ISSN 0024-4902, Lithology and Mineral Resources, 2006, Vol. 41, No. 4, pp. 303–316. © Pleiades Publishing, Inc., 2006.
Original Russian Text © S.A. Kashik, T.K. Lomonosova, 2006, published in Litologiya i Poleznye Iskopaemye, 2006, No. 4, pp. 339–353.

Cenozoic Deposits of the Underwater Akademicheskii Ridge in Lake Baikal

S. A. Kashik and T. K. Lomonosova

Institute of the Earth's Crust, Siberian Division, Russian Academy of Sciences, ul. Lermontova 128, Irkutsk, 664033 Russia

e-mail: kashik@crust.irk.ru

Received June 8, 2005

Abstract—This paper presents data on the lithological composition of Cenozoic deposits penetrated for the first time by boreholes BDP-96-1, BDP-96-2, and BDP-98 down to a depth of 600 m on the underwater Akademicheskii Ridge in Lake Baikal. The deposits are subdivided into the upper (Angara) and lower (Barguzin) sequences, which span the Middle Miocene–Holocene period. They formed under different climatic conditions and tectonic settings. Sources of the terrigenous material were also different. Outbursts of diatom- and mineral formation in Lake Baikal can be related to not only climatic fluctuations in the Miocene–Holocene, but also the endogenous activity. By the analogy with the World Ocean, underwater gas–hydrothermal fluid discharge detected at the water–bottom interface in this lake may be accompanied by the formation of diatomaceous oozes and ferromanganese nodule fields and the concentration of rare elements.

DOI: 10.1134/S0024490206040018

Lake Baikal is a unique object for studying present-day and ancient sedimentation, as well as specificity of postsedimentary processes. Having emerged as a result of collision between the Eurasian and Indian plates, Lake Baikal represents the central and oldest core of the largest continental rift zone of Asia (Logachev, 2003). Therefore, this region retained the paleorecord of geological and climatic events over many million years. Deciphering of these events began in 1990 with investigations carried out by the international scientific community within the framework of the Baikal Drilling Project (BDP).

In 1996 and 1998, three boreholes BDP-96-1, BDP-96-2, and BDP-98 were drilled in the axial zone of the Akademicheskii Ridge, which represents an underwater diagonal block separating the northern and central parts of the Baikal Basin (Fig. 1). The choice of this zone for drilling was prompted by the following fact. Since sedimentation rate in this region is low (4–5 cm/ka), we can obtain here the longest geological record. In addition, we can correlate the bottom sequence with the subaerial part of the Akademicheskii Ridge, which represents an elevated block of Ol'khon Island.

In addition to bottom sediments of separate Baikal basins, considerable attention was given to the diagonal crosspiece between the northern and central basins of the Baikal. The crosspiece includes the underwater block (Akademicheskii Ridge) and the subaerial Ol'khon (Ol'khon Island) and Ushkanii (Archipelago) blocks. Their subaerial and underwater investigations provided insights into the structure of the crosspiece, in general, and the evolution of the Akademicheskii Ridge (Kudryavtsev and Nikolaev, 1989; Zonenshain et al., 1992, 1993; Hutchinson et al., 1992; Kaz'min et al., 1995; Grachev et al., 1997, 1998; Bukharov and Fialkov, 1996; Moor et al., 1997; *Nepreryvnaya* …, 1997; *Pozdnekainozoiskaya* …, 2000; *Glubokovodnoe* …, 2001).

The purpose of this work is to elucidate lithological features of sediments on the Akademicheskii Ridge and to interpret on this basis some paleogeographic features of sedimentation.

MATERIALS AND METHODS

In order to solve the problem posed, we used a complex of modern optical, chemical, mathematical, and instrumental methods. More than 200 samples of different-age sediments taken from the Akademicheskii Ridge down to the depth of 600 m were analyzed. The upper part of the section was studied based on boreholes BDP-96-1 and BDP-96-2, whereas the lower part was based on borehole BDP-98.

The grain size composition of sediments was studied by the sieving method (fractions 1–0.5, 0.5–0.25, 0.25–0.1, 0.1–0.05, and <0.05 mm). Fractions 0.01 and <0.001 mm were separated by elutriation in 20 min and 24 h, respectively.

Light and heavy fractions in different-age sediments were studied by the immersion method with the preliminary separation of the sand–silt material in heavy liq-

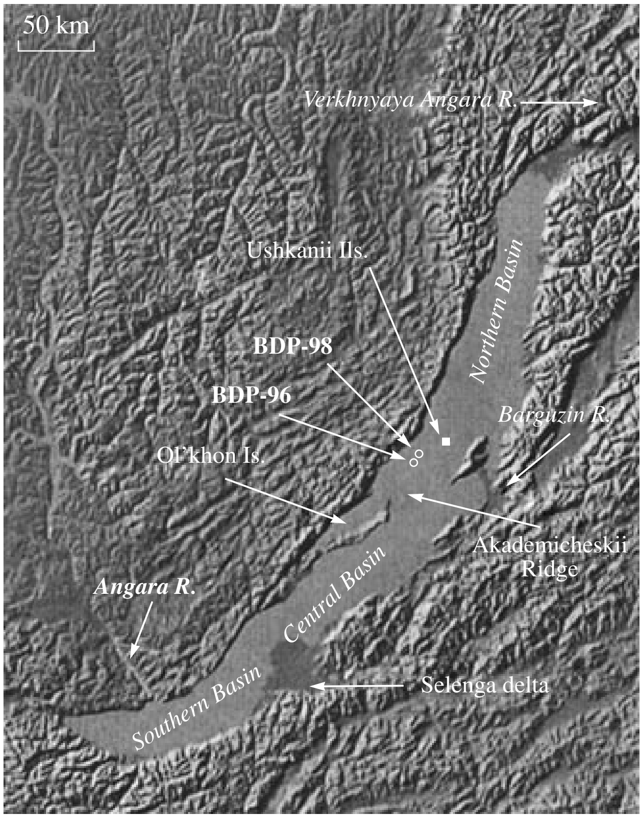

Fig. 1. Topography of the Baikal rift zone and sites of deep boreholes BDP-96 and BDP-98.

uid with the specific gravity of 2.8. After calculating the percentages of minerals, we determined the correlation between separate heavy-fraction minerals at different stratigraphic levels that indicate the formational affiliation of sediments recovered by boreholes.

The percentage and mineral composition of the clayey component were determined. Mineral associations of the clayey component were studied simultaneously in the primary rock and fraction <0.001 mm by the X-ray diffractometry and optical methods coupled with the scanning electron microscopy. X-ray diffractometry was carried out with a DRON-3.0 diffractometer (CoK_α radiation, Fe-filter). Oriented preparations of clay minerals were photographed in the air-dry, glycol-saturated, dimethylsulfoxide-saturated, and calcined (up to 550 and 600°C) states.

Electron microscopic analyses were carried out using a SEM-525M microscope on the preliminarily gold-shadowed samples with undisturbed texture. Special attention was given to authigenous formations, single crystals or clusters of which are usually concentrated around a pore space. Moreover, in order to identify minerals of the fine pelite fraction and elucidate their quantitative proportions in polymineral mixtures, we used chemical (silicate) analyses coupled with the mathematical procedure of linear programming and the calculation of stoichiometry of individual mineral phases (Kashik, 1973; Kashik and Mazilov, 1984). We also determined absorption capacity and the exchange complex of minerals of the fine pelite fraction, the composition of which changes with depth according to variations in the chemical composition of interstitial waters.

The factor analysis was used to elucidate associations of heavy fraction minerals and establish trends of their distribution in rocks. Calculation and plotting of hierarchical dendrograms of the cluster analysis were realized based on special software packages (Kashik and Mazilov, 1984).

We also investigated low-temperature hydrothermal metasomatites, which were studied previously and taken in the course of dredging (Mats et al., 2000).

BASIC STRUCTURAL FEATURES AND THE AGE OF SEDIMENTS

Cenozoic deposits are retained as fragments in the subaerial (Ol'khon Island) and underwater (Akademicheskii Ridge) blocks of the crosspiece that separates Lake Baikal into the northern and southern basins. The deposits include Cretaceous–Paleogene, Neogene, and Quaternary weathering crusts, as well as Paleogene, Neogene, and Quaternary sediments (Logachev et al., 1964; Rybakov, 1964; Mats et al., 1982, 2001).

Crust formation related to climatic fluctuations and stabilization of tectonic regimes was a periodic (latent, in some cases) process during the Baikal region evolution. The Cretaceous–Paleogene kaolin-type weathering was replaced by the formation of kaolin–laterite crust in the Paleocene–Early Eocene, smectite–redrock crust in the Neogene, and detritus–gruss crust in the Pleistocene–Holocene. Present-day fields of weathering crusts represent relicts of linear–areal eluvial profiles (Kashik and Mazilov, 1994). Weathering crusts are retained beneath Paleogene and Neogene sediments in the adjacent Baikal foredeep.

Insignificant (in area and thickness) exposures of Paleogene deposits are represented in the subaerial part of the crosspiece by red-colored and variegated (subaqueous, subaerial, and lacustrine) sediments of essentially kaolinite composition (humid climate formation).

Neogene sediments constitute the bulk of the Cenozoic cover (in terms of thickness and area) in the Ol'khon block and adjacent continental part (semihumid or semiarid climate formation). Previously, based on the geological survey data, Neogene deposits in the Ol'khon land block was limited by the Miocene–Early Pliocene Khalagai Formation (Logachev et al., 1964). Later, the Middle Miocene Tagai, Upper Miocene–Lower Pliocene Sasin, and Upper Pliocene Kharantsin formations, which occur on the weathering crust of the crystalline basement and Paleogene deposits, were also referred to the Neogene (Mats et al., 1982, 2001). They are represented by lacustrine, subaqueous, and subaerial sediments of essentially clayey deposits with a

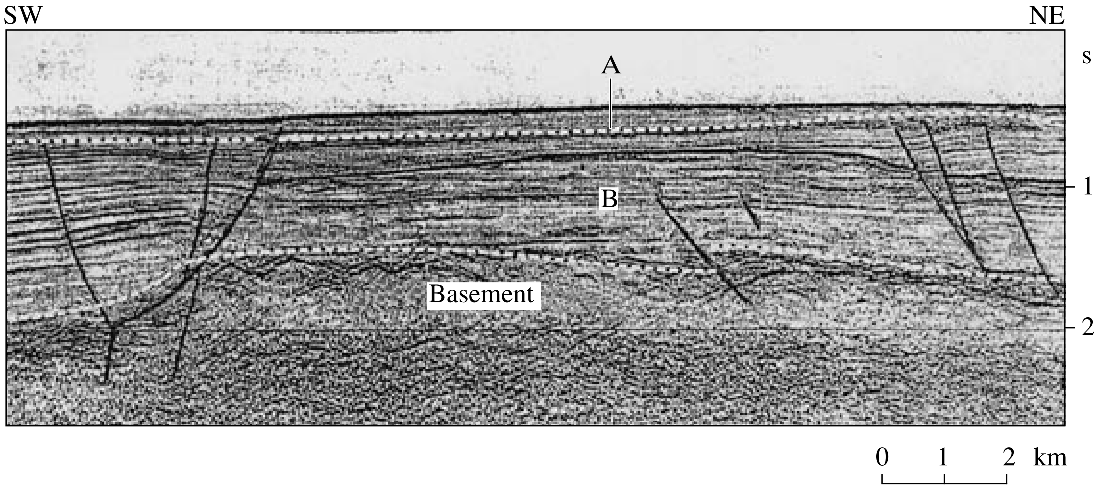

Fig. 2. Seismic profile along the Akademicheskii Ridge (Moor et al., 1997).

sharp prevalence of smectites in the lower (Miocene–Early Pliocene) part of the section and hydromicas (with the smectite admixture) in the upper (red-colored carbonate and gypsum-bearing) part.

Quaternary lacustrine, subaerial, and aerial sediments on the Ol'khon Island occur at different hypsometric levels.

The underwater block (Akademicheskii Ridge) represents an asymmetric uplift (more than 1000 m above the lake bottom) with a steep high southeastern slope and a gentle northwestern slope. The axial Akademicheskii longitudinal fault separates the ridge of the same name into the southeastern and northwestern segments. Moreover, the underwater Akademicheskii block is crosscut by transverse and diagonal faults. The southeastern segment is subsided along the Akademicheskii Fault. According to seismic profiling data, this segment is covered with thick sediments (up to 1–1.5 km) penetrated by boreholes BDP-96-1 and BDP-96-2 (200 m) and borehole BDP-98 (600 m) less than one-third of their thickness. An unconformity was recorded in the sedimentary sequence (Kuz'min et al., 1997). Basal units occur on the weathering crust traced during underwater geological investigations (Zonenshain et al., 1993).

Cenozoic sediments occur on the weathering crust of the basement crystalline rocks (gneiss, schist, and marble) in the northwestern segment. The crust was penetrated by corers (Goldyrev, 1982) and confirmed by underwater geological investigations as well (Zonenshain et al., 1993).

The sedimentary cover of the Akademicheskii Ridge is represented by two seismostratigraphic sequences *A* and *B* (Moor et al., 1997). The lower sequence *B* occurs on the crystalline basement and reflects the early (Barguzin) stage of sedimentation in the Central Basin. Its thickness is maximal (>1000 m) in the southeastern part. The upper (Angara) sequence *A* (~200–230 m) overlies with unconformity sequence *B* and generally tends to the southwestern slope of the basin (Moor et al., 1997) (Fig. 2). Moreover, seismic profiling of the southeastern segment revealed a wedge, which was interpreted by some researchers as a paleodelta (Kaz'min et al., 1995; Moor et al., 1997). Since sequence *B* has not been penetrated completely, its age is problematic.

Palynological data reported by V.A. Misharina from the lower (Barguzin) part of the section in borehole BDP-98 (260–600 m), suggest that sedimentation in this area was marked by the existence of spruce–pine forests with the admixture of cedar, podocarpus, hemlock, birch, hazel, alder, araucaria, dacrydium, larch, exotic spruce, yew-tree, ephedra, Juglandaceae, oak, linden, and honeysuckles. Such exotic relicts as rhododendron, beech, liquidamber, Proteaceae, magnolia, and others are rare. The subordinate spores and herbage are generally represented by sphagnum, myrapods, fern royal, sedge, grasses, Chenopodiaceae, Onagraceae, persicaria, Compositae, and others.

The existence of the assemblage with the predominance of temperate-zone coniferous and deciduous species associated with a few broad-leaved thermophile and subtropical exotic plants in forest phytocenoses suggests that the warm climate was replaced at that time by the temperate–cold climate. Taiga forest gradually replaced the broad-leaved forest. Pine and spruce became the predominant species. Alder, birch, and hazel predominated among deciduous plants. Nut-tree, hornbeam, beech, hickory, oak, linden and other plants were subordinate in phytocenoses. Exotic magnolia, podocarpus, and other species could grow in the underbrush.

The assemblage mentioned above has much in common with Middle–Upper Miocene assemblages in the Barguzin, Selenga, and Tunkin depressions, the southeastern shore of Lake Baikal (the lower part of the

Taikhoi Group), Ol'khon Island (Tagai Subformation of the Khalagai Formation), and the Bayanda Formation at the Angara–Lena interfluve. Hence, the age interval of the Barguzin sequence may fall within 5.4–12 Ma.

Paleomagnetic data also yield a close age interval of 5 to 14–15 Ma (Kuz'min et al., 1997; *Nepreryvnaya* …, 1998; *Pozdnekainozoiskaya* …, 2000). According to (Kravchinsky et al., 2003), the lower boundary of the Gilbert epoch in borehole BDP-98 passes at a depth of ~240 m, which corresponds to the Miocene/Pliocene boundary. Therefore, the age of the upper (Angara) sequence can be dated back to the Pliocene–Holocene.

Based on the ^{10}Be isotope content in rocks of borehole BDP-98, Sapota (2004) considered that the age of the penetrated part of the Barguzin sequence (200–600 m) is 4.8–8 Ma. Hence, the upper sequence *A* can confidently be dated back to the Pliocene–Holocene.

Study of diatoms in bottom sediments from boreholes BDP-96-1 and BDP-96-2 (0–200 m) revealed that the Angara sequence contains abundant and diverse flora of freshwater diatoms of two major (plankton and benthos) assemblages (determination by N.V. Ignatova). Planktonic diatoms are represented by species of the *Aulacosira, Cyclotella*, and *Stephanodiscus* genera. Benthic diatoms are represented species of the following genera: *Achnanthes, Cocconeis, Cymbella, Diploneis, Epithemia, Eunotia, Fragilaria, Gomphonema, Navicula, Opephora*, and *Tabellaria*. Benthic diatoms are more diverse. However, the planktonic forms are more abundant than the benthic ones, indicating that the paleobasin was deeper during the deposition of the studied sediments. The diatom fossil flora comprises the following different (in age and origin) groups: (1) Baikalian endemic long-living (Pliocene–present day) species: *Aulacosira baicalensis* (K. Meyer) Simonsen, *Cyclotella baicalensis* Skv., and *C. minuta* (Skv.) Antipova; (2) Baikalian endemic species that were abundant in the Pliocene and disappeared by the end of the Pliocene: *Stephanodiscus grandis* Churs. et Log., *S. bellus* Churs. et Log. var. *bellus* et var. *minor* Churs. et Log., and *S. carconeiformis* Churs. et Log.; (3) Late Pliocene–Middle Pleistocene extinct species characteristic of other regions: *Cyclotella radiosa* var. *lichvinensis* (Jouse) Log. comb. nov., *C. radiosa* var. *pliocaenica* (Krasske) Hakansson, and *C. temperiana* (Log.) Log.; and (4) currently existing benthic species with a wide distribution range.

In terms of appearance and composition, the diatom flora from the studied bottom sequence seems to be rather old (probably, Pliocene). The sequences are characterized by the abundance of old (extinct) species, which often dominate in the whole borehole section. Species typical for Late Pliocene freshwater basins of West Europe are also present. The Pliocene flora is suggested by the morphological variability of some species and the presence of the following transitional forms: *Cyclotella radiosa* var. *radiosa** *C. radiosa* var. *lichvinensis*, *C. radiosa* var. *lichvinensis** *C. radiosa* var. *pliocaenica, C. radiosa* var. *radiosa** *C. temperiana*, and *Stephanodiscus carconeiformis** *S. flabellatus* Churs. et Log. This fact indicates the genetic relationship between the species listed above. The presence of spores of some species in the assemblage, probably, suggests its relatively old age. For instance, no spores are formed in *C. radiosa* at present. The formation of spores was apparently typical for representatives of an older flora. The presence of previously unknown species in diatom assemblages is an undoubted indication of old age and specificity of the flora. We have found more than ten (previously unidentified) forms, which are likely to be new for science.

LITHOLOGICAL INVESTIGATIONS

Grain Size Composition of Sediments

Sections penetrated by boreholes BDP-96-1, BDP-96-2, and BDP-98 are primarily composed of silty clays or silty–clayey sediments (according to classification suggested by Rukhin, 1961), which are almost everywhere dominated by the fine-dispersed fraction (<0.01 mm) that makes up 15–96% (Fig. 3).

Coarse sandy fractions (>1.0 mm) are extremely rare and only found in 17 samples out of 215. Their content does not usually exceed 1% and varies within 0.03–3.46% (Fig. 3). The maximal content is recorded at a depth of 186.4 m.

In general, sandy fractions (2.0–0.01 mm) are common in borehole sections (0.1–81.5%, average 3%). The highest sand contents are confined to the lower part of sequence *A*.

The average content of the silty fraction (0.1–0.01 mm) in sediments is ~18% (1–80%). The sandy–silty material is poorly sorted. This is suggested by values of mean square deviations and average diameters of grains in fraction 2.0–0.01 mm. The mean square deviation (0.2–4.1, average 0.56) is always higher than the grain size (0.02–0.7 mm, average 0.07).

In general, results of the grain size analysis showed that the Akademicheskii Ridge section is a uniform silty–clayey sequence with episodic thin interlayers of medium-, fine-, and varigrained sands (intervals 186, 193, 477, and 490 m). These interlayers, probably, correspond to acoustic interfaces B7, B8, B9, and B10 distinguished in (Moor et al., 1997). The more detailed analysis of the sandy–silty fraction distribution in the borehole section revealed that this fraction increases toward the lower parts of the sequence (Fig. 3). This is likely to indicate a shallow-water regime during sedimentation of lower units of the Barguzin sequence.

The appearance of sandy interlayers in the lower parts of sequence *A* is most likely related to the late orogenic evolution of the Baikal rift zone identified as the Angara phase in (Moor et al., 1997). This stage was marked by activation of vertical tectonic movements and displacement of major provenances from south-

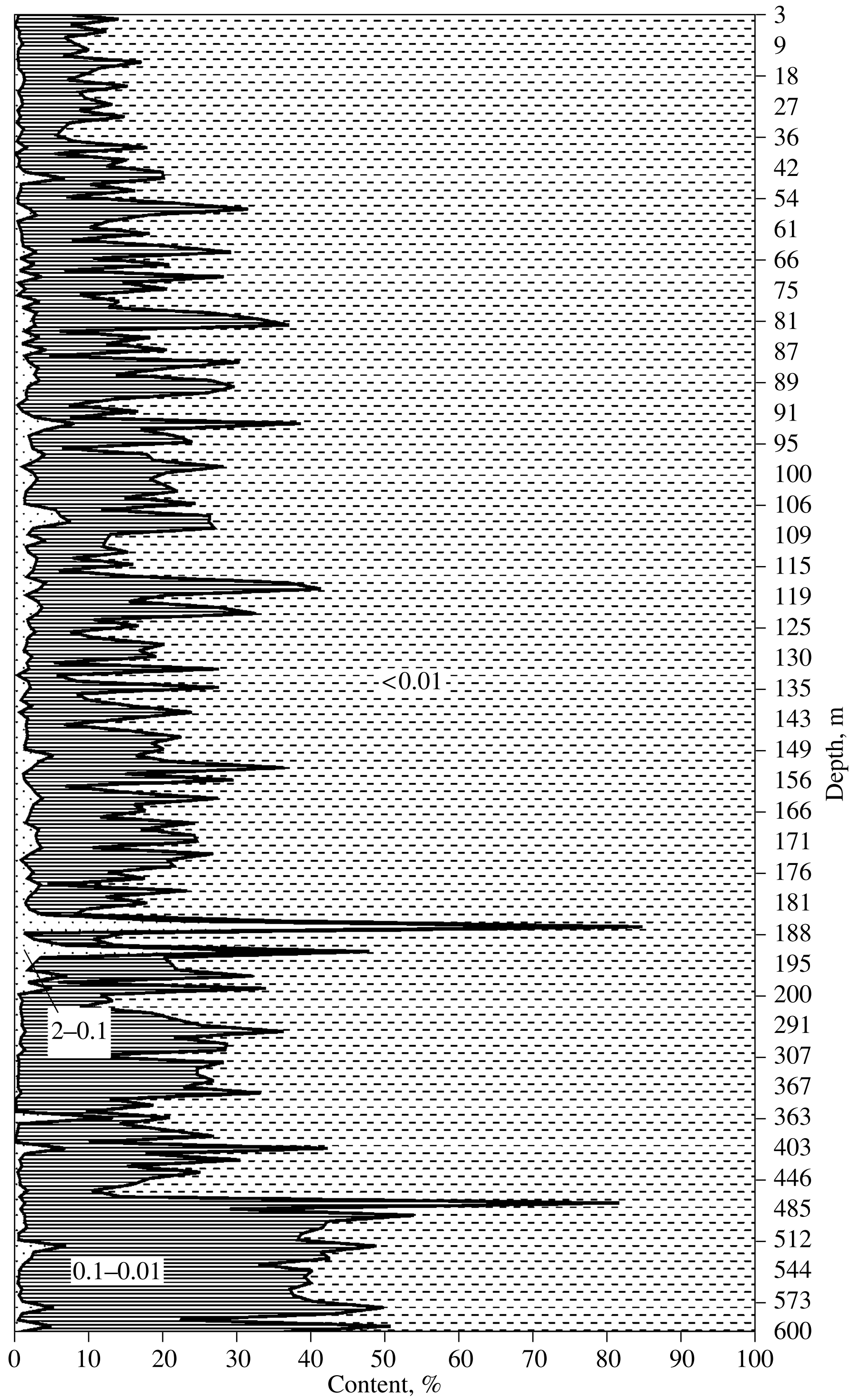

Fig. 3. Grain size composition of sediments (%) recovered by boreholes BDP-96 and BDP-98.

west (the paleo-Barguzin delta) to northeast (the present-day Angara region). At the Miocene/Pliocene boundary, the "slow rifting" environment (primarily, shallow and medium-depth basins) gave way to the "fast rifting" environment, which produced a deep lake that resembled the present-day Lake Baikal in terms of morphology.

It should also be noted that alteration of the structural pattern of sediments at the Miocene/Pliocene boundary was accompanied by variation in the sedimentation rate. Data on main centers of paleomagnetic dating (Fig. 4) including the Brunhes–Matuyama Chron (Kravchinsky et al., 2003) show the abrupt replacement of the slow sedimentation rate (average

3.77 cm/ka) in the Miocene by a faster rate (up to 5.4 cm/ka) in the Pliocene. This is also confirmed by data on the thickness of the upper and lower sequences accumulated during that time. The sedimentation rate increased abruptly at a depth of 240–260 m, which corresponds to 6.9–7 Ma. The lower part of the penetrated sequence is estimated at 11 Ma. Hence, the accumulation period of the major portion of Barguzin sediments was two times shorter relative to the Angara complex.

Mineral Composition of the Light Fraction

The light fraction (0.25–0.05 mm) includes the following minerals: quartz, plagioclases, potash feldspar, biotite, muscovite, chlorite, graphite, carbonates (calcite), and vivianite. The fraction also contains rock detritus, clayey aggregates, carbonized plant tissues, diatom shell remains, and sponge spicules. Figure 5 illustrates the distribution of major mineral components in the section.

Quartz is nearly universal in sediments of the penetrated section. In the majority of analyzed samples, its content exceeds the total percentage of feldspars. The average content is 20%. The maximal content of quarts fragments is 58%, while the minimal content (<1%) is recorded in places dominated by clayey aggregates. Quartz fragments are usually angular, subrounded, and, more rarely, rounded. Both pure colorless transparent and dull semi-transparent grains with powderlike inclusions are found.

Feldspars are the second most abundant minerals in the bottom sediments. Plagioclase is mostly represented by acid oligoclase and twinned varieties with $N = 1.543–1.550$, which generally correspond to basic oligoclase with the anorthite content of 24–25% (acid andesine, in rare cases). The average and maximal contents of plagioclase are 11.6 and 34%, respectively.

The mica group is represented by biotite, muscovite, and chlorite. Biotite is the major mineral (0.4–39%, average 14%). Biotite is found as brown, yellowish brown, greenish brown, dark green, and nearly black plates.

The maximal muscovite content in the borehole section does not exceed 8%. This mineral is entirely lacking in some samples. Muscovite shows an increasing trend toward the lower parts of the sedimentary sequence (from 2.2 to 3%).

Chlorite is also encountered not in all the samples analyzed. Its content varies within 0–3.2% (average 0.6%).

Graphite and vivianite are minor components in the studied section. Their maximal contents are 1 and 2.4%, respectively. Graphite is uniformly distributed in the section, while vivianite exhibits several peaks (15–17, 26–50, 95–100, and 175–200 m). Vivianite is found as both oxidized grayish blue and unaltered varieties. The unaltered variety forms colorless and light-colored prismatic crystals. According to the quantitative spectral analysis, the Co and Ni contents in vivianite are close to the clarke abundance in the lithosphere.

The content of clayey aggregates in the light fraction varies substantially (from 0 to 88%). They are usually composed of hydromica (more rarely, smectite), quartz, and feldspar. The subrounded, subangular, and shapeless aggregates are characterized by beige and light brown color. Their genesis is related to coagulation of a fine-dispersed clayey material in water.

The content of diatom shells varies within a wide range (from traces to 92%). If the shells are abundant, they form diatom interlayers. High concentrations of diatom shells generally coincide with intervals enriched in vivianite and sponge spicules.

Judging from the mineral composition, the sediments can be assigned to polymictic graywackes of terrigenous sediments (Shvanov, 1987).

Despite a rather uniform mineral composition of Neogene–Quaternary sediments, lacustrine sediments recovered by the borehole can be subdivided into two parts with the boundary at a depth of ~200 m. At this level, the quartz and feldspar contents substantially decrease, whereas the mica content increases. Moreover, rock detritus disappears almost completely below this level (Fig. 4). Nearly at the same level, the value of the chemical index of alteration $CIA = Al_2O_3/(Al_2O_3 + CaO + Na_2O + K_2O)$ (Nesbit and Young, 1984), reaches the maximum, indicating warmer climatic conditions during the Barguzin sequence formation (Fig. 6).

Mineral Composition of the Heavy Fraction

In general, the heavy fraction yield in the analyzed samples is insignificant (0.003–17 g/kg, average 1.4 g/kg of sediment). Maximal concentrations of heavy minerals are observed in areas characterized by the postsedimentary sideritization of sediments, which occur in the lowermost parts of the section (586, 573, and 477 m), as well as at the boundary between the lower and upper sequences (199 m).

Among approximately 30 members of the heavy mineral assemblage, no more than 10 minerals are found constantly. They are represented by minerals of the amphibole, pyroxene, and epidote groups. The average content of amphiboles (primarily, hornblende) is 43% (73% in some samples). The tremolite content is lower (average ~1%). Its grains are elongate, prismatic, angular, and subangular. Depending on the mineral species of amphiboles, the grains vary from colorless (with a slight gray and grayish green shade) to dark green (almost black). The amphibole content is often several times higher than the pyroxene content in the Quaternary section.

Pyroxenes occur as both monoclinic and orthorhombic varieties. The diopside content is slightly higher (average 3%), whereas the average content of hypersthene (mineral of the orthorhombic pyroxene group)

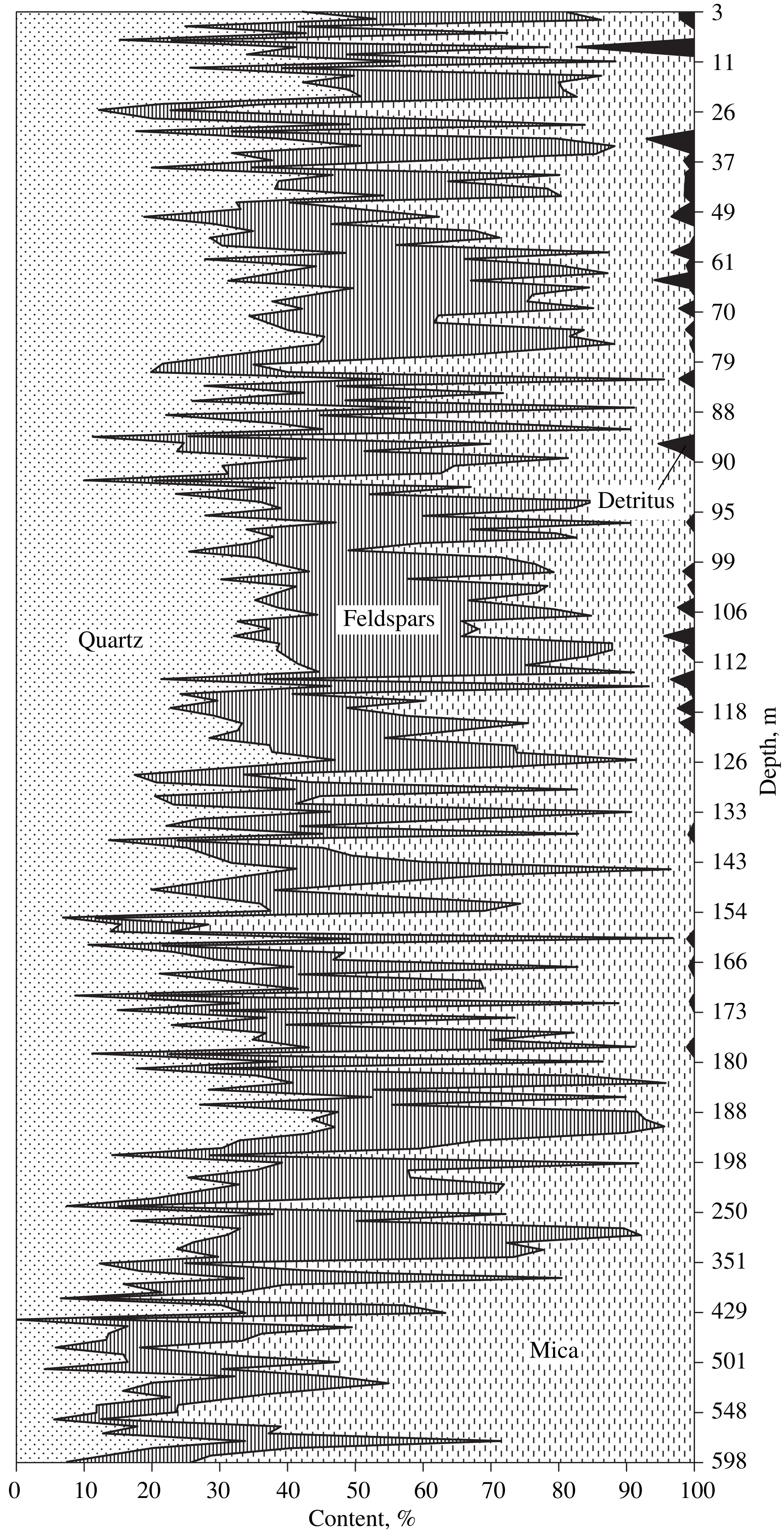

Fig. 4. Mineral composition of detritus of the light fraction.

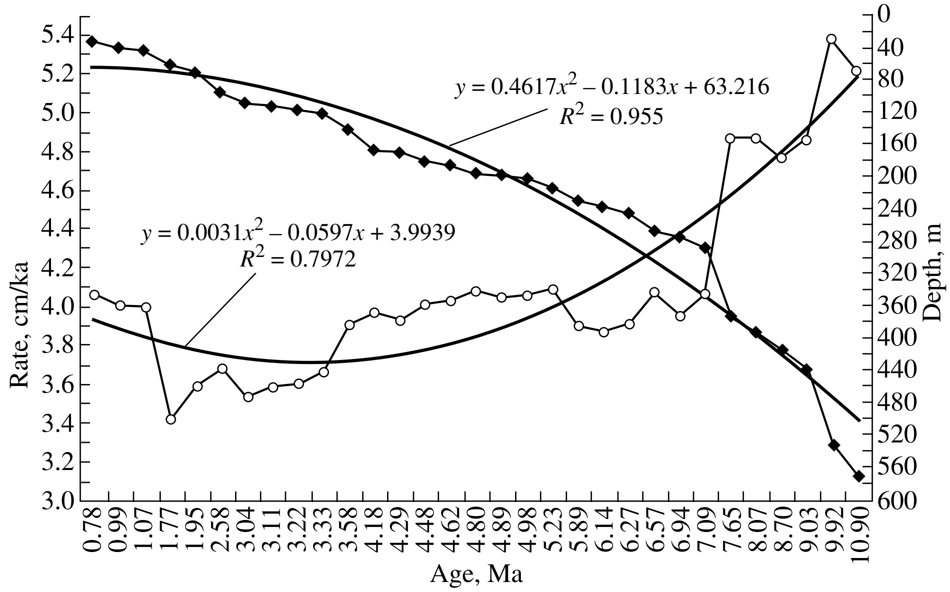

Fig. 5. Major centers of paleomagnetic ages of sediments and variations in sedimentation rates. Circles show the rate in different sedimentation periods. Boxes designate the age of different units.

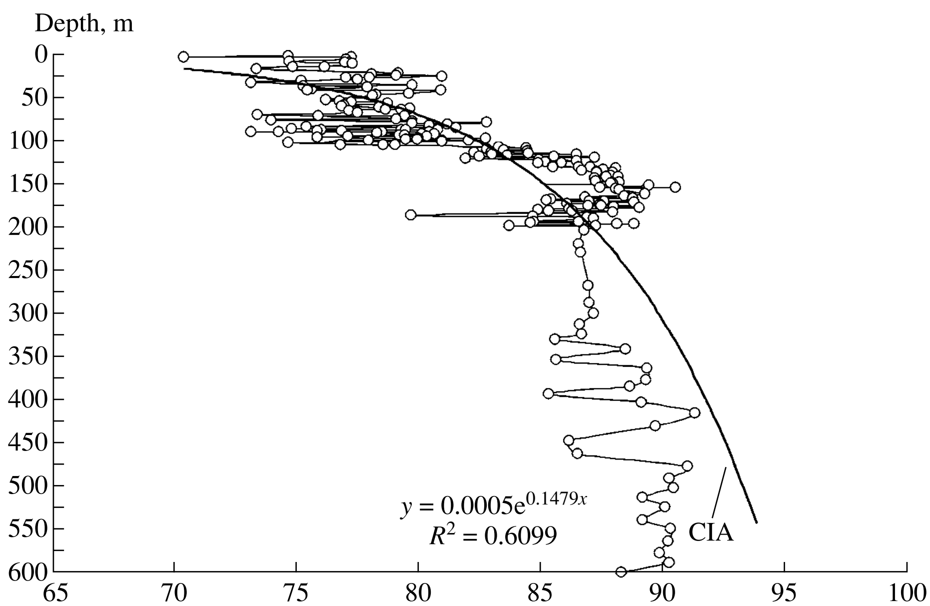

Fig. 6. Variations of the chemical index of alteration (CIA) in the bottom sequence of the Akademicheskii Ridge.

does not exceed 1%. It is usually found as elongate-platy grains. The mineral is characterized by brown color and distinct pleochroism.

The epidote group is represented by epidote and the subordinate zoisite and clinozoisite. The content of epidote group minerals varies from 0 to 26% (average 10.5%).

In addition to the above-mentioned minerals of the heavy fraction, the borehole section constantly includes ilmenite, magnetite, garnets, titanite, zircon, and apatite.

Sillimanite, kyanite, spinel, chrome spinels, anatase, staurolite, tourmaline, brookite, leucoxene, chloritoid, biotite, and chlorites are found as minor components (up to *n*%) at some levels of the Akademicheskii Ridge section. Secondary minerals are represented by siderite, pyrite, marcasite, goethite, and vivianite. Although these minerals are not common, they sometimes form substantial concentrations, especially in the lower part of the Barguzin sequence.

The cluster analysis of heavy-fraction mineral components showed that the upper (Angara) part of the section contains only one distinct association (listed according to increase in discrepancy value): barite, anatase, kyanite, brookite, cuprite, hematite, spinel, siderite, staurolite, biotite, chlorite, sillimanite, and tourmaline (Fig. 7a).

The lower (Barguzin) sequence includes the following mineral association: staurolite, chloritoid, barite, red lead, fluorite, anatase, spinel, siderite, chlorite, tourmaline, sillimanite, hypersthene rutile, biotite, and tremolite (Fig. 7b).

Thus, the appreciable difference in mineral associations between the upper and lower parts of the Neogene–Quaternary sediments confirms the change of provenances during different sedimentation stages.

Clay Minerals

The study of clay minerals in bottom sediments of Lake Baikal is an integral part of the comprehensive investigation of their lithological composition. Based on the grain size analysis of samples taken from the section (boreholes BDP-96-1, BDP-96-2, and BDP-98), the content of the clayey component (<0.001 mm) varies from 16 to 47% and rarely reaches 52%. Hence, different-age sediments recovered by the boreholes are characterized by an extremely limited distribution of clays and the predominance of silts, clayey silts, diatom oozes, and diatomites. Clay minerals are insignificant in diatom oozes and diatomites. In diatomites, they are found as a minor admixture. At the beginning of the study of clay minerals in the mid-20th century, researchers had established the polymineral composition of the clayey component in the Baikal bottom sediments (Knyazev, 1954; Rateev, 1954; Kazenkina, 1960; Goldyrev, 1982, and others). However, only the upper (up to 10–12 m) part of sediments recovered by corers was studied.

The polymineral composition of the fine-pelite fraction was also revealed during detailed mineralogical investigations of different-age (Holocene–Miocene) sediments of the Akademicheskii Ridge. Depending on the lithological type of sediments, the content of clay minerals varies in a wide range (Fig. 8).

At the bottom of borehole BDP-98 (depth 674 m, core sampling down to 600 m), Middle–Upper Miocene sediments have a polymineral composition of the clayey component most often represented by a four-component mixture (smectite, hydromica, chlorite, kaolinite) and mixed-layered hydromica–smectite or chlorite–smectite. The role of kaolinite in the fine pelite fraction is reflected by the content of aluminum oxide, which does not exceed 25%. According to the X-ray and electron microscopic data, clay minerals are characterized by highly dispersed state and low degree of structure perfection. Miocene sediments of the underwater crosspiece differ in these two parameters from synchronous sediments of the subaerial block (Ol'khon Island). The presence of vermiculite in sediments is another distinguishing feature. It is sporadically encountered throughout the whole stratigraphic section penetrated by boreholes, but the frequency of occurrence of vermiculite in Miocene sediments of the Akademicheskii Ridge is considerably higher than in Pliocene–Pleistocene–Holocene sediments. Diffractograms of the glycol-saturated vermiculite-containing samples show a reflection with d_{001} = 1.42 Å, which decreases to 1.00 Å after calcination. When saturated with dimethylsulfoxide, a small peak appears at 1.66 Å. The presence of mixed-layered phases mica–vermiculite and chlorite–vermiculite is also possible. In the fine pelite fraction of vermiculite-containing sediments, the MgO content is 2–2.5%. In the exchange complex, the Mg^{2+} content varies from 1.25 to 2.44 mg-eq./100 g of rock. Both vermiculite and mixed-layered phases can be terrigenous varieties. At the same time, in all basins of Lake Baikal, one can see direct relationship between the content of components and the possible change in the composition of interstitial fluids in bottom sediments with depth. According to (Granina et al., 2001), the composition of interstitial fluids changes and the content of some elements increases by more than one order of magnitude in deeper zones. Facts recorded in the Akademicheskii Ridge (tectonic crushing of the underwater block and presence of paleothermal fields) suggest that such a dependence also exists in the underwater ridge due to the inflow of endogenous fluids. The distribution and content of pelitomorphic carbonates in this part of the drilled section is characterized by specific features relative to coeval sequences of the subaerial block in the crosspiece, where the carbonates form separate thin interlayers (Logachev et al., 1964).

The Miocene/Pliocene boundary (5.0–5.4 Ma) passes in sediments at a depth of 200–220 m (*Neprereryvnaya* …, 1998). The Pliocene part of the Akademicheskii Ridge section is also characterized by polymineral composition of the fine pelite fraction with the predominance of hydromica and smectite (Fig. 8) and the presence of kaolinite, chlorites, vermiculite and mixed-layered phases (mica–smectite and chlorite–smectite). Specificity of the clay mineral composition at different levels of the Pliocene–Pleistocene section is considered an indicator of paleoclimatic changes (*Nepreryvnaya* …, 1998; Solotchina et al., 2001). Clay mineral associations in glacial and interglacial deposits exhibit specific features. In our opinion, they make it possible to distinguish arid phases in the Late Pliocene and trace global climatic changes in the Pleistocene–Holocene.

According to some researchers, the alternation of diatom oozes (with abundant spore-and-pollen assemblages and diatom remains) with silty–pelitic sediments and clays (without organic fossils) also reflects climatic changes in interglacial–glacial periods and continuous sedimentation during the Middle–Late Pleistocene and Holocene (Grachev et al., 1997).

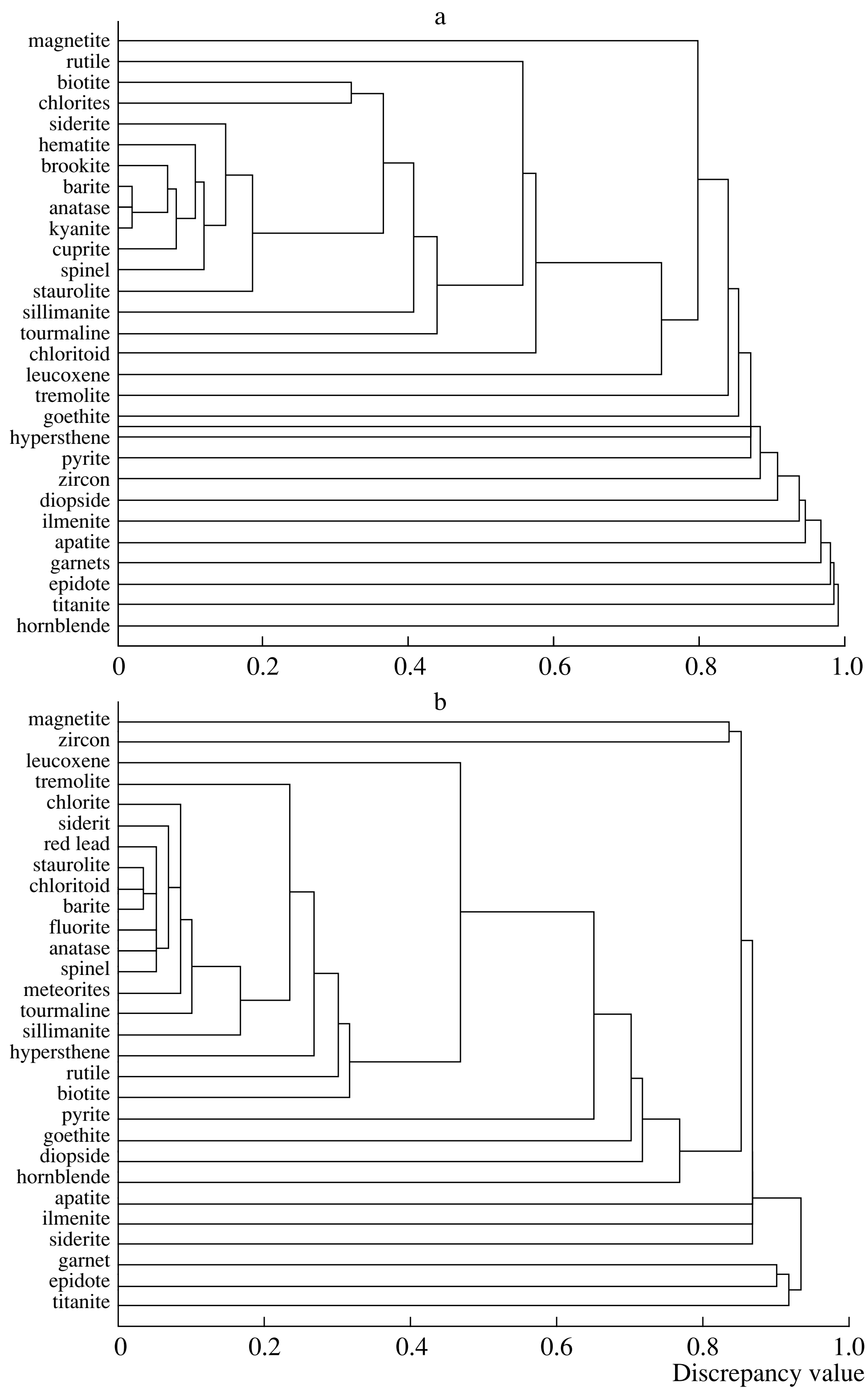

Fig. 7. Heavy-fraction mineral associations based on the cluster analysis. (a) Upper (Angara) sequence, (b) lower (Barguzin) sequence.

The thickness of Pleistocene–Holocene sediments penetrated by boreholes is ~60 m, including 0.5–0.7 m of Holocene sediments.

Calculations based on the Simplex software package (Karpov, 1981) and XSA data indicate that the clayey component of silty–pelitic and diatom oozes is also characterized by the polymineral composition with the predominance of smectite and hydromica in the major part of the section, whereas chlorite and kaolinite are insignificant. The biogenic silica and quartz–feldspar admixture also play a significant role in sediments. The silica content sharply increases (up to 73%) in biogenic–terrigenous oozes and diatomites. Clay minerals are characterized by a low degree of structure perfec-

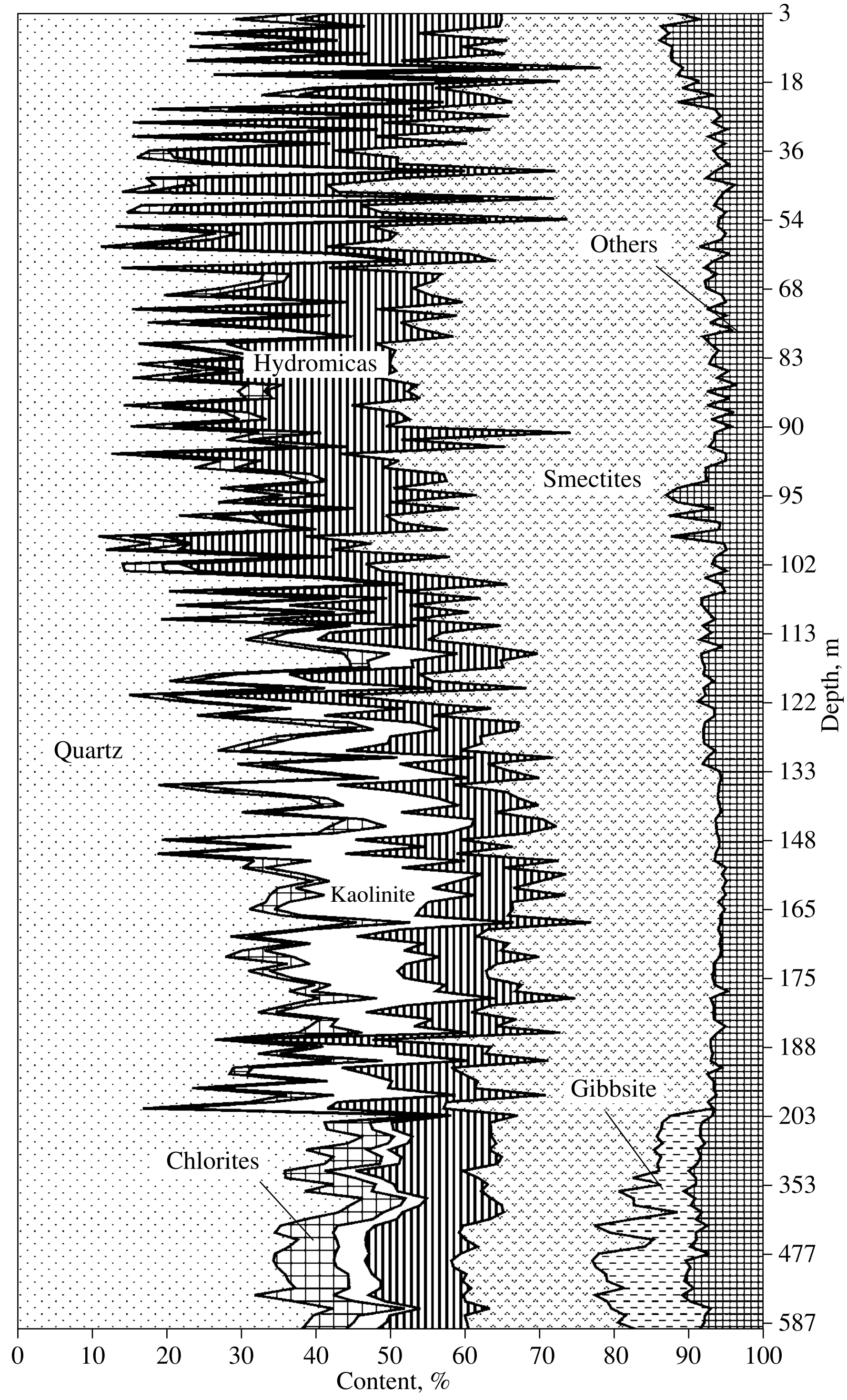

Fig. 8. Mineral composition of the clayey fraction in sediments of the Akademicheskii Ridge recovered by boreholes BDP-96 and BDP-98.

tion, high dispersion, and presence of mixed-layered phases (hydromica–smectite and chlorite–smectite) with a variable content of swelling packets. In terms of the degree of structure perfection and dispersion, the clay minerals are identical to typical varieties in the coeval sediments from different basins of the lake (Kashik and Mazilov, 1997; Kashik et al., 2001; Müller et al., 2001). This fact indicates the influence of degradation (during dissolution) and aggradation (during synthesis) in the whole lake watermass. They control not only the character of material transport from the provenance, but also the dispersion and perfection degree of the structure of terrigenous and authigenous clay minerals.

Clay minerals of hydrothermally altered rocks

Cenozoic lithogenesis in the Baikal rift zone is characterized by low-temperature hydrothermal metasomatism. The role of tectonic factor in the formation of different-age hydrothermal metasomatites in Lake Baikal was revealed by dredging (Kudryavtsev and Nikolaev, 1989). Relicts of paleohydrothermal fields include metasomatites in Precambrian granites of the Akademicheskii Ridge, where a fault-line metasomatic zone was formed during the two-phase argillization under the influence of different-temperature hydrothermal solutions (Kudryavtsev and Nikolaev, 1989). According to these authors, the first (higher-temperature) phase is related to the Jurassic magmatism (new generations of epidote, albite, and laumontite), whereas the second (Cretaceous–Paleogene) phase is superimposed on the previously altered rocks (new generations of smectites and kaolinite).

Younger metasomatites include probably Pliocene red-colored sandy–clayey sediments and cavernous silty clays of the polymineral composition, which were altered by paleothermal solutions. The crystalline basement with relicts of the weathering crust is overlain by pebbly and boulder–pebbly–sandy sediments that are, in turn, overlain by massive cavernous clays of the polymineral composition. These sediments could be dredged, because they are often exposed on the bottom surface (Khlystov et al., 2000; Mats et al., 2000).

Red-colored clays comprise clayey pellets, ferromanganese nodules, and spindle-shaped siliceous concretions, the washout of which by underwater currents creates the cavernous texture. The sandy–silty admixture in clays comprise quartz, micas, and subordinate feldspars.

The fine pelite fraction includes kaolinite, smectites, and hydromicas with chlorite and vermiculite admixture. According to XSA data, clay minerals exhibit a higher degree of structure perfection relative to Pleistocene–Holocene sediments of Lake Baikal.

The sandy–silty admixture and the clay matrix of red-colored sediments are altered by superimposed processes. Low-temperature hydrothermal metasomatism was accompanied by alterations of the mineral composition of the clayey matrix, the corrosion of individual mineral grains, and the sequential pseudomorphous replacement of feldspar and mica (primarily, biotite) by clay minerals and carbonates.

Authigenous carbonates replace feldspars and micas. They also corrode quartz grains, which acquire intricate shapes. In addition to clay minerals, authigenous minerals related to paleothermal solutions comprise rare zeolite crystals, which are confined to areas unaltered by carbonatization, and short-columnar prismatic tourmaline (dravite) crystals. The assemblage of authigenous minerals in low-temperature metasomatites of the Akademicheskii Ridge is similar to that in red-colored metasomatites of the Mindei Depression (Kashik et al., 1997) with the only difference that sediments of different ages were subject to argillization. Tectonic fracturing of the crosspiece fostered the development of separate metasomatic rock areas. For instance, low-temperature metasomatites were revealed not only on the Akademicheskii Ridge, but also on a scarp of the vertical wall of Bol'shoi Ushkanii Island (Bukharov and Fialkov, 1996). According to these authors, the vertical wall of Precambrian bedrocks is covered in some places with a crust (1–5 mm) of secondary minerals. The mineral composition of the crust (smectite, hydromica, calcite, zeolite, and an admixture of quartz, feldspar, and mica) suggests their genetic relation to hydrothermal processes.

CONCLUSIONS

The study of the lithological composition of sediments, penetrated for the first time by boreholes on the Akademicheskii Ridge in Lake Baikal, confirmed their stratigraphic subdivision into the upper (Angara) and lower (Barguzin) sequences, which differ in many parameters: structural features of sediments, maturity of the mineral material, mineral composition of the heavy fraction, sedimentation rates, and composition of clay minerals.

According to biostratigraphic and magnetostratigraphic data, both sequences span the Middle Miocene–Holocene period. They correlate with different-age formations of the continental Ol'khon region, Ol'khon block, and Baikal foredeep.

Differentiation of the sedimentary cover into two parts reflects changes in sedimentation conditions provoked by different tectonic and climatic factors. The Lower–Middle–Upper Miocene section formed under warmer climatic conditions. The terrigenous material was delivered from southeast and transported by the paleo-Barguzin River.

The upper (Pliocene–Holocene) sequence formed under the influence of the predominant delivery of material from northeast by the ancient Verkhnyaya Angara River under the temperate to temperate–cold transitional conditions.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research, project nos. 05-05-64749-a, 05-05-97268_p_Baikal_a, and 05-05-97269_p_Baikal_a.

REFERENCES

Bukharov, A.A. and Fialkov, V.A., *Geologicheskoe stroenie dna Baikala: vzglyad iz "Paisisa"* (Geological Structure of Lake Baikal Bottom: View from the M/S *Pisces*), Novosibirsk: Nauka, 1996.

Glubokovodnoe burenie na Baikale – osnovnye rezul'taty (Deep-Water Drilling in Lake Baikal: Principal Results), Geol. Geofiz., 2001, vol. 42, no. 1/2, pp. 8–34.

Goldyrev, G.S., *Osadkoobrazovanie i chetvertichnaya istoriya kotloviny Baikala* (Sedimentation and Quaternary History of the Baikal Basin), Novosibirsk: Nauka, 1982.

Grachev, M., Fialkov, V., and Nacamura, T., Extend Fauna of Ancient Carbon, *Nature*, 1995, vol. 374, pp. 123–124.

Grachev, M.A., Likhoshvai, E.V., and Vorob'eva, S.S., Signals of Upper Pleistocene Paleoclimates in Sediments of Lake Baikal, *Geol. Geofiz.*, 1997, vol. 38, no. 5, pp. 957–980.

Granina, L.Z., Kallender, E., Lomonosov, I.S., et al., Anomalies of Pore Water Composition in Bottom Sediments of Lake Baikal, *Geol. Geofiz.*, 2001, vol. 4, no. 1–2, pp. 362–372.

Hutchinson, D.R., Golmshtok, A.S., and Zonenshain, L.P., Depositional and Tectonic Frame Work of the Rift Basin on Lake Ba from Multichannel Seismic Data, *Geology*, 1992, vol. 20, pp. 589–592.

Karpov, I.K., *Fiziko-khimicheskoe modelirovanie na EVM v geokhimii* (Computer-Based Physicochemical Modeling in Geochemistry), Novosibirsk: Nauka, 1984.

Kashik, S.A., Estimation of Mineral Composition from Bulk Chemical Analysis, *Sov. Geol.*, 1973, no. 10, pp. 144–147.

Kashik, S.A. and Mazilov, V.N., *Mnogomernyi analiz v litologii* (Multidimensional Analysis in Lithology), Novosibirsk: Nauka, 1984.

Kashik, S.A. and Mazilov, V.N., Main Stages and Paleogeography of Cenozoic Sedimentation in the Baikal Rift System (Eastern Siberia), *Bull. Centres. Rech. Explor.-Prod. Elf Aquitane,* 1994, vol. 18, no. 2, pp. 453–462.

Kashik, S.A. and Mazilov, V.N., Lithology of Quaternary Sediments Drilled in Lake Baikal, *Litol. Polezn. Iskop.,* 1997b, vol. 32, no. 5, pp. 484–491 (*Lithol. Miner. Resour.* (Engl. Transl.), 1997, vol. 32, no. 5, pp. 420–426).

Kashik, S.A., Lomonosova, T.K., and Fileva, T.S., Genetic Types of Clay Minerals in Bottom Sediments of the Southern Basin of Lake Baikal, *Geol. Geofiz.*, 2001, vol. 42, no. 1–2, pp. 164–174.

Kaz'min, V.G., Golmshtok, A.J., and Klitgord, K., Structure and Evolution of the Akademicheskii Ridge Based on Seismic and Underwater Survey Data, *Geol. Geofiz.*, 1995, vol. 36, no. 10, pp. 164–176.

Kazenkina, G.A., Mineral Composition of Recent Sediments in the Proval Bay, *Dokl. Akad. Nauk SSSR*, 1960, vol. 130, no. 4, pp. 850–855.

Khlystov, O.M., Mats, V.D., Vorob'eva, S.S., et al., Structure and Evolution of the Underwater Akademicheskii Ridge, *Geol. Geofiz.*, 2000, vol. 41, no. 6, pp. 819–824.

Knyazeva, L.M., Lacustrine Sedimentation in the Humid Zone of the USSR: Southern Baikal, in *Osadkoobrazovanie v sovremennykh vodoemakh* (Sedimentation in Modern Water Basins), Moscow: Akad. Nauk SSSR, 1954, pp. 180–236.

Kravchinsky, V.A., Krainov, M.A., Evans, M.E., et al., Magnetic Record of Lake Baikal Sediments: Chronological and Paleoclimatic Implication for the Last 6.7 Myr, *Paleogeogr. Paleoclimat. Paleoecolog.*, 2003, vol. 195, no. 2, pp. 281–298.

Kudryavtsev, D.I. and Nikolaev, V.G., Hydrothermal Mineralization in Precambrian Granites of the Akademicheskii Ridge, *Litol. Polezn. Iskop.*, 1989, vol. 24, no. 5, pp. 119–125.

Kuz'min, M.I., Grachev, M.A., and Williams, D.I., Continuous Paleoclimatic Record of the Last 4.5 Ma from Lake Baikal (First Information), *Geol. Geofiz.,* 1997, vol. 38, no. 5, pp. 1021–1023.

Logachev, N.A., History and Geodynamics of the Baikal Rift, *Geol. Geofiz.*, 2003, vol. 44, no. 5, pp. 391–406.

Logachev, N.A., Lomonosova, T.K., and Klimanova, V.M., *Kainozoiskie otlozheniya Irkutskogo amfiteatra* (Cenozoic Sediments in the Irkutsk Amphitheater), Moscow: Nauka, 1964.

Lomonosov, I.S. and Lomonosova, T.K. Hydrothermal Lithogenesis in the Baikal Rift Zone, in *JPPCE Newsletter*, Innsbruck: Universitaetsverlag Wagner, 1997, no. 10, pp. 31–39.

Mats, V.D., Pokatilov, A.G., and Popova, S.M., *Pliotsen i pleistotsen srednego Baikala* (Pliocene and Pleistocene of the Middle Baikal), Novosibirsk: Nauka, 1982.

Mats, V.D., Khlystov, O.M., Batist, M.De., et al., Evolution of the Academician Ridge Accommodation Zone in the Central Baikal Rift: Evidence from High-Resolution Reflection and Geological Field Investigations, *Int. Earth Sci.*, 2000, vol. 89, pp. 229–250.

Mats, V.D.., Ufimtsev, G.F., and Mandel'baum, M.M., *Kainozoi Baikal'skoi riftovoi vpadiny. Stroenie i geologicheskaya istoriya* (The Cenozoic of the Baikal Rift Trough: Structure and Geological Evolution), Novosibirsk: Sib. Otd. Ross. Akad. Nauk, 2001.

Moor, T.C., Jr., Klitgord, K.D., Golmshtok, A.J., and Weber, E., Sedimentation and Subsidence Patterns in the Central and North Basins of Lake Baikal from Seismic Stratigraphy, *GSA Bull.*, 1997, vol. 109, no. 6, pp. 746–766.

Müller, I., Vologina, E.G., and Sturm, M., Distribution of Modern Clay Minerals as Possible Indicator of Sediment Sources in Deep Drilling Cores BDP93-2 and BDP-96, *Geol. Geofiz.*, 2001, vol. 42.

Nepreryvnaya zapis klimaticheskikh izmenenii v otlozheniyakh ozera za poslednie 5 millionov let (Continuous Record of Climate Changes in Lacustrine Sediments over the Last 5 Million Years, *Geol. Geofiz.*, 1998, vol. 39, no. 2, pp. 139–156.

Nesbit, H.B. and Young, G.M., Prediction of Some Weathering Trends of Plutonic and Volcanic Rocks Based on Thermodynamic and Kinetic Correlation, *Geochim. Cosmochim. Acta,* 1984, vol. 48, pp. 1523–1534.

Pozdnekainozoiskaya paleoklimaticheskaya zapis v osadkakh ozera Baikal (po rezul'tatam issledovaniya 600-metrovogo kerna glubokogo bureniya (Late Cenozoic Paleoclimatic Record in Sediments of Lake Baikal: Evidence from Results of the Analysis of 600-m-Deep Drilling Core), *Geol. Geofiz.*, 2000, vol. 41, no. 1, pp. 3–32; nos. 1–2, pp. 157–163.

Rateev, M.A., Clay Minerals in Sediments of Southern Lake Baikal, in *Obrazovanie osadkov v sovremennykh vodoemakh*

(Sedimentation in Modern Water Basins), Moscow: Akad. Nauk SSSR, 1954, pp. 339–371.

Rukhin, L.B., *Litologiya* (Lithology), Leningrad: Gostoptekhizdat, 1961.

Rybakov, V.G., Pre-Neogene Weathering Crust and Neogene Sediments in Ol'khon Island, in *Novye dannye po geologii, neftegazonosnosti i poleznym iskopaemym Irkutskoi oblasti* (New Data on the Geology, Petroleum Potential, and Mineral Resources of the Irkutsk District), Moscow: Nauka, 1964, pp. 262–270.

Sapota, T., *Late Cenozoic Geoarchives from Lake Baikal, Siberia*, Uppsala: Acta Univ. Upsaliensis, 2004.

Shvanov, V.N., *Petrografiya peschanykh porod* (Petrography of Sandy Rocks), Leningrad: Nedra, 1987.

Solotchina, E.P., Prokopenko, A.A., and Kuz'min, N.I., Differences between Glacial and Interglacial Clay Mineral Associations from Sediments of Lake Baikal in Deep Drilling Cores BDP-92-2 and BDP-96, *Geol. Geofiz.*, 2001, vol. 42, nos. 1/2, pp. 175–185.

Yuretich, R., Melles, M., Sarata, B., and Grobe, H., Clay Minerals in the Sediments of Lake Baikal: A Useful Climate Proxy, *J. Sedim. Res.*, 1999, vol. 69, no. 3, pp. 582–596.

Zonenshain, L.P., Golmshtok, A.J., Hutchinson, D., et al., Structure of the Baikal Rift, *Geotektonika,* 1992, **27** (5), pp. 63–77.

Zonenshain, L.P., Kaz'min, V.P., Kuz'min, M.I., et al., Geology of the Baikal Bottom: Evidence from the M/S *Pisces*, *Dokl. Akad. Nauk*, 1993, vol. 330, no. 1, pp. 84–88.