyama/Gauss paleomagnetic reversal boundary.

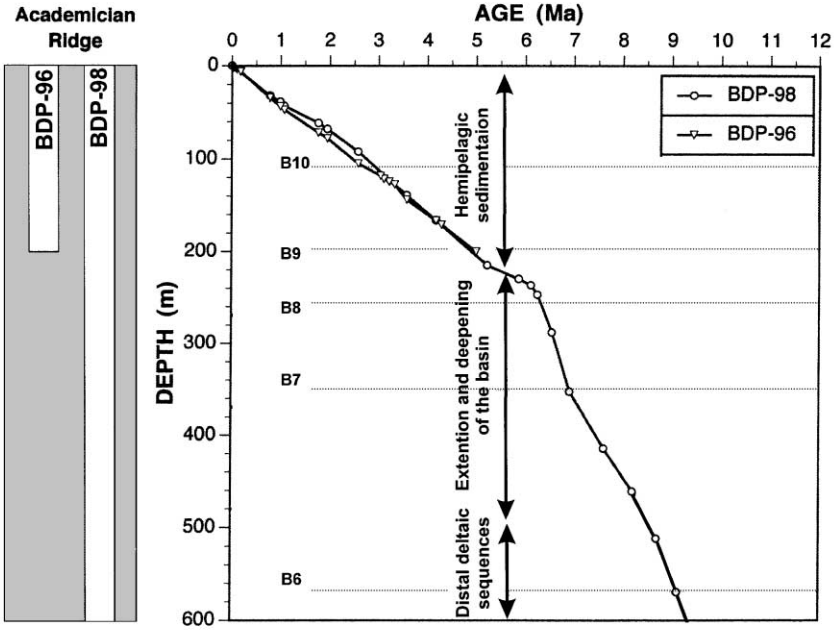

Fig. 11. Paleomagnetic age models for drill core sections BDP-98 (circles) and BDP-96 (triangles), showing a remarkable agreement for the past 5 Ma. According to the current interpretation, the BDP-98 drill site was characterized by high sedimentation rates from 10 to 6 Ma BP followed by the period of slow steady sedimentation from ca. 6 Ma BP till present time. Despite the notable inflection in the profile of sedimentation rate at 230–260 m core depth, no clear evidence for erosion was found in lithological composition of the BDP-98 drill core.

The first layers of diatom-barren clay, typical of glacial conditions, are found at about 100 m core depth (Figs. 5 and 12). At this core depth the average content of diatoms drops dramatically, and the clay content, on the contrary, dramatically increases (Fig. 5), changing the nature of the diatom response, as reflected in the diatom abundance profiles (Figs. 5 and 12). This lithological response in the BDP-98 corroborates the earlier paleoclimatic interpretation of a similar response in the BDP-96 drill cores (Karabanov et al., 2000; Prokopenko et al., this issue). In comparison with the discontinuous onshore sections of subaerial and fluvial deposits, the BDP-98 drill core makes available an expanded and continuous late Pliocene–Pleistocene section of over 140 m in thickness (Fig. 11).

From comparison between the composite onshore section of the Baikal depression and the new BDP-98 drill core, there is ample evidence for reliable correlation. The lowermost deformed and discontinuous sediments of the B sequence set at the Academician Ridge correspond stratigraphically to the oldest onshore Tagai Formation. The Sasinsky Formation may be correlated with the lower member of the B seismic–stratigraphic sequence, whereas the Kharantzi and Nyurgan Formations correspond to the upper A seismic–stratigraphic sequence above the B10 acoustic reflection boundary (Fig. 4). Thus, the new BDP-98 drill core section presents a previously unavailable expanded and continuous sedimentary section from the Late Miocene to present detailed studies of the environmental and climatic changes of the past 9 million years in continental interior Asia.

12. Sedimentary environments at academician ridge during the past 10 Ma

As noted earlier, lithological features of the BDP-98 sediments, and their physical properties, allow the demarcation of a number of relatively homogenous intervals, whose boundaries coincide with positions of seismic reflectors. At the same time, lithological investigations do not show any marked breaks in sedimentation. The entire studied sequence had been deposited in a relatively deep subaqueous basin.

However, the lowermost interval of the BDP-98 section (600–480 m core depth) differs considerably from the overlying sediments in terms of high contents of silt, sand, and gravel. This lower interval also has lower water content and higher sediment densities, and is characterized by abundant fossilized plant fragments, by sand–silt interbeds and by turbidite beds. These lithologic features indicate that the sediments of this interval were deposited in the more near shore, shallower environment with high inputs of terrigenous clastic material. The delta of a large river, apparent from the seismic profiles below the B6 acoustic boundary (Fig. 2), is a most likely source. The BDP-98 drill site during B6 time was apparently located on a distal slope of this delta formed by Paleo-Barguzin River

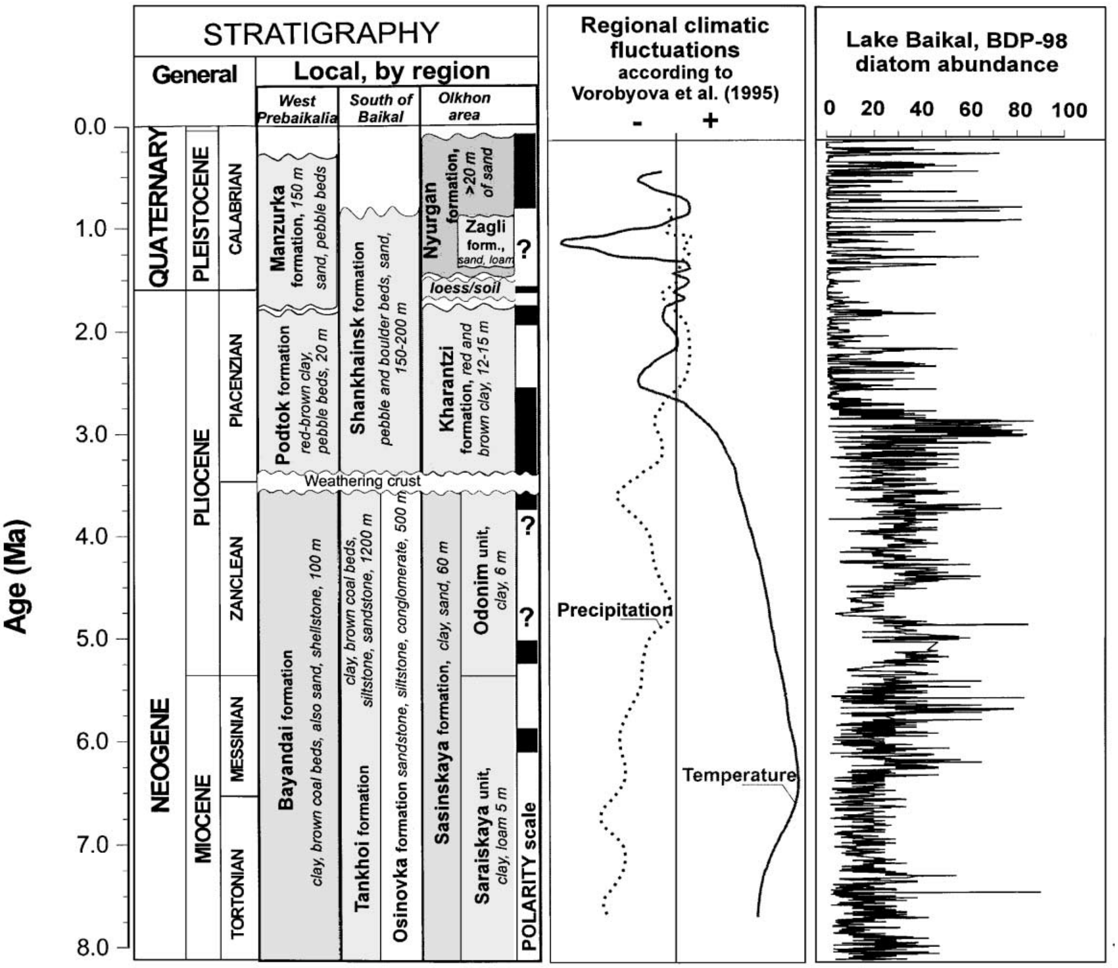

Fig. 12. Regional Late Miocene–Pleistocene stratigraphy for the Lake Baikal depression and a paleoclimatic interpretation based on palynological and pedological studies (based on Vorobyova et al., 1995) compared with the BDP-98 diatom abundance profile. The continuous sedimentary record from this drill core makes available an expanded Late Miocene–Pleistocene section to reveal regional paleoclimate variations and to better constrain their timing (see text). Interestingly, the broad temperature optimum from 6.5 to 3 Ma BP reconstructed from the onshore sections corresponds to the interval of the highest diatom accumulation in Lake Baikal; however, the BDP-98 record shows high degree of variability over this time interval.

(Zonenshain et al., 1993; Moore et al., 1997). The new BDP-98 data confirm the interpretation by Moore et al. (1997) that a deep basin existed at the Academician Ridge of Lake Baikal during B6 time. We interpret the lithology of the 600–480 m interval in BDP-98 as a distal deltaic facies (Figs. 5 and 6).

The progressive decrease in the content of coarse material, the occurrence of sand, silt laminae and plant debris observed between the depths of B6 and B7 acoustic boundaries (Figs. 5 and 6) indicate that the distance between the drill site and the terrestrial sediment source have been gradually increasing over the core depth interval of 480–380 m (Figs. 5 and 6). Above 380 m core depth, roughly corresponding to the B7 acoustic boundary, the steady increase in diatom content was paralleled by the continued decrease in the coarse fraction content (Figs. 5 and 6). We interpret this facies change to represent the transition to hemipelagic sedimentation from the water column at the BDP-98 drill site in response to the extention and deepening of the basin separating Academician Ridge from the southeastern shore of Lake Baikal (Fig. 1). This transition appear to have completed by B8 time, when diatom-rich fine sediments with abundant vivianite inclusions began accumulating (Fig. 6), forming relatively uniform strata at 280–110 m core depth. The dramatic lithologic changes above the B10 acoustic boundary at ca. 104 m core depth did not represent a change in the overall sedimentary environment at the Academician Ridge. Instead, they indicate the sources and transport mechanisms of sedimentary material, involving introduction of dense glacial clay and coarse ice and iceberg-rafted detritus. The undisturbed sediments of the upper A sequence at the Academician Ridge were still evidently accumulating in a stable hemipelagic environment.

13. Implications from BDP-98 for rifting at academician ridge during the past 10 Ma

The above changes of the sedimentary environments at BDP-98 drill site, the correlation of core lithology with acoustic boundaries, and the paleomagnetic age scale of the BDP-98 section provide a robust basis for a new conceptual model for the development of the Academician Ridge within the time span of 0–10 Ma, building on previous paleotectonic reconstructions (Zonenshain et al., 1993; Kazmin et al., 1995; Moore et al., 1997).

According to the seismic data and obtained age estimates, the seismic–stratigraphic sequence B began to form at the Academician Ridge from the Middle Miocene (Moore et al., 1997). However, the reconstruction by Moore et al. (1997) shows that although the South and North Basins existed at that time, the part of the Academician Ridge where the BDP-98 drill site is located was subaerially exposed. The new drilling data indicate that about 10 Ma ago, a vast paleobasin, deepening in a westward direction, existed at the present location of the Academician Ridge and that the location of the BDP-98 drill site corresponded at that time to the

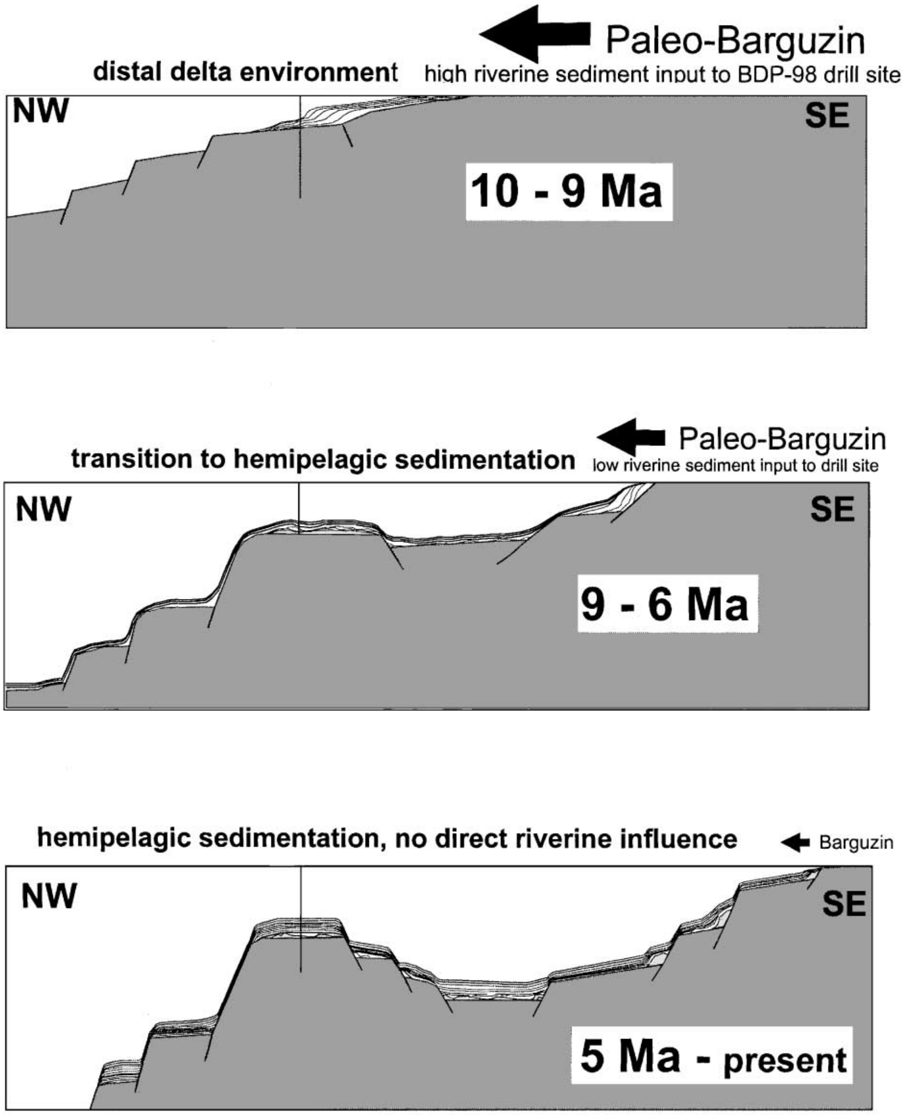

Fig. 13. Schematic representation of changes in sedimentation processes at the drill site BDP-98 (indicated by vertical line) in response to tectonic development of the Academician Ridge of Lake Baikal. Figure is not to scale. Black arrows schematically represent the amount of fluvial supply of clastic material from Paleo-Barguzin River to the BDP-98 drill site. About 10 Ma ago a relatively shallow basin existed at the present location of the Academician Ridge and the location of the BDP-98 drill site corresponded to the eastern slope of this basin. Between 9 and 6 Ma the rift basin further extended and deepened, whereas the relatively stable block of Academician Ridge formed a bathymetric high. The material brought from the Paleo-Barguzin River delta was a major source of sedimentary material at the BDP-98 drill site almost until the end of Late Miocene. Some time between 7 and 5 Ma BP, the direct fluvial source material was completely cut off and since then the elevated block of Academician Ridge was an area of undisturbed hemipelagic sedimentation.

eastern slope of this basin. Material brought from the Paleo-Barguzin River delta was the major source of sedimentary material at the BDP-98 drill site almost until the end of the Late Miocene (Fig. 13) and was deposited as distal deltaic and pro-deltaic facies.

As the rift basin further extended and deepened, the relatively stable block of the Academician Ridge formed a topographic high of the lake bottom, separating the North and Central basins (Fig. 13). The acoustic boundary B7, demarcating the end of significant fluvial input to the BDP-98 drill site, is dated around 7 Ma BP (Fig. 11). It is hypothesized that during this period a fluvial source could have been located in the northeast, perhaps north of the Ushkanie Islands (Zonenshain et al., 1993; Kazmin et al., 1995).

Between 7 and 5 Ma BP the fluvial source material was completely cut off at the elevated block of Academician Ridge (Fig. 13). The sedimentary environment thus became similar to the presently observed undisturbed hemipelagic sedimentation from water column with the slowest sedimentation rates for Lake Baikal. The change between 7 and 5 Ma BP is readily observed in the inflection of the slope of sedimentation rate profile at the interval of 200–240 m core depth in Fig. 11.

14. Conclusions

The new 600-m drill core section of BDP-98, obtained at Academician Ridge of Lake Baikal, has successfully recovered a sedimentary record of the past 10 Ma. The entire section is represented by reduced lacustrine sediments, thus indicating virtually uninterrupted sedimentation in the water-filled basin of paleo-Baikal. The upper part of the section (roughly 100 m) records typical glacial/interglacial lithologic cycles of alternating layers diatomaceous ooze and glacial silty clay. The middle part of the BDP-98 section is comprised of thick strata of diatomaceous mud, whereas in the lower part (600–380 m core depth), turbidites, sand beds and abundant coalificated terrestrial plant debris are found. The lithologic evidence suggests that the facies at the drill site have gradually changed from distal deltaic environments represented by the lower 120-m interval of BDP-98 to undisturbed hemipelagic sedimentation from the water column represented by the upper 200-m interval. The gradual facies changes followed the evolution of basin morphology and changes in sediment supply at the Academician Ridge of Lake Baikal. These lithologic changes are also reflected in significant changes in sedimentation rates.

The lithological features and physical features of sediments agree well with the seismic profile of the Academician Ridge. Moreover, the comparison shows the best agreement of seismic boundaries with the change of sediment density characteristics. This is quite reasonable as the velocity of elastic wave distribution is proportional to the environment density.

The BDP-98 section puts several important time constraints on the rifting history of Lake Baikal and shows reliable correlation between lithology and physical properties of the sediments with calculated positions of acoustic reflection boundaries interpreted from studies of multichannel seismic profiles. For instance, the BDP-98 sedimentary record suggests that deposition of the relatively coarse, distal deltaic sediment sequences of B6 were fed by the Paleo-Barguzin River from a time prior to 10 Ma until approximately 8.5 Ma BP. With subsequent propagation of the Central Basin to the north, the fluvial sediment source at the Academician Ridge was cut off. By 7–5 Ma BP the sedimentary environment at the Academician Ridge became similar to the presently observed undisturbed hemipelagic sedimentation.

The paleomagnetic age model BDP-98 section allows the ages of significant seismic–stratigraphic sequence boundaries to be defined. All these boundaries are associated with similar lithologic responses: drops in diatom abundance, increases in clay and coarse fractions, paralleled by increases in gamma-activity, and increases in sediment density. The lithological composition of the drill cores indicates that at the stable block of Academician Ridge, where the BDP-96 and BDP-98 drill sites are located, these acoustic reflection boundaries are not associated with major erosional events producing unconformities, but instead are the result of changes in sediment density and composition.

The entire 10-Ma lacustrine section contains abundant diatoms and thus allows previous Plio–Pleistocene diatom and biogenic silica records to be extended into the Miocene. Similar to previous shorter Baikal Drilling Project sections, the BDP-98 record is characterized by high-amplitude variations of diatom content above the Matuayama/Gauss paleomagnetic reversal boundary, the time corresponding to the onset of periodic glaciations in the Lake Baikal area. Below this paleoclimatic threshold, the nature of the diatom signal in BDP-98 is quite different: the average diatom content is higher and variations are of lower amplitude. Most likely paleoclimatic in origin, these variations presumably reflect past changes in the regional moisture regime of southeast Siberia under conditions of warm subtropical climate during the Miocene and Early–Middle Pliocene.

The continuous BDP-98 drill core is a key section for refining reconstructions of the Neogene–Quaternary climatic evolution of continental Asia, because it represents a greatly extended and continuous Late Miocene–Pleistocene sedimentary section and covers the hiatuses often present in composite continental sections. The preliminary data from BDP-98 have already yielded important paleoclimatic information. For instance, BDP-98 supports the conclusion that the first regional glaciation occurred around the Matuyama/Gauss reversal, whereas previous studies have suggested that the earliest regional evidence for cooling and permafrost development was found in the Olkhon sections only at the bottom of the Olduvai subchron.

Several lithologic indices suggest that significant changes have occurred in physics and chemistry of Lake Baikal itself during the past 10 Ma. Among the most evident is the presence of sedimentary carbonates, which are abundant in the lower part of the BDP-98 section, although they are not normally preserved in modern Baikal. The presence of vivianite inclusions might appear to be an indicator of past oxygen availability in the lake and its effects on the phosphorus cycle. These inclusions are abundant in the upper part of the BDP-98 section, but are virtually absent in the lower part. It is quite possible that prior to 6 Ma BP, despite relatively shallow water depths (presumably 200–300 m) at the BDP-98 drill site throughout the studied 10-Ma interval, the waters of paleo-Baikal at Academician Ridge were hypoxic due to restricted mixing under conditions of warm subtropical climates.

Acknowledgements

The BDP-98 campaign of the Baikal Drilling Project was supported by the NSF grant EAR-9614770, the Siberian Branch of Russian Academy of Sciences, the Russian Ministry of Geology and by the Science and Technology Agency of Japan (STA). We thank B.N. Khakhaev and the entire NEDRA Scientific Drilling Team for the successful drilling effort. We are grateful to the crew of R/V *Baikal* for successfully navigating in the extreme conditions. The first BDP-98 report was published by *Russian Geology and Geophysics* (BDP-Members, 2000). This manuscript was prepared by A. Prokopenko, E. Karabanov, D. Williams and M. Kuzmin based on new and revised data.

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