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PRELIMINARY RESULTS OF THE FIRST DRILLING ON LAKE BAIKAL, BUGULDEIKA ISTHMUS

BDP-93 Working Group*

The Baikal Drilling Project (BDP) is a multinational effort to investigate the paleoclimatic history and tectonic evolution of the Lake Baikal sedimentary basin in the Late Neogene. In March 1993 the Baikal drilling system was started up from a barge frozen into position over a topographic high in the southern basin of Baikal called the Buguldeika isthmus. With this system, the BDP-93 working group successfully recovered first long (> 100 m) hydraulic piston cores from two boreholes beneath a 354-m thick body of water. High-quality cores of 98 and 102 m were collected in 78 mm diameter plastic liners with an average recovery of 72 % and 90 % in BH-1 and BH-2, respectively. Magnetic susceptibility logging of BH-1 and BH-2 reveals excellent core-to-core correlation. Recovered sediments appear to represent sedimentation over the last 500,000 years. In this report the BDP-93 working group including Russian, American and Japanese scientists describes preliminary analytical results from the cores of BH-1. Radiocarbon dating by accelerator mass spectrometry provides an accurate chronology for the upper portion of BH-1 cores. Detailed lithological characteristics, rock magnetic properties and inorganic chemical element distributions show a significant change in the depositional environment at the Buguldeika isthmus over the last 500,000 years. The 50-m thick sedimentary formation beneath the lake bottom is mainly of pelitic composition with thin layering whereas beneath the 50-m mark occur more sandy and gravelly interlayers, often with turbidite-type gradation. Sediments of the lower part of the section are mainly transported from the west through the Buguldeika R. basin. Sedimentation on the Buguldeika isthmus reflects a combination of deeper lake sedimentation admixed with fine-grained materials from the Selenga R. drainage basin in the east of Lake Baikal. Variations in spore-pollen complexes, diatom microflora, biogenic silica content, rock magnetic properties, clay mineralogy and organic carbon in the upper 50 m of BH-1 reveal a detailed record of how climatic changes impacted the Baikal limnological system in Late Pleistocene and Holocene.

Lithology, drilling, grain size, radiocarbon dating, paleomagnetism, palynology, thermal conductivity

INTRODUCTION

Scientific goals. The Baikal Drilling Project [1] is an international investigation of the paleoclimatic history and tectonic evolution of the Lake Baikal sedimentary basin.

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Lake Baikal is the oldest, deepest and largest (by its water volume) fresh-water lake in the world. The sediments of Lake Baikal offer unparalleled opportunities to study the paleoclimatic and geological evolution of Central Asia and southeastern Siberia. Unlike any other northern hemisphere lake at the same latitude, Baikal contains a continuous sedimentary record that spans the last 30 to 20 Ma. This record is continuous because the deep basin of Baikal was not glaciated by northern hemisphere ice sheets which disrupted and scoured much of the sediments in Europe, western Siberia and North America during the Pleistocene [2].

The Baikal basin however has been and is sensitive to past and present climate changes. For example, during the last glacial maximum, glaciers existed in the mountains surrounding the northern shore of Baikal. Today the Baikal region is strongly affected by two atmospheric centers of the Northern hemisphere, the Siberian high which dominates the winter climate of the Baikal region and the Asian low which strongly influences the summer climate [3]. The seasonal interplay of these centers of action significantly influences global climate and produces the highest seasonal contrast observed on the Earth. Comprehensive studies of Baikal sediments therefore provide an opportunity to understand how seasonal factors of the global climate system have influenced long-term climatic change in central Asia, including such phenomena as the intensification of northern hemisphere glaciation during the Plio-Pleistocene, and how large tectonic events, e. g. uplifting of the Tibet Plateau, influenced the Siberian Atmospheric High and climate of southeastern Siberia [4].

In addition, Lake Baikal is the largest basin in the Baikal Rift Zone (BRZ), one of two major continental rift zones of the world. Baikal sediments contain a record of the recent evolution of one of the most important active intracontinental rifts.

Logistics of BDP. Lake Baikal and the Baikal Rift Zone comprising it have been studied for many years by well-known Russian scientists N. A. Florensov, N. A. Logachev, G. S. Goldyrev, B. D. Mats, et al. In 1989, a comprehensive study of the structure, geochemistry and mineralogy of sedimentary sequences of Baikal was started. At that time the USSR Academy of Sciences adopted a new research program "Deep-water ecology, paleolimnology and geodynamics of Baikal." At the same time, the Baikal Drilling Project was proposed [5]. Initially, this project was discussed by representatives of the USSR Academy of Science, MinGeo, scientists of US Universities and USGS, as well as University of Kyoto (Japan). In 1990, the BDP became important part of the program to be accomplished by the Baikal International Center for Ecological Research (BICER) headquartered at the Limnological Institute, Irkutsk. Most recently, the BDP objectives have become part of the IGBP program of Past Global Changes (PAGES).

Prior to the first BDP drilling at the Buguldeika in 1993, bottom sediments were sampled by cores, and geophysical surveys (reflection seismic profiling) were carried out under the sponsorship of the USGS, BICER and the Japan Baikal Association (JABIRP). The 1990–92 expeditions resulted in: (1) 3,600 km of high-resolution seismic-reflection profiles to delineate the sedimentation setting and facies beneath the lake (in the future this will help us to clear up how those environments have responded to climate change and to locate and correlate the best sites for coring) and (2) a set of 209 cores of various types at 38 sites that provide raw materials for analyses aimed at detailed reconstructions of paleoenvironmental conditions [1, 6, 7].

During 1992–93, participation in BDP has expanded to include a large, multidisciplinary team of Russian, American and Japanese scientists who study geochronological, geochemical, micropaleontological, and sedimentological characteristics of the Baikal sediments. Costs for the site selection surveys, drilling/coring and subsequent analytical work are borne equally by the BDP partners. Plans, financial support, and scientific goals are competence of BDP Steering, Technology and Scientific Advisory committees.

Technological requirements. Because of Baikal's great depth, intense weather changes and high tectonic activity, it is necessary to solve some technical problems of drilling lacustrine sediments in Baikal in order to fulfill the scientific tasks posed. A specialized light-weight drilling system, using aluminum drill pipe to reduce the overall weight of the system, was developed in the Nedra Enterprise, Yaroslavl, Russia. To maximize recovery of undisturbed sediment, Nedra engineers have developed a hydraulic piston coring system based on the design of the advanced hydraulic piston corer (APC) of the Ocean Drilling Program. In addition to the Baikal APC, the Nedra drilling team also had a hydrostriker, vibrocorer and rotary corer for use under varied conditions. In 1992, this drilling rig was tested by the Nedra enterprise from the surface of Slyudinskoe Lake, a small nearshore lagoon in the coastal zone of Northern Baikal. These tests confirmed that the equipment would able to perform, within the designed specifications, the full-scale drilling scheduled for next year. In January 1993, the Baikal drilling system was deployed from a 15× 30 m barge frozen into position, using two ships, at a point whose coordinates were determined by means of high resolution seismic and satellite navigation. With the Baikal coring system, high-quality cores of 98 and 102 m were collected in March 1993 from the Buguldeika site in 354 m of water (Fig. 1). The cores were recovered in 78 mm diameter plastic

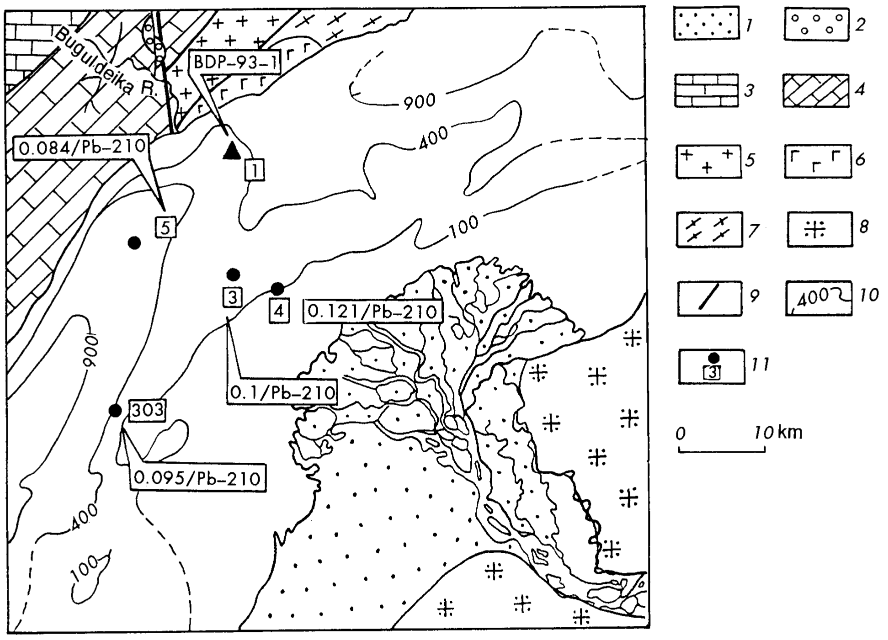

Fig. 1. Schematic geological map of BDP-93-1 Drill Site. ***1*** **— Cenozoic sediments of the Selenga R. delta;** ***2*** **— Paleogene and Neogene: clay, sand, brown coal;** ***3*** **— Upper Cambrian: carbonate-terrigenous gypsum-bearing deposits;** ***4*** **— Lower—Middle Cambrian: salt-bearing-carbonate deposits;** ***5, 6*** **— Proterozoic:** ***5*** **— granite gneisses, chloritized and epidotized granites,** ***6*** **— diorites, basites and hyperbasites;** ***7*** **— Upper Archean—Paleozoic (Olkhon complex): gneisses, granite gneisses, crystalline schists, amphibolites, marbles, pegmatites,** ***8*** **— Precambrian—Paleozoic (non-dismembered): mainly granitoids,** ***9*** **— major faults,** ***10*** **— isobaths,** ***11*** **— sampling points for piston coring with modern sedimentation rates (cm/year) estimared by Pb (V. M. Kuptsov and Yu. A. Bogdanov). The triangle shows location of BH-1.**

liners with an average recovery of 72 % and 90 % in BH-1 and BH-2, respectively. Magnetic susceptibility and thermal conductivity measurements were made prior to fractioning the BDP-93-1 cores, with the cores described and photographs taken prior to sampling. Approximately 200 specimens were precollected from BH-1 and distributed among Russian, Japanese, and U.S. scientists. Following the ODP protocols, a BDP sampling protocol was compiled to identify the analysts teams to be involved in the reconnaissance of BDP-93-1 cores. The research to be fulfilled included radiocarbon dating by accelerator mass spectrometry, measurement of rock magnetic parameters, organic constituents (biogenic silica and total C, N, S), diatom and spore/pollen contents, and study of major and trace element chemistry, clay mineralogy, porosity/water contents and grain size.

The results of these analyses are reported here and are being used to design a more comprehensive and detailed sampling program, which will utilize samples from both boreholes. The cores are kept on deposit in a refrigerated (4 °C) core storage facility at the Institute of the Earth's Crust, Irkutsk.

CHARACTERISTICS OF THE STUDY SITE

The Baikal Rift Zone began to form about 30–35 Ma ago [8, 9]. Lake Baikal occupies the deepest part of the Baikal Rift Zone. The Baikal depression is divided into the northern, central and southern basins [10, 11]. The Buguldeika isthmus lies on the western margin between the central and southern depressions, offshore of the Buguldeika R. and directly opposite to the Selenga Delta (see Fig. 1). The Buguldeika R. basin drains a territory composed of three tectonic blocks of different geological structure. Every block is an independent fault-bounded morphostructure. Granite gneisses, metamorphic rocks of amphibolite and granulite facies are widespread on this territory. The Primorsky Range is characterized by deposits of Riphean phosphorites, Cambrian salt-bearing and carbonate deposits (see Fig. 1). The Buguldeika basin is known to have widespread laterite-kaoline crust of weathering of Cretaceous-Paleogene age [12–15]. Deposition at the Buguldeika isthmus was likely influenced by the Selenga delta. The composition of rocks in the Selenga basin is similar to that in the Buguldeika basin but in addition it includes sedimentary rocks of Mesozoic age.

Two erosional-tectonic stages, Manzurka and Neobaikalian, are recognized in the evolution of the Baikal Rift Zone.

A slightly incised channel net formed in the Manzurka stage. One of the valleys — the pra-Manzurka valley — was the ancient (Late Pliocene — Middle Pleistocene) outlet of the Baikal waters flowing into the Lena River [14, 16]. Sediments of this paleoriver are widespread in the Buguldeika upper reaches. In the late Middle — early Late Pleistocene (150–120 thousand years ago) large tectonic movements took place along the faults of the western flank of the Baikal Depression. This led to restructuring of the channel net, reviving of deep-seated erosion of the Baikal inflows, and formation of their recent deeply incised ravines in the lowermost valleys. Since then a new thalweg of the Buguldeika has formed toward Baikal (Neobaikalian stage). There are two phases in this stage. The first corresponds to the river incision period, when the river carry coarse-grained material, and the delta to be formed (a fan) is chiefly situated beneath the lake level. The second phase, from the end of the Middle Pleistocene to recent time, is characterized by a more quiet laminary flow and transfer of fine-grained material into Baikal.

Previous seismic profiling showed that in the drill site the upper part of the sedimentary sequence of Baikal was made up of two seismostratigraphic complexes. The boundary between them, regarded as unconformity, occurs at a depth of 100–300 m. In the drill site it lies below 100 m and thus, the borehole revealed the upper seismostratigraphic complex only.

The high-resolution seismic profiles obtained by means of a special 3.5 kHz water gun show that the Buguldeika Drill Site is located on the top of a fault block bounded by listric faults of the Baikal Rift Zone. This block is one of the downthrows with its surface inclined toward the elevated rift shoulder (Figs. 2, *A* and 2, *B*). The upper 100 m of the section are characterized by continuous, subparallel reflections suggesting a thick sequence of hemipelagic deposits. South of the drill site, disturbed reflections and mounded surface morphology localize the Buguldeika submarine fan deposits interlayering with the pelagic deposits at the drill site. The fault block on which the drill site is located is tilted southwestward and is raised above the slope of the adjacent Selenga delta. In accordance, the sedimentary beds at the hole-penetrated section bottom are inclined shoreward. Up the section the beds are graded to become horizontal, and at the top their inclination reverses toward the rift axis.

At a depth of about 50 m, reflections on the profile change their character to become irregular. Simultaneously, changes are observed in other geophysical characteristics generally correlating with lithologic variations in the core.

Below 100 m at the drill site, several prominent reflections and a distinct unconformity are observed, which seem to be due to changes in tectonic activity. One of these horizons may relate to the period when the lake water discharged into the Angara rather than pra-Manzurka river, a tributary of the Lena River.

RESULTS OF BDP-93-1 CORE STUDY

Lithological characteristics of BDP-93 BH-1. Over 900 smear slides have been examined to characterize the major lithological parameters of BH-1. Figure 3 shows a sedimentary record of BH-1 based on the primary core description. The sediments of this core are chiefly of silt-pelitic composition and contain lenses and interbeds of sand and silt, which become more abundant down the section with simultaneously increased proportion of fine gravel. Calculated in smear slides, the content of diatoms in some interbeds varies from 3 to 90 % and diminishes sharply in the lower part of the BH-1 section.

The texture of the sediments ranges from massive to laminated, thin-laminated and lenticular. Some interbeds show gradational layering. Turbidites occur more frequently down the section. Their interbeds are typically 3–5 cm thick and commonly consist of fine silt-pelitic or silty material. The underlying surface of some turbidite interbeds is uneven, because the underlying sequence is eroded by suspension flows. Deposition from temporary suspension flows is likely to be related to phases of river flooding.

The lithological section of BH-1 shows a rhythmic structure, each rhythm consisting of two units. One unit is composed of silt-pelitic mud with a high content of diatoms (25–30 %). The other is commonly made up of clay material with small amounts of diatom frustules (< 3 %). A total of 7 rhythms is revealed, particularly well-expressed in the upper part of the core (Fig. 3). Thus, the lithological section suggests that the BH-1 sequence at the Buguldeika site experienced fairly continuous accumulation of pelagic deposits from the water mass and fine-grained sediments regularly supplied from the coast by suspension flows, wind, and ice rafting.

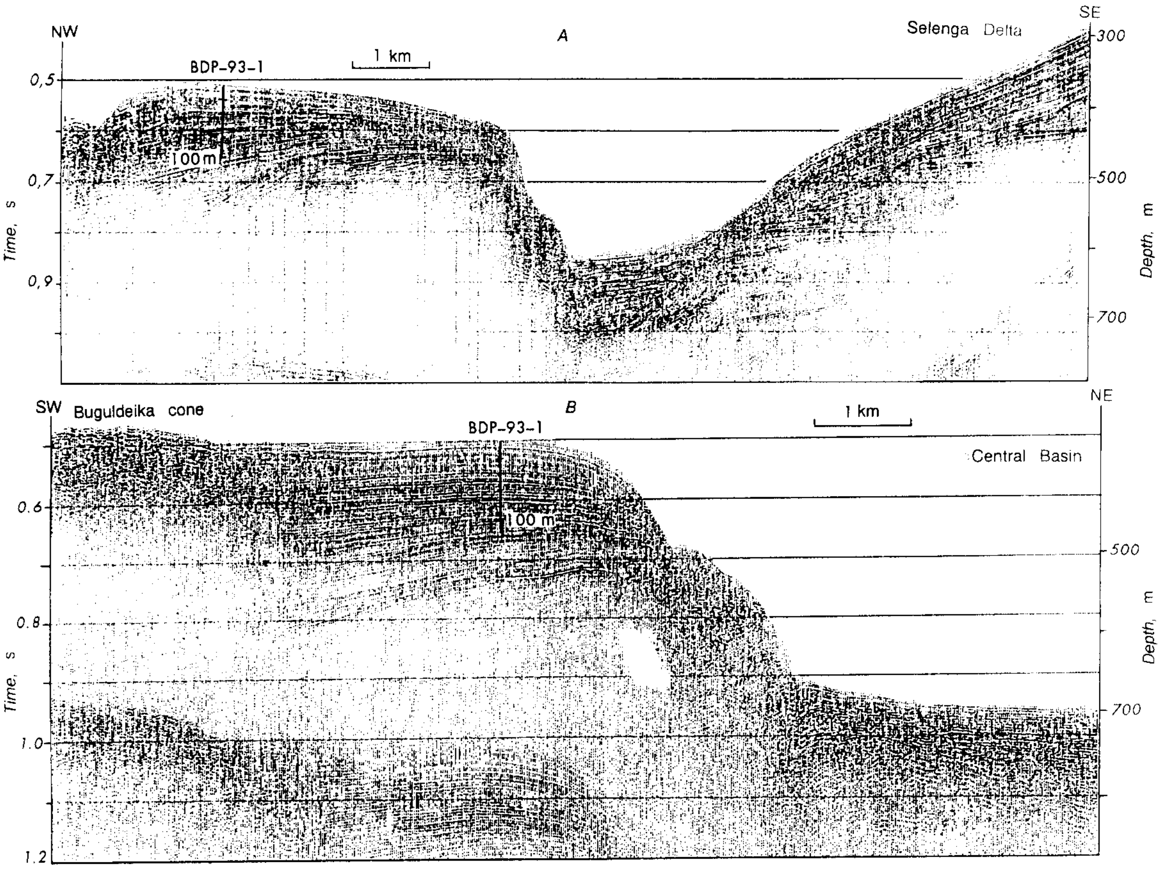

Fig. 2. Seismic-reflection profiles through Buguldeika borehole:
***A* — from NW to SE, *B* — from NE to SE, parallel to the rift axis.**

The patterns of sedimentation and composition of sedimentary material clearly show two units. The first, from top to 50-m depth, is more fine-grained, contains a lot of diatom material and displays a pronounced rhythmic structure. This upper unit apparently formed under relatively quiet conditions of lake sedimentation. The lower unit below 50 m is more coarse-grained with abundant turbidites against the background of pelite material. It includes more interbeds of sand and silt. This unit formed under lacustrine conditions, with a large volume of terrigene material brought off the coast. Most probably, its origin coincided with the stage of the intense formation of the "Baikal" discharge of the Buguldeika R.

Figure 3 illustrates variation of the effective porosity of bottom sediments throughout the core. The porosity steadily diminishes from 0.855 at a depth of 0.03 m to 0.428 m in the borehole shaft (102.5 m). In the upper part of the section (0–10 m) variations of porosities are well correlated with the observed changes in bottom sediment porosity from 10 m piston cores. Thus, it may be inferred that this pattern of porosity variation in the upper (100 m) layer of sediments at the Buguldeika isthmus is typical of Baikal as a whole. As seen on the plot, the porosity values deviating from the averaged curve are related to changes in the lithologic composition of individual beds.

Mineralogy and grain size characteristics. Granulometric analysis of the BDP-93-1 core showed that 80 % of the core is composed of fine-grained (< 62.5 μm), silty-clay ooze. Only at 39 m, 61 m and 66 m, where sand interbeds of a few tens of centimeters occur, do coarse-grained fractions dominate. The sand and silt grains are poorly rounded and ill-sorted. These granulometric characteristics suggest that the bulk of the suspended material was transported into a sedimentary basin of medium depth as it occurs at present.

Over 90 % of the light minerals in the core sediments are quartz, plagioclase, K-feldspar, micas (biotite, muscovite) or clay aggregates. These latter are loosely cemented formations of quartz, K-feldspar and clay

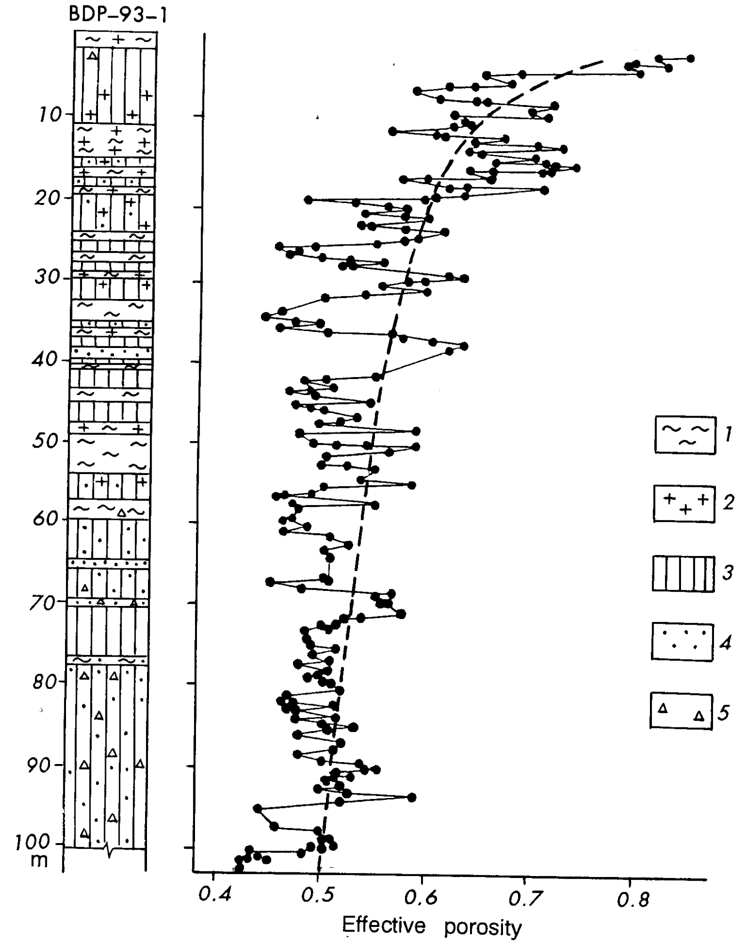

Fig. 3. Lithological column of BDP-93 BH-1 and sediment porosities.
***1* — silt-clay mud; *2* — diatom ooze; *3* — clay; *4* — sand; *5* — gravel.**

minerals, mainly smectites. Plagioclase is more abundant than K-feldspar. Biotite mica exceeds the amount of muscovite by several times.

Heavy minerals constitute only a very small fraction of the sand and silt grains (a few grams per ton of sediment). At only a few horizons the heavy fractions concentration reaches 30 to 76 ppm. A total of thirty heavy minerals were identified, but only ilmenite, magnetite, garnets, sphene, zircon, apatite, minerals of the amphibole group, pyroxene and epidote are found in all samples. The rock-forming minerals and epidote as a rule make up about 50 wt.% of the heavy fraction. The authigenic minerals pyrite and marcasite amount to 70 % in some heavy fraction specimens.

According to some characters (quartz-to-plagioclase ratio, ratio of weatherig-stable to weathering-unstable heavy fraction minerals, amount of rock particles and plant remains, type of clay minerals, etc.), the borehole section may be conventionally divided into two portions: upper part, to a depth of 45–50 m, and lower one (Figs. 4, 5).

On studying the Baikal bottom deposits by piston corers in 1990–92, four major types of clay minerals were recognized in the fine sediment fraction (< 2 μm): illite, smectite, chlorite, and kaolinite. Geographically, these clays are weakly differentiated; therefore, a conclusion can be made that their composition is sensitive to changes in weathering conditions within the sourcelands. Relative contents of the four clay minerals in the BDP-93-1 core vary with depth. Although the smectite abundances vary considerably, two features are evident (Fig. 4). First, a noticeable and persistent decrease in smectite abundance occurs below 50 m, which is correlated with the earlier documented changes in the lithological section. Second, there are increases and decreases in smectite abundance in the upper 50 m, from which climatic changes may be inferred. Kaolinite abundance fluctuates around a slightly increasing mean to a depth of approximately 35 m, then it drastically

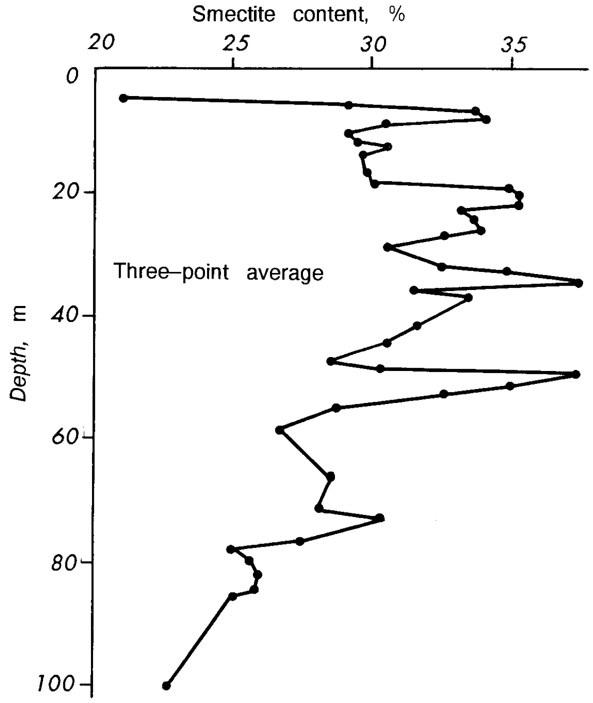

Fig. 4. Variations of smectite content in BDP-93-1.

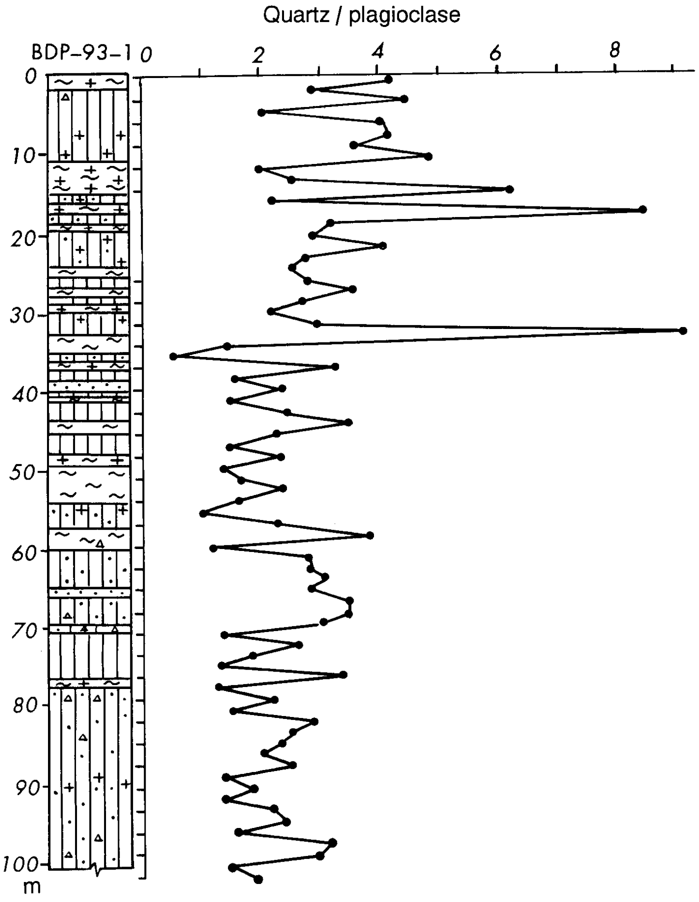

Fig. 5. Quartz/plagioclase variations through the borehole section.

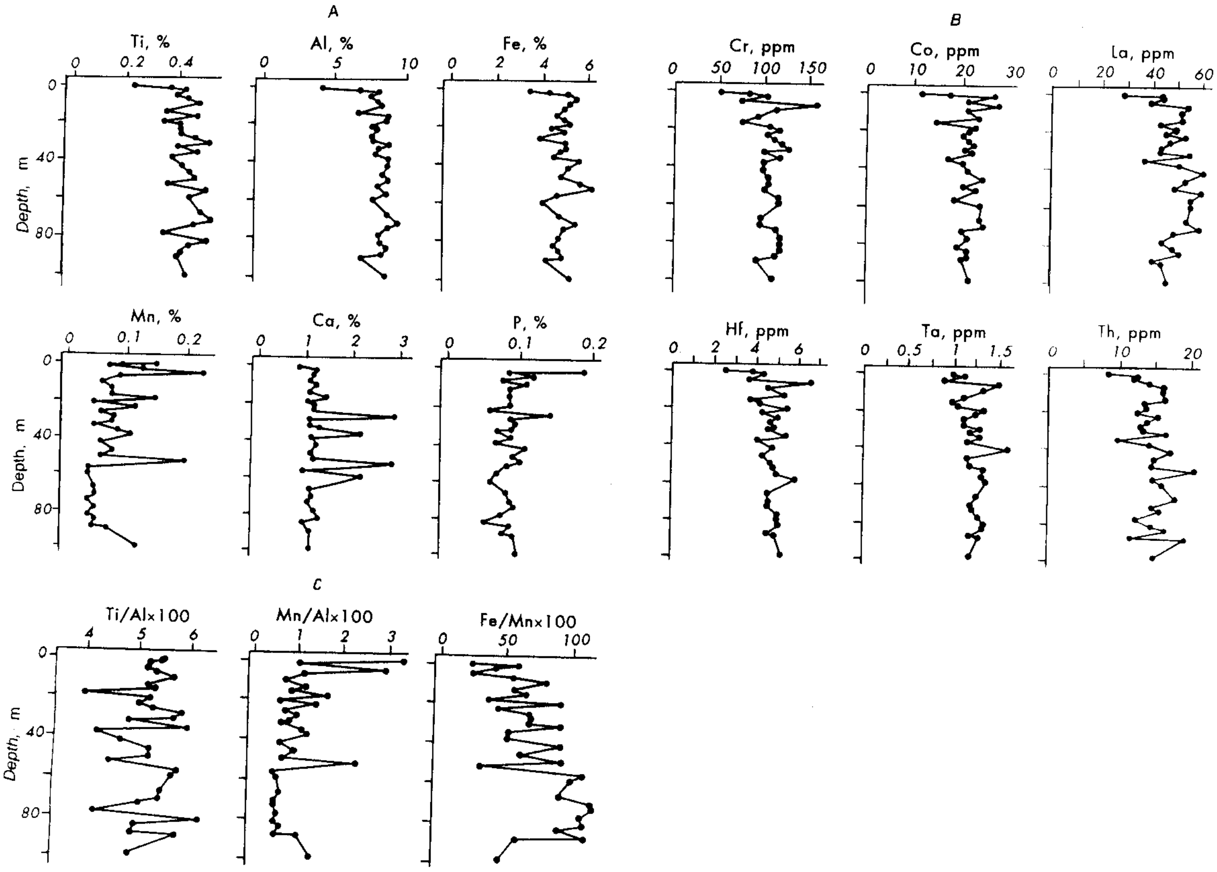

Fig. 6. Distribution in the BDP-93-1 borehole: *A* — major rock-forming elements, *B* — trace elements, *C* — Ti/Al, Mn/Al and Fe/Mn.

decreases and remains relatively constant to the bottom of the core. Chlorite tends to increase more gradually down the core. Comprehensive environmental interpretation of these data should provide a correlation with climatic conditions. So, preliminary examinations of piston cores 305 (Selenga Delta) and 333 (Akademichesky Ridge) demonstrate a distinct correlation between the abundance of smectite and biogenic silica. These results suggest that, in some instances, smectite may have been produced in the soils around Lake Baikal during the same warmer episodes which stimulated the productivity of siliceous microorganisms.

Geochemical parameters. The geochemical studies including determinations both of major and trace elements, rare and rare-earth elements were performed by atomic-emission spectroscopy and inductively bound plasma (ICP-AES), ICP-mass spectrometry and instrumental neutron-activation analysis (INAA) (Japan) as well as X-ray fluorescence (XRF) and atomic absorption (AA) with electrothermal atomizer (Institute of Geochemistry, Irkutsk). The resultant statistical data are presented in Table 1.

The Japanese researchers studied distribution of major elements and trace elements through the vertical section of BH-1 (Figs. 6, *A*, *B* and 7). Figure 6, *A* provides plots of Ti, Al, Fe, Mn, Ca and P distribution in the core. In the uppermost part the abundances of Al, Ti, Fe and Ca are relatively low, while P content is comparatively high.

Figure 6, *B* yields plots of trace elements' distribution. In the upper part the concentrations of all trace elements are low as for the most of major elements. Differences between the upper and lower parts of the core are observed on the plots of Cr, Co, Hf and Ta distribution.

Figure 6, *C* shows how relative concentrations of some elements vary throughout the section. It is well-known that Ti/Al value is indicative of changes in the source of terrigenous components in sediments. However, in contrast to the 1,400-m borehole on Biwa lake [17], there are not marked changes on the Baikal Ti/Al profile.

Some differences between the upper and lower portions of the core are observed on the Mn/Al and

Table 1

Chemical Composition of Upper (to 49 m) and Lower (below 49 m) Portions of the Section in BDP-93 BH-1

Compo-nent	Upper portion			Lower portion			Student's t-criterion	Method
	$\bar{x} \pm \Delta\bar{x}$	s	n	$\bar{x} \pm \Delta\bar{x}$	s	n		
SiO_2, %	57.2+1.1	9.61	35	56.35+0.48	1.69	31	1.48	XRF
TiO_2	0.86+0.024	0.0046	35	0.91+0.012	0.0011	31	3.25	»
Al_2O_3	17.71+0.56	2.56	35	18.54+0.26	0.49	31	2.78	»
$Fe_2O_{3\ tot}$	7.29+0.21	0.35	35	7.27+0.20	0.30	31	0.16	»
MgO	2.91+0.15	0.19	35	3.00+0.08	0.053	31	1.06	»
MnO	0.11+0.01	0.001	35	0.08+0.01	0.00036	31	4.74	»
CaO	1.75+0.08	0.048	35	1.75+0.07	0.032	31	0.20	»
K_2O	2.69+0.08	0.048	35	2.85+0.07	0.036	31	3.18	»
Na_2O	1.85+0.07	0.048	35	1.94+0.12	0.102	31	1.32	»
P_2O_5	0.19+0.02	0.0052	35	0.20+0.02	0.0041	31	0.60	»
S	0.11+0.02	0.0031	35	0.16+0.03	0.0083	31	2.65	»
Sr, ppm	222+5	361	69	166+20	3136	31	5.43	»
Zn	95+5	196	36	177+7	400	37	5.46	AA
Pb	15+1	15.2	36	20+2	29.2	37	4.54	»
Cd	0.56+0.050	0.022	36	0.54+0.2	0.4	37	0.19	»
Ag	0.22+0.06	0.032	36	0.34+0.2	0.36	37	2.78	»
Cu	51+3	90.2	36	46+3	62.4	37	2.44	»
Ni	76+3	100	36	67+4	121	37	3.66	»
Co	28+1	13.7	36	23+2	23	37	4.99	»
Cr	96+5	196	36	94+6	289	37	0.55	»
V	121+4	169	36	149+9	784	37	5.50	»
Zr	157+2	32	35	193+5	169	31	14.25	XRF
Rb	111	—	20	119	—	12	—	NAA
Sc	17	—	20	18.9	—	12	—	»
Ta	1.17	—	20	1.26	—	12	—	»
Th	11.8	—	20	15.5	—	12	—	»
La	48	—	20	52	—	12	—	»
Ce	94	—	20	106	—	12	—	»
Sm	8.2	—	20	8.5	—	12	—	»
Nd	40	—	20	42	—	11	—	»
Y	29	—	18	31	—	12	—	»
Lu	0.45	—	18	0.49	—	12	—	»

Note: $\bar{x}$ — arithmetic mean, $\Delta\bar{x}$ — error of the mean at a 95 % level of significance, s — dispersion, n — number of samples, Student's t-criterion — value of difference of selections of elements in the "upper" and "lower" portions of the section. At t > 1.95 selections are different. XRF — X-ray fluorescence analysis, Institute of Geochemistry (analyst T. Gunicheva), AA — atomic absorption analysis, Institute of Geochemistry (analyst O. Proidakova), NAA — instrumental neutron-activation analysis, Japan, Tokyo, University (analyst K. Toyoda).

Fe/Mn plots. On the right plot the ratio values are higher in the upper portion, on the left one they are relatively higher in the lower portion. The Mn/Al and Fe/Mn ratios in the lacustrine sediments are regarded as indicators of the lake depth (thickness of the water body) and redox conditions, respectively [17].

Figure 7 represents a chondrite-normalized REE distribution for three samples. They display a poor enrichment in LREE with a negative Eu anomaly. The same REE distribution is common for continental clay schists [18] but the Baikal samples are somewhat richer in HREE than in LREE. These results suggest that the alkaline rocks occurring in the surroundings of Baikal played a certain role in the formation of the borehole sediments [19].

Analytical data of Russian scientists are generalized in Table 1 and in Fig. 8, *A*, *B*. According to the table the entire sedimentary sequence penetrated by BH-1 is clearly divided into two portions: upper (above

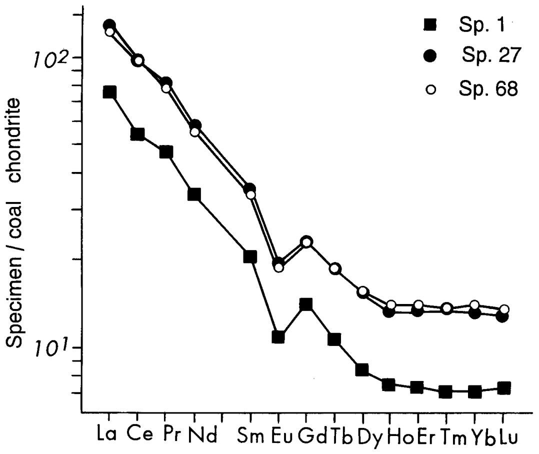

Fig. 7. Plot of rare-earth elements distribution in the rocks of the borehole.

49 m) and lower (below 49 m). The values of abundances of elements, their dispersions and Student's *t*-criterion prove significant differences between these two units, primarily in distribution and abundances of Al_2O_3, TiO_2, K_2O, MnO, Zr, Sr, Co, V, Zn, Pb, Ni, Cu, and S. To illustrate these geochemical differences, we preferred Ti, Zr and Sr distribution in rocks (Fig. 8). There is asymmetric distribution of TiO_2 in the upper and lower parts of the section obviously connected with the presence of the element in different minerals. In the lower part its distribution is nearly normal, and this is due to the predominance of one mineral form of this element in the sediment.

The elements' distribution in the upper and lower sequences differ both in abundance and degree of variability. Thus, the upper part is richer in silica (SiO_2 contents may achieve 64.5 %), MnO (up to 0.23 %) and Sr (260 ppm). On the other hand, the lower sediments contain somewhat higher concentrations of Ti (0.99 % TiO_2), Al (to 19.6 % Al_2O_3), K (3.22 % K_2O), S, Zn, P, Ag, V, Zr, Rb, Th and some of rare-earth elements. Close values of ratios K/Na=1.45–1.47 and Ca/Na=0.94–0.90 indicate a relative homogeneity of mineral composition of K-feldspar light fraction throughout the section. However a significant difference of K/Sr ratio from 171 for the upper and 228 for the lower part indicates noticeable changes in the trace element composition of plagioclase fraction. Both parts of the core show variations in ratios of bulk contents of heavy fraction elements: Ti, Zr, Ta, Th, Ce, La and other rare-earth elements. The chemical composition of both parts differs from the medium composition of bottom sediments of Baikal and fluvial deposits of its tributaries [20], which is determined by the Student's *t*-criterion of K_2O, TiO_2, Al_2O_3, MgO, Cr and SiO_2.

Radiocarbon dating. A total of twenty-one samples from the upper portion of the BH-1 have been dated using standard accelerator mass spectrometry (AMS) at the Woods Hole AMS Facility and at Nagoya University.

Dating was based on total organic carbon in all samples except for one wood fragment at a depth of 25 cm. There is good agreement among the ages in the upper 400 cm (Fig. 9), spanning the last 21,000 years and giving a linear constant sedimentation rate of approximately 20 cm a thousand of years. Below 400 cm, the data indicate significant changes in sedimentation rate. Seven of ten dates indicate a surprisingly similar rate over 100 cm a thousand of years for the period 20,000–30,000 years (see Fig. 9). The line of regression for eleven uppermost dates having a good linear location (R^2 = 0.9000) crosses the line of surface sediment at the point with a relative age of approximately 1000 years. Three of ten dates downcore (at depths of 420 cm and 1,175 cm, and the oldest, more than 30,000 years, at a depth of 1,575 cm) deviate far from the linear location and are possibly anomalous.

The ages for the upper portion of BH-1 are consistent with the spatial pattern of Late Quaternary (Holocene—last glacial maximum) sedimentation rates determined from more than 80 AMS radiocarbon ages of box cores, gravity cores, and piston cores throughout the lake [7, 21]. For example, AMS radiocarbon ages for the BH-1 core, and the ages from core PC2, station 339, less than one kilometer away from it, are remarkably consistent in depths corrected by means of magnetic susceptibility profiles for the two sites. The age dates for 339-PC2 core suggest a sedimentation rate about 24 cm a thousand of years. The data obtained from the sites close the Selenga delta indicate sedimentation rates in the glacial periods to be higher than in interglacial ones and comparable with the recent rates in this region.

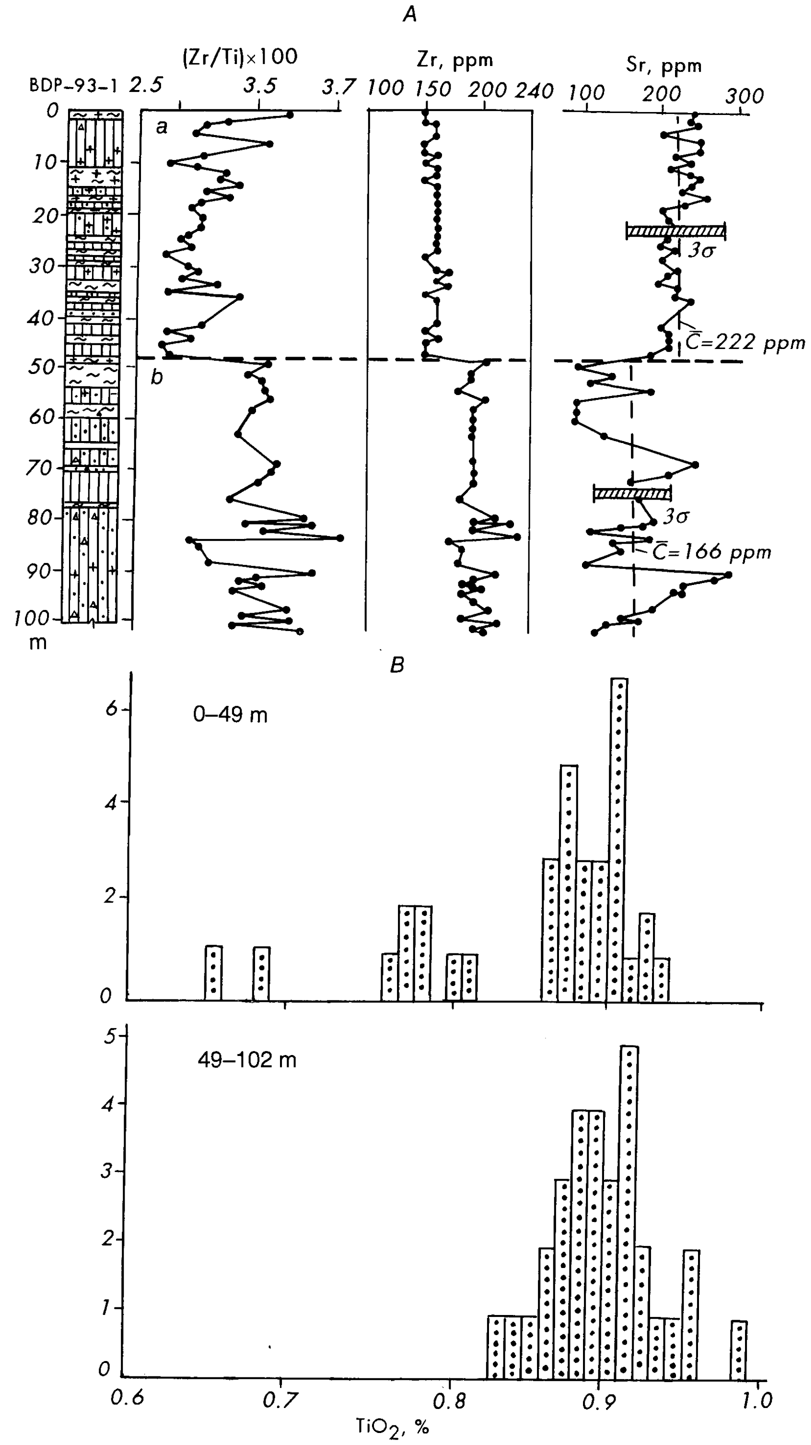

Fig. 8. Geochemical features of the borehole. *A* — Zr/Ti × 100 and Zr and Sr abundances, 3σ — confidence interval for Sr contents, *B* — histograms of TiO_2 distribution.

Magnetic susceptibility studies of rocks. Magnetic susceptibility, *K*, permitting estimation of magnetic minerals' concentration in sediments, was measured in the two BDP-93 boreholes at 3 cm intervals using a susceptibility meter of Burtington Instruments. Whole-core measurements can be used in several ways. First, magnetic susceptibility provides an accurate core correlation between the two boreholes to a depth of 84 m (Fig. 10). Second, magnetic susceptibility can be used to correlate the uppermost sediment

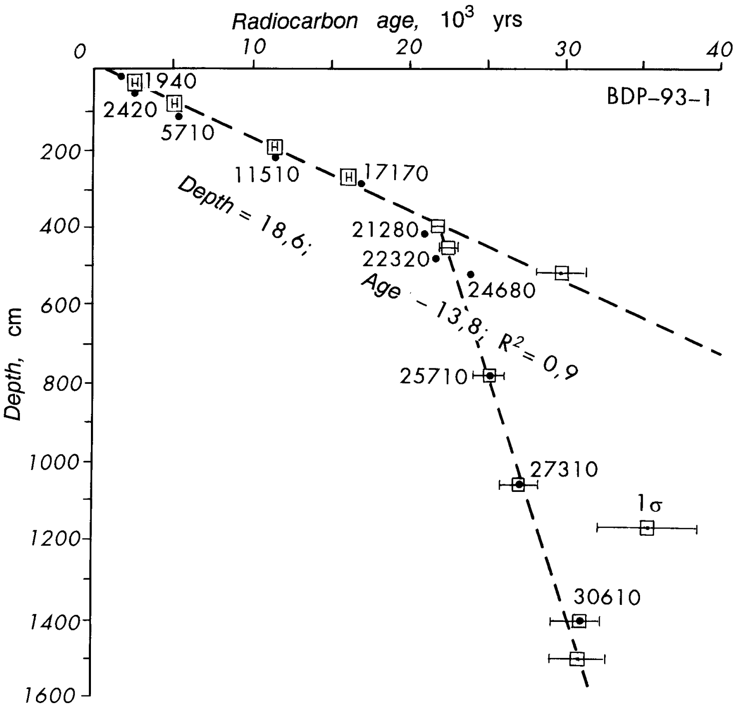

Fig. 9. Accelerator mass spectrometry (AMS) radiocarbon ages for BDP-93-1. The uppermost sample is wood; the rest of the samples are analyzed according to total organic carbon. Analytical error bars (1σ) are shown. The linear regression line is constructed for upper seven samples.

in BH-1 and BH-2 to soil columns from nearby stations 305 and 339. As the soil columns retain the near-surface sediments intact, their similarity to the drilled deposits suggests that the BDP-93 boreholes also penetrated the undisturbed near-surface sediments. Third, magnetic susceptibility can help to identify contamination caused by the drilling process. Unusually high *K* values at the tops of individual cores result from contamination caused by grease and metal filings in the drill casing accumulated between successive hydraulic piston coring runs. The *K* profiles suggest that a series of intervals in BH-1 and BH-2 may contain contaminated sediment at the core tops. Anomalous *K* values in core 15 of BH-1 suggest that the entire core may be contaminated. These data should be taken into account in all examinations. Fourth, the *K* profile for BH-1 shows a high degree of correlation with the lithology in the upper 50 m. Diatomaceous sediment is characterized by low *K* values reflecting the dilutional effect of diamagnetic biogenic silica. Clayey sediment is characterized by relatively high *K* values. The same relationship has been seen in previously collected cores from other parts of Lake Baikal [7, 22].

For the purpose of paleomagnetic analysis, oriented samples were taken from the BDP-93-1 core at an interval of 30 cm and placed into plastic boxes of 5 cm^3 in volume. These samples were then used for measuring declination, inclination, and vector of natural remanent magnetization (Fig. 11). Some of the of samples were measured for rock-magnetic properties (concentration, grain size, and mineralogy). Stepwise alternating field (AF) demagnetization has shown that the sediment has a stable primary remanence, an extremely small secondary viscous remanence, and a relatively high intensity of magnetization. The inclination record for the BH-1 indicates that the sediment record is entirely of Brunhes age (Fig. 11). Shallow or negative inclinations observed in single samples from depths of 4.55, 14.76 and 52.62 m are not found in the neighboring samples and therefore, these are not likely to reflect excursions in the Earth's magnetic field. There are, however, two more intervals of shallow or negative inclinations, represented by multiple samples and likely reflecting excursions in the Earth's magnetic field. The first excursion is located between 25.5 and 27 m (Fig. 11). Interpretation of the rock-magnetic parameters indicates that this interval corresponds to glacial conditions. Since the magnetic susceptibility profile correlates with the curve of oxygen isotope variations in marine sediments SPECMAP [23] this excursion may be referred to stage 6. This excursion also correlates with the excursion identified in core 287 K-2 from the Akademichesky Ridge region of Lake Baikal. If this climatic

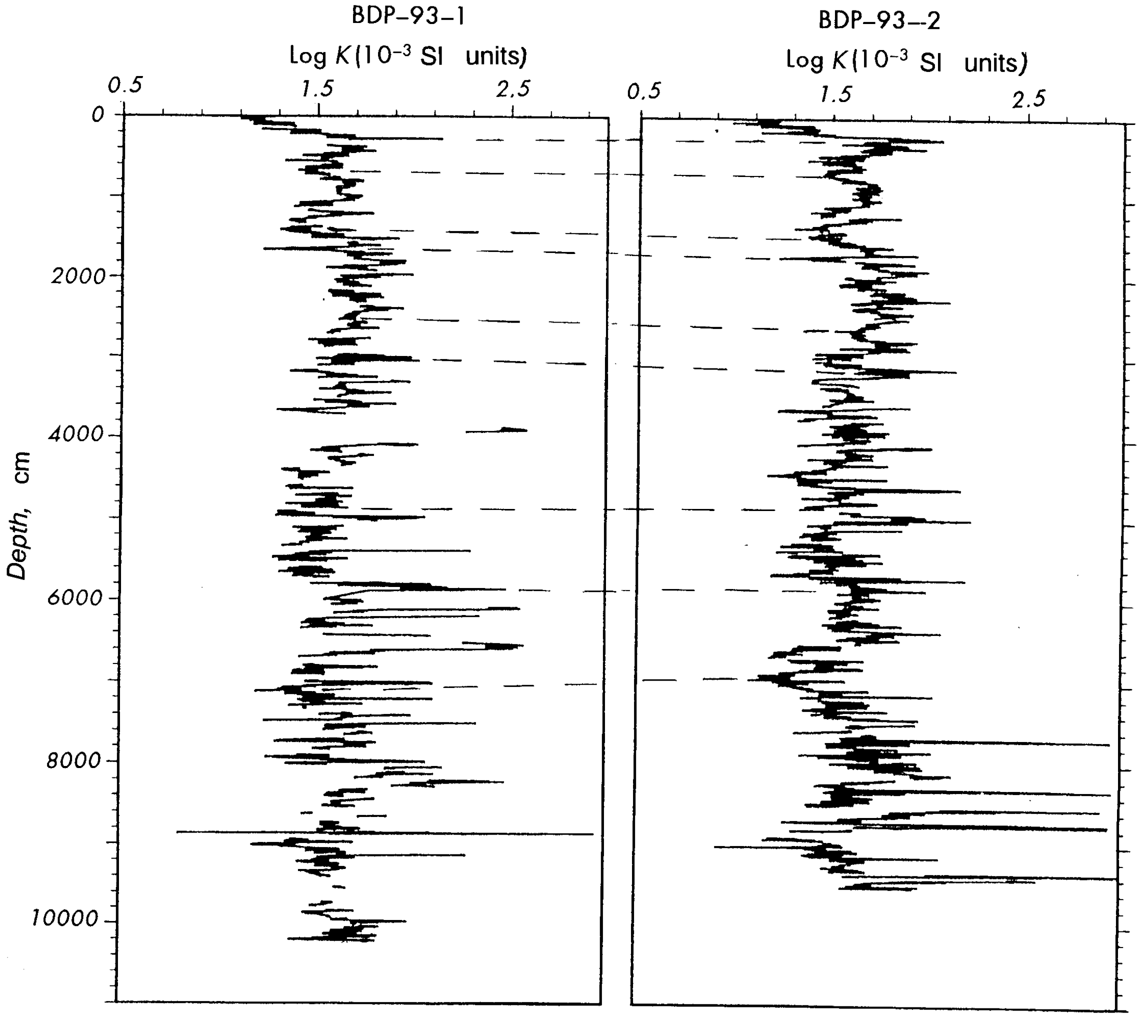

Fig. 10. Whole-core magnetic susceptibility (*K*) profiles for BDP-93-1 and 2. Magnetic susceptibility is a measure of concentration of magnetic minerals in sediments (Log *K* was taken to reduce large *K* values for display purposes. A good correlation between boreholes is evident.

interpretation is correct, then the excursion would be approximately 180,000 ka, corresponding to the Biwa I — Jamaica double excursion. To find a more precise time reference, it is necessary to carry out additional paleomagnetic measurements over this interval as well as to use data of other methods of paleoclimate estimation (study of biogenic silica, diatoms, clay composition, and palynological investigations). Another double excursion located between 67 and 71 m requires further investigation in order to place it within a time framework because the rock-magnetic properties indicate radical changes in depositional environment at a depth of about 50 m.

Rock-magnetic measurements in the upper 50 m (concentration, grain size, and mineralogy of the magnetic component of the sediment) are well correlated with climatic changes. Supposed interglacial and interstadial periods are characterized by low magnetic concentrations (SIRM) with their composition dominated by low-coercivity minerals (Fig. 12). Inferred glacial periods are characterized by higher magnetic concentrations (*K*, KARM, SIRM) and increased amounts of high-coercivity minerals (HIRM, *S*-ratio). We infer that during the warm periods increased diatomaceous sedimentation resulting from increased lake productivity dilutes the magnetic concentration. In addition, during warm periods enhanced soil development in the Selenga and Buguldeika River catchments yields increased amounts of low-coercivity minerals. Below 50 m the magnetic concentration generally increases, low-coercivity minerals predominate throughout, and increased amounts of sand and gravel are present (Fig. 12). This change in magnetic parameters and lithology suggests a change in deposition environment at this site, in particular, a dominating role of fluvial additions.

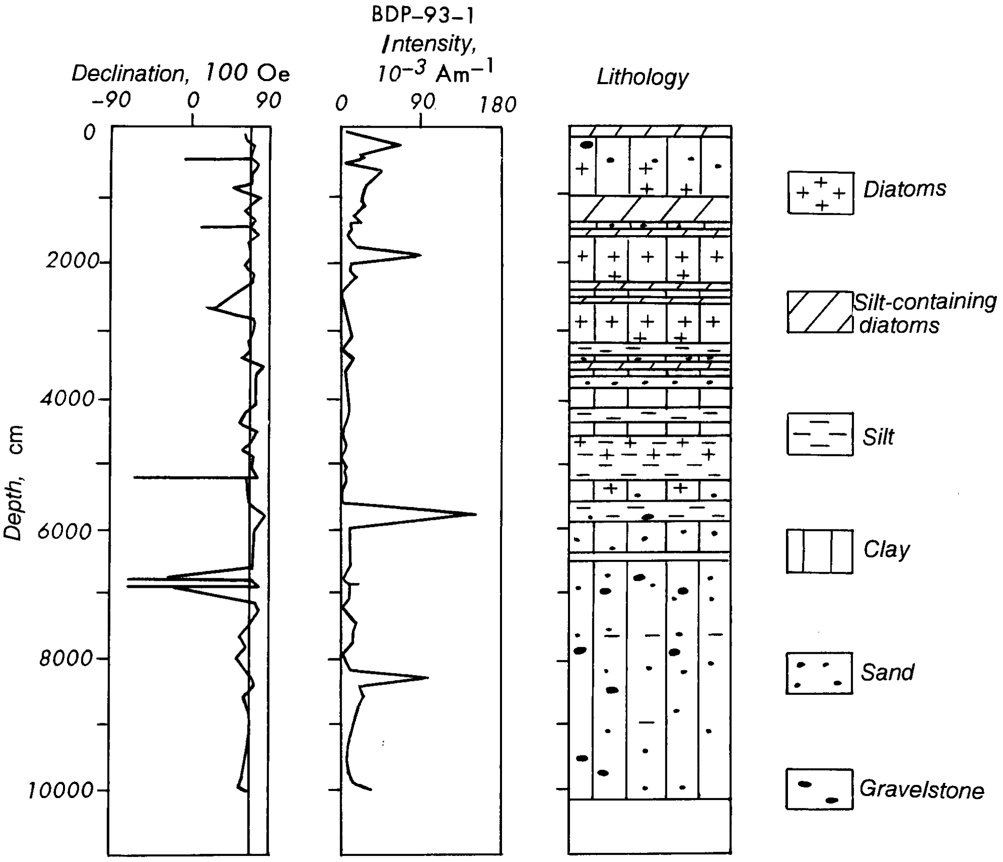

Fig. 11. Magnetic inclination and intensity of magnetization after AF-demagnetization at peak field 10 mT. Two excursions are present between 25.5–27 m and 67–71 m.

Results of palynological analysis. Seventy seven samples were analyzed to obtain spore-pollen spectra (SPS) for the BDP-93-1 core. Fluctuations in the abundance of 74 taxa (families, genera and species) record changes of the terrestrial vegetation in the Baikal area. Nearly 85 % of the samples contain some portion of terrigenous material which consists predominantly of plant tissue.

The pollen material exhibits variable preservation, but in general the SPS's are very diverse including elements of present-day plants as well as pollen of Paleogene-Neogene age and some Jurassic species. Palynological analysis identified three different types of SPS: "forest", "forest-steppe", and "steppe". SPS's of the "forest" type contain up to 80 % arboreal pollen. They are rich in pollen material, particularly that of coniferous plants: *Picea*, *Larix*, *Pinus* (*sibirica*, *silvestris*, *pumila*). Species of *Abies* and *Tsuga* occur occasionally. Pollen of small-leaved species, *Betula*, *Alnus*, *Duschekia fruticosa*, and *Salix*, makes up 5–20 %. Pollen of the warm-requiring genera *Corylus*, *Carpinus*, *Quercus*, and *Ulmus*, is abundant.

The SPS's of "forest-steppe" and "steppe" types contain 50 and 70 % non-arboreal pollen, respectively, most of which are herbs. The most abundant herb pollen is from the families *Cyperacae*, *Asteraceae*, and *Chenopodiacea*, and from the genus *Artemisia*. The SPS's of these types almost always include pollen grains of warm-requiring genera of flora: *Ulmus*, *Corylus*, *Quercus*, *Carpinus*, sometimes *Ilex*.

As evident from the spore-pollen diagram (Fig. 13), the total composition of pollen and spores reflects alternation intervals of "forest" type SPS with its "steppe" and "forest-steppe" types. Based on this evidence, 13 palynologic zones have been distinguished. The boundaries of these zones are drawn conventionally because the sampling was made with large breaks. A more detailed study of the core may result in a shift of these boundaries.

The zones from top to bottom are:

XIII — 0–5.50 m — *Picea*, *Abies*, *Pinus sibirica*, *Pinus silvestris*

XII — 5.50–13.00 m — *Asteraceae*, *Cyperaceae*, *Poaceae*

XI — 13.00–19 m — *Picea*, *Pinus sibirica*

X — 19–13.5 m — *Cyperaceae*, *Asteraceae*, *Poaceae*

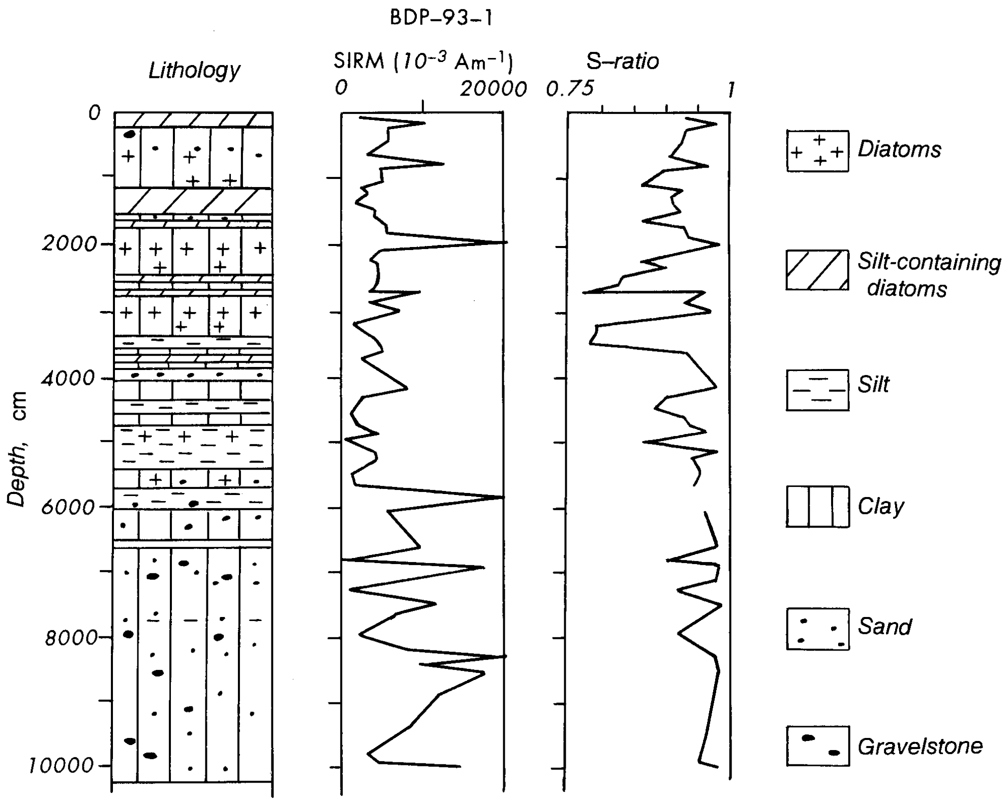

Fig. 12. Selected rock-magnetic parameters for the borehole. SIRM is remanent magnetic concentration within the sediment. Parameter *S* (IRM–0.3 T/SIRM) characterizes the ratio of high-coercivity minerals (i.e., hematite, goethite) to low-coercivity minerals (i.e., magnetite, maghemite). *S*= 1 indicate 100 percent of low-coercivity minerals, whereas lower values *S* indicate an increasing proportion of high-coercivity minerals.

IX — 23.5–35.5 m — *Picea*, *Pinus sibirica*, *Pinus silvestris*, *Betula*; *Cyperaceae*, *Artemisia*, *Chenopodiaceae*
VIII — 35.5–40.0 m — *Picea*, *Pinus sibirica*
VII — 40.0–43.0 m — *Cyperaceae*, *Artemisia*
VI — 43.0–53.0 m — *Larix*, *Picea*, *Pinus sibirica*; *Cyperaceae*
V — 53.0–64.0 m — *Larix*, *Picea*, *Pinus subirica*, *Betula*; *Asteraceae*, *Polypodiaceae*, *Sphagnum*
IV — 64.0–80.0 m — *Pinus sibirica*, *Picea*, *Larix*; *Salix*, *Cyperaceae*
III — 80.0–86.0 m — broad-leaved arboreal; *Asteraceae*, *Poaceae*, *Artemisia*
II — 86.0–92.0 m — *Larix*, *Picea*, *Pinus sibirica*
I — 92.0–104.0 m — *Larix*, *Pinus sibirica*, *Betula*; *Cyperaceae*, *Poaceae*, *Artemisia*.

The zones delineated display alternation of moderately warm, relatively dry and moderately cold wet epochs. Zones II, IV, IX, XI, and XIII contain floras dominated by dark conifers: spruce, cedar pine, and, occassionally, larch. These floras are characteristic of moderately cold wet climatic conditions. Zones I, III, V, VI, and XII are characterized by floras of relatively dry climates (the dominating spores belong to non-arboreal forms — grass, *Compositae*, Artemisia, meadow-steppe herbage). Zones VII, VIII, and X should be considered transitional because their flora is common for still wetter and colder environments, and they show a low content of arboreal species. Shrub (willow, dwarf birch) and herbaceous (sedge) floras are present.

A very interesting regularity is noted within the range 30–104 m: the intervals containing moderately cold wet species of SPS are followed by a sharp increase in ancient redeposited species*. It is likely that a sharp increase in precipitation contributed to washout of ancient rocks, resulting in redeposition of Mesozoic and Cenozoic pollen by waters of the Buguldeika and Selenga rivers.

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* The top horizons were investigated only by Japanese palynologists and research workers from the Institute of the Earth's Crust, Irkutsk. Unfortunately, they did not calculate absolute contents of spore-pollen material and, correspondingly, amount of redeposited forms. These studies are to be continued, for according to the rest of parameters the material obtained is well comparable.

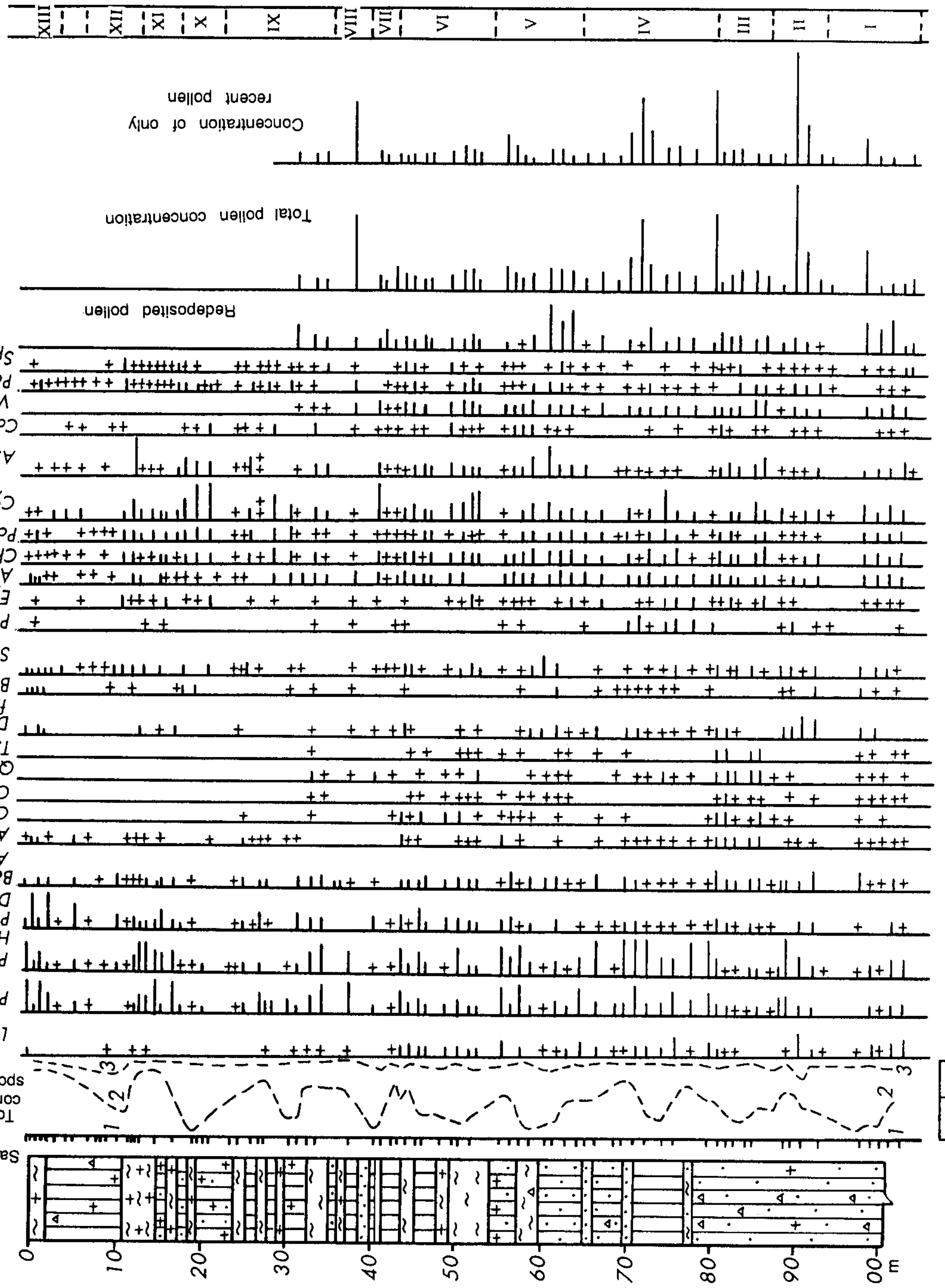

Fig. 13. Distribution of spore and pollen in BDP-93-1 sediments. ***1*** **— arboreal pollen;** ***2*** **— non-arboreal pollen;** ***3*** **— spores; + — pollen abundance < 1 %.**

Peaks in the concentration of spore-pollen material reflect epochs of dark-coniferous forest vegetation; high pollen productivity is characteristic of these conifers. The SPS's of zone III contain pollen of the group "mixed oak forest" (*Quercetum mix.*). These are representatives of warm-requiring flora: oak, elm, linden, filbert, and hornbeam. During the warm periods of the Lower and Middle Pleistocene, they could grow in Transbaikalia, Mid-Siberian Upland and, possibly, in the Tunka Depression, in the Irkutsk-Cheremkhovo Valley. In our opinion, pollen of these plants is brought by the Selenga River, running over Transbaikalian steppes and forest-steppes. It is not likely that this flora was transported by the Buguldeika River, because the Quercetum mix group was not growing in its basin. While the sediments formed, there was a repeated

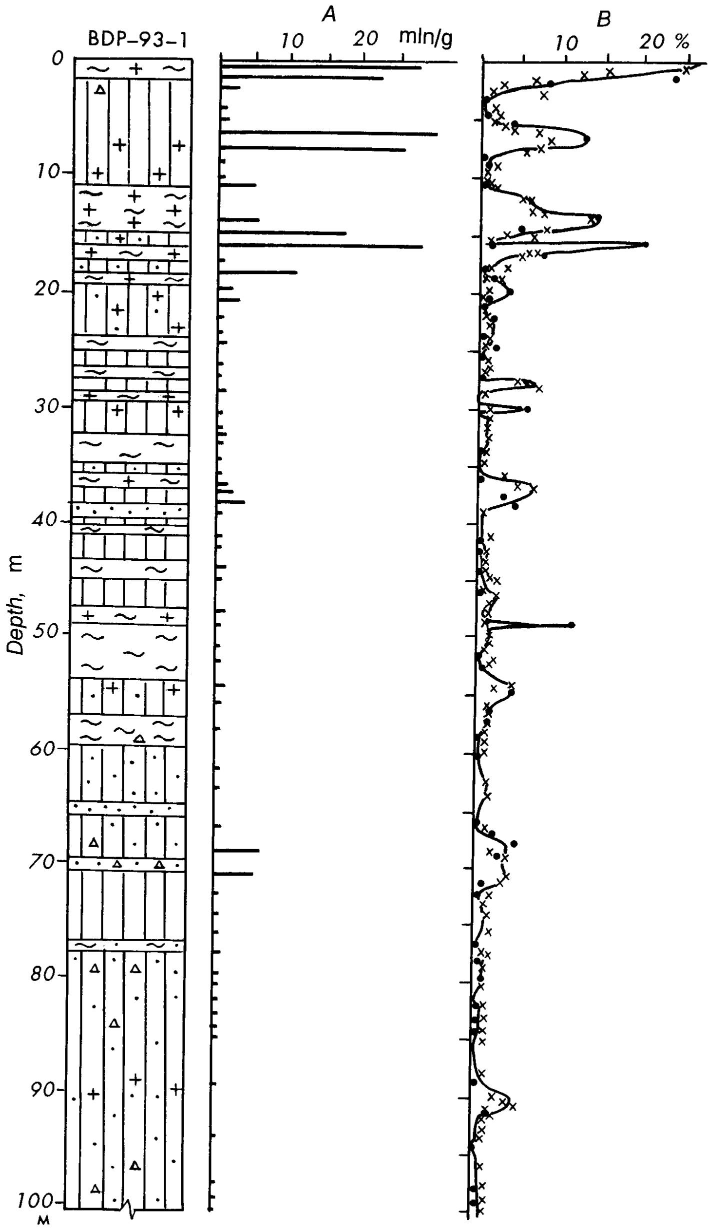

Fig. 14. Distribution of diatom valves in millions per gram of dry residue (*A*) and biogenic silica abundance (*B*) in BH-1

alternation of moderately cold wet epochs with moderately warm dry ones. The deposits are considered to be of Pleistocene age.

Analysis of diatoms' distribution. To study the distribution of diatomic algae in the sediments by means of light microscopy at 0.64–51.11 m, preparations were made using a heavy liquid [24]. The preparations of electronic microscopy of the entire core from 0.64 to 99.76 m were made by the technique described previously [6] with preservation of inorganic particles. This technique permitted quantitative estimation of diatom frustules per unit of dry sediment weight. In addition, smear-slides were examined.

Studies of diatom distribution in BDP-93-1 core revealed large variations of total number of frustules preserved in sediments (Fig. 14). Some portions are relatively poor in diatoms (less than 1 frustule per 0.1 mg of sediment). These core portions correspond to the depths: 4.13–5.21; 8.75–10.13; 21.03–27.17; 30.45–35.80; 39.02–42.21; 49.12–52.28; 56.29–63.26; 72.31–87.71; 90.48–99.79 m.

All the diatom-bearing samples under study are dominated by endemic species. Down to a depth of

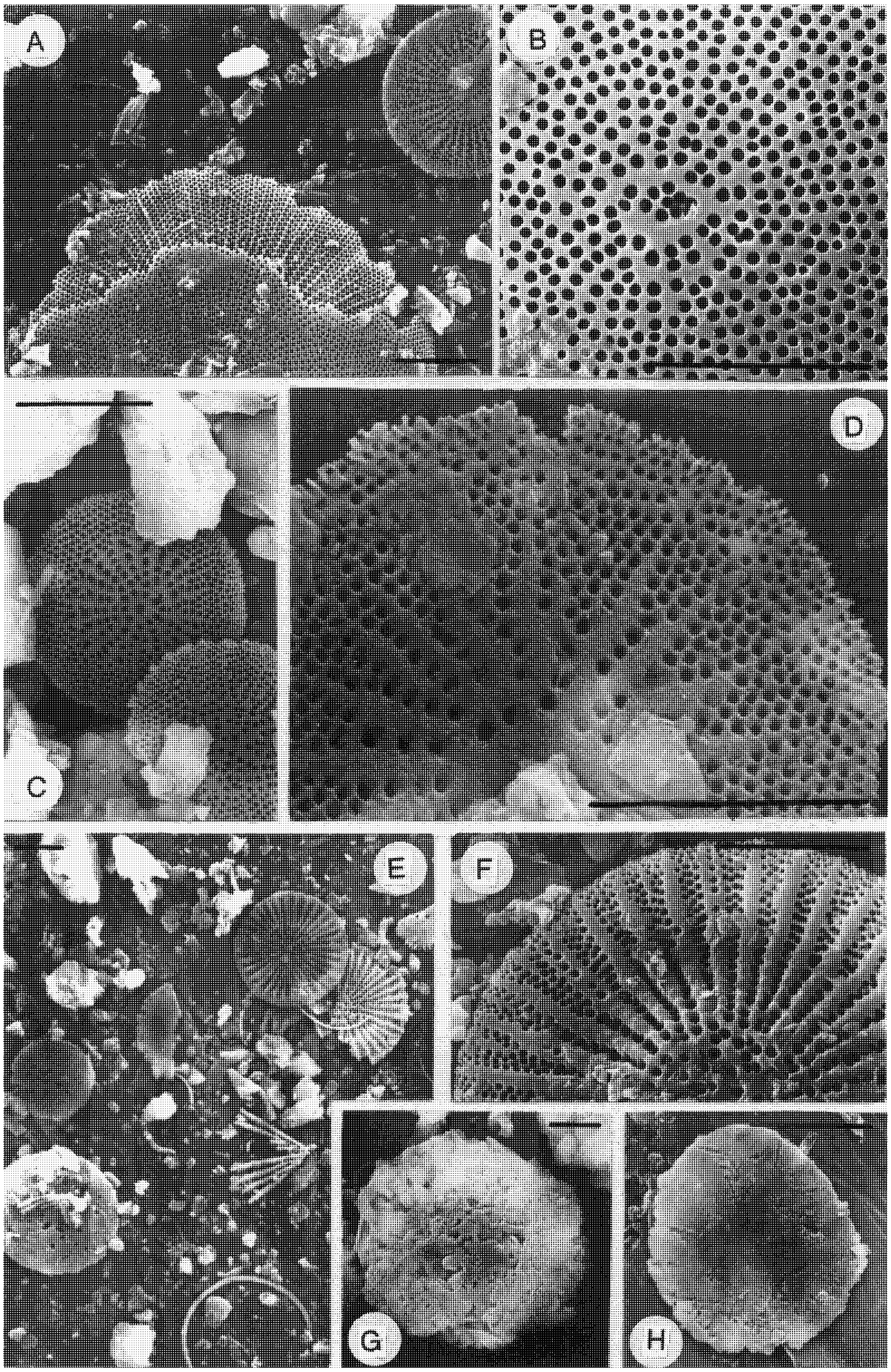

Fig. 15. Diatom algae from BDP-93-1 borehole. A — *S.grandis* and *S.carcaneiformis* from a depth of 16.65 m; B — fragment from valve *S. grandis*; C, D — *Stephanodiscus* species from a depth of 70 m; E — general appearance of sediment from a depth of 90 m; F — *Stephanodiscus sp.* fragment from the same depth; G, H — disc-shaped formations from a depth more than 70 m. Scale — 10 μm.

20.98 m the sediments contain the diatom complexes common for the Baikal sediments described earlier. Below are the species involved in these complexes (in decreasing order of their number). At a depth of 0.64–0.70 m — *Cyclotella minuta*, *Synedra acus*, *Aulacoseira baicalensis*, *A. islandica* (spores), *C. baicalensis* at 1.77–1.83 m; *Stephanodiscus flabellatus*, *C. baicalensis*; at 6.30–7.82 m — *C. minuta*, *A. baicalensis*, *C. baicalensis*. At 10.95 m, species composition of diatomic community drastically changes: the fossil species of *Stephanodiscus* genera (*S. grandis*, *S. carconeiformis*, *S. bellus*) (Fig. 15, *A*, *B*) disappear thus marking a drastic change in climatic conditions. This complex occurs downward to 20.98 m and also contains species *A. baicalensis* and *C. minuta*.

The pattern of distribution of diatom species in BDP-93 core to a depth of 20.98 m agrees with the data obtained for an 11 m piston core collected from the Akademichesky Ridge [25]. The difference is that BDP-93-1 core is more "extended", i.e. in this case the boundary of disappearance of the *Stephanodiscus* fossils is at 10.95 m, while on the Akademichesky Ridge it runs at a depth of 5 m [25], which is evidently due to a different sedimentation rate.

Diatoms occur more rarely in the lower horizons of the core at a depth of 21.03 to 63.20 m. They represent the fossil group *Stephanodiscus* at horizons 27.76; 28.72; 36.77 and 44.01 m; together with *C. baicalensis*, *C. minuta* and spores *A. islandica* these species occur also at 54.52 m.

Two new complexes of algae, not reported earlier elsewhere (see Fig. 15), were found at 66.82–70.98 and 90.20–90.42 m. They do not contain *S. grandis* which is common for the Upper Pleistocene bottom sediments of Baikal, whereas some species of *Stephanodiscus* dominate at 70 m (see Fig. 15, *C*, *D*), with their characteristics different from the diagnoses of *S. carconeiformis*, *S. flabellatus* and *S. bellus*. They are supplemented by species *C. minuta*, *A. islandica* (spores), as well as *S. carconeiformis* and *S. bellus* common for the Holocene-Upper Pleistocene sediments. At a depth of 90 m the complex contains two dominant species, *C. minuta* and *Stephanodiscus* (Fig. 15, *E*, *F*), the latter being never described before.

A low content of diatom frustules in the above-mentioned horizons may be due to two reasons. First, the sediments are diluted by terrigenous material transported off the shore; second, it is likely that the frustules were partly dissolved during their long stay in sediments. Disc-shaped formations of 30–40 μm in diameter with smoothed or crystalline surface are in favor of this possibility (Fig. 15, *F*, *G*). These can be masked frustules of diatom algae which experienced partial dissolution, with silicon recrystallized on their surfaces.

The data obtained on the quantitative distribution of diatom frustules in the BDP-93-1 core agree with the data on the percentage of biogenic silica (see Fig. 14, *B*). The described change of diatom complexes is an excellent instrument in biostratigraphic correlation of cores and is undoubtedly related to change in the past climatic, environmental, hydrological and other conditions.

Biogenic silica and other organic constituents. Biogenic silica (BSi), which has been shown to correlate with diatom productivity in the lake, shows major fluctuations with depth in the Buguldeika Site (Fig. 16). The sediments in the upper 2 m of the core, dated as Holocene by the radiocarbon method, have maximum BSi contents of 20–25 %. The sediments at a depth of 2–5 m, which, according to radiocarbon dating, correspond to last glacial maximum, have mostly a few percent or less. The next maximum occurs at a depth of 7 m, but it is relatively small, less than 15 %. Extrapolation of sedimentation rate for 30,000 years from the upper part of core suggests that the age of this peak is 36,000 years. The following maximum is at a depth from 11 to 17 m and has several peaks. Below this depth the BSi peaks vary within the range 5–12 %. Majority of these peaks are confined to the upper 50 m of the core, over the boundary of lithological changes. Small but significant peaks of BSi are available in the lower portion of sediments at 55.68–71 and 90 m.

We believe that the interglacial periods were characterized by high diatom productivity, and that the previous glacial periods are marked by their low productivity. This inference is based on the assumption that BSi has not been significantly altered by diagenetic processes. However for such a correlation we need more reliable age data.

The concentrations of organic carbon and total nitrogen in sediments make up 0.4–3.4 % and 0.06–0.3 %, respectively. The maximum of organic carbon in the upper part of the core corresponds to the Holocene maximum of organic carbon (absolute age is 6,000 years) which is observed in the piston cores throughout Baikal [7, 26]. Downcore there are multiple peaks of maximum organic carbon contents, but analogous peaks of biogenic silica do not correspond to all of them. The distribution of total nitrogen concentrations downcore is in general similar to the distribution of organic carbon. The value of atomic ratio C/N of 7 to 18, averaging to 10 in core, is the evidence that productivity of the water column of the lake was the primary source of organic matter of the Buguldeika basin sediments. At 44–80 m the values of atomic ratio C/N are above average which suggests an increase in terrigenous material supplied to the lake at that time. There is a good correlation between organic carbon contents and values of atomic ratio C/N.

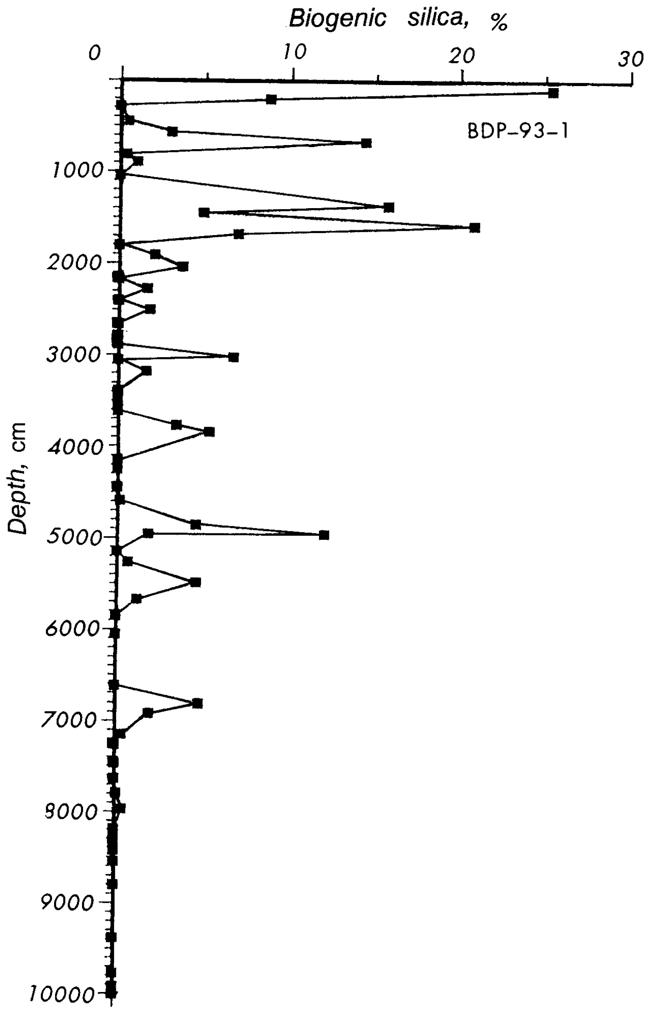

Fig. 16. Biogenic silica abundances obtained by Mortlock and Froelich method [35]. Data are corrected with regard to clay minerals dissolution.

Chemical and isotope composition of pore waters. The abundances of chlorides, sulfates and bromides, as well as main cations — calcium, magnesium, sodium and potassium were measured in the pore waters squeezed out from the core samples just after they were recovered. The concentrations of anions were determined by the method of ion chromatography with a precision of ± 0.1 for chlorides, ± 0.3 for sulfates, and ± 0.1 mg/l for bromides. The concentration of cations was measured in the direct flowing plasma with a precision of 2–3 %.

The results obtained (Fig. 17) indicate a tendency toward gradually increased pore water mineralization downcore. Not only concentrations of anions and cations increase in this direction but also cation ratio varies: Na/K increases approximately from 2 to 9, while Ca/Mg decreases from 5–6 to 4. The hydrocarbonate-potassium type of porous waters in the upper part of the core is replaced for hydrocarbonate-sodium-potassium type in its lower part. A similar increase in mineralization and the change of the porous waters type are characteristic of porous waters of Baikal sediments obtained by piston coring, and are due to the processes of leaching and cation exchange.

There is a noticeable anomalous increase in chloride concentration at a depth of 31–37 m, and concentrations of sulfates at 50–55 m (see Fig. 17). The 53 m horizon shows the highest content of bromide ions (4.5 mg/l). A similar drastic increase in chloride- and sulfate-ion concentrations is observed in the porous waters of Baikal sediments from piston cores.

It is probable that an anomalous increase in sulfates and chlorides is due to the effect of mineralized ground waters widespread in this region. This assumption confirms isotope data to some extent. For East

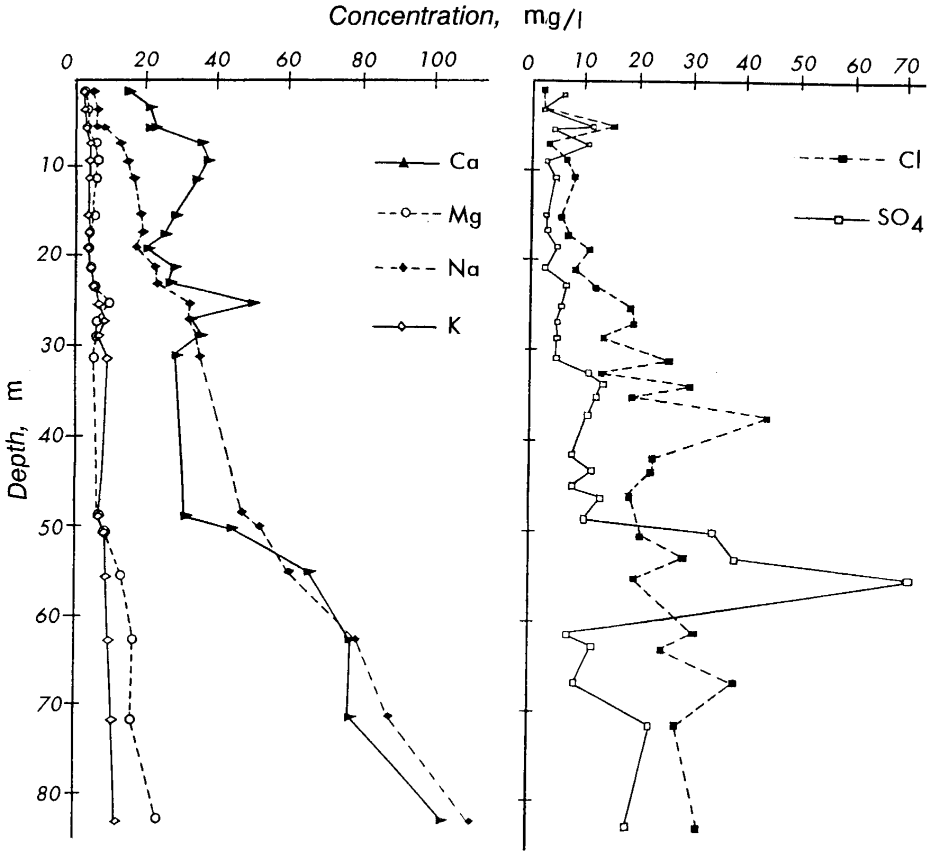

Fig. 17. Concentrations of some ions in pore waters of BDP-93-1 borehole.

Siberia it was found that composition of δ^2H and $\delta^{18}O$ isotopes of fresh and saline waters of shallow horizons, thermal waters and sodium-chloride brines is close to isotope composition of meteoric and surface waters from feeding areas [27]. It is valid for porous waters of BDP-93-1. On the diagram δ^2H — $\delta^{18}O$ the main field of isotope compositions of these waters is located between the line of local meteoric waters and the line of thermal waters of southern East Siberia (see Fig. 18). Some points, corresponding to the samples of porous waters with maximum values $\delta^{18}O$ lie along the line of thermal waters of southern East Siberia. Thus, the porous waters of BDP-93-1 core have isotope characteristics of meteoric waters. Their composition was formed by interaction with hosting rocks under a probable influence of ground waters.

Temperature and thermal conductivity of sediments. The temperature was measured at four points of BDP-93-1 using a set of temperature-sensitive recorders. They were lowered down to a depth of 88 m just after drilling had been completed. Restitution of the temperature field was recorded during 300 hours by numerical ohmmeter and autonomous geothermal station "GETAS" [28]. The results are shown in Fig. 19 and Table 2. The geothermal gradient was found to vary with depth. These variations are supposed to be partially related to the climate changes in the Holocene.

Thermal conductivity of sediments was measured twice: by the sounding needle ("PATsIT" instrument, 109 measurements) right after the core had been recovered and some months later under laboratory conditions using a thermal comparator (553 measurements). Measuring instruments are described in [28]. The comparator was calibrated against standard thermal conductivities with the range of 0.2 to 14.7 W/m· K. The instrument had an error of 1–3 % over typical temperature ranges. The results given in Table 2 indicate that in the second series of measurements (λ_2) the thermal conductivity values are much higher than in the first one (λ_1). Such differences in values cannot be attributed to the instrumental errors but they could be caused by degassing of sediments with time.

The heat flow on the drill site was about 70 mW/m^2 if it is evaluated by laboratory determinations of thermal conductivity (λ_2). This value is somewhat higher than was previously supposed, based on the results

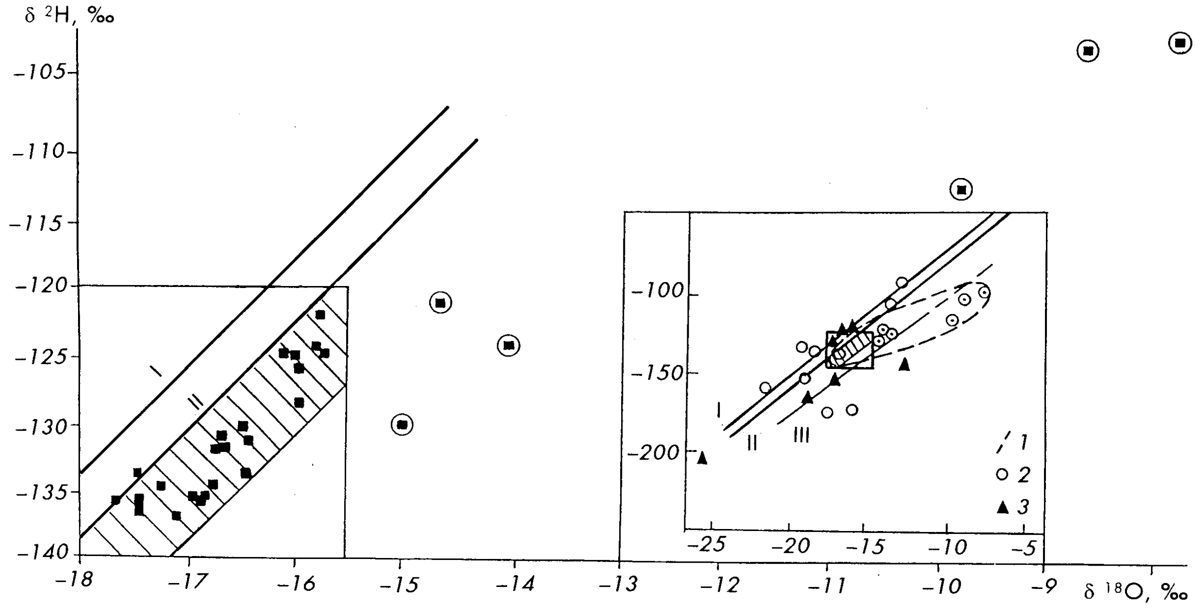

Fig. 18. Stable isotopes of pore waters. The main field of isotope compositions is hatched, dots in circles denote maximum values of δ ^{18}O in pore waters [27]. Inlet: I — line of global meteoric waters, II — the line of meteoric waters of the Baikal region, III — thermal waters of southeastern Siberia. ***1*** **— pore waters from BDP-93-1 borehole;** ***2*** **— deep chloride-sodium brines;** ***3*** **— fresh and mineralized waters of upper horizons.**

of heat flow measurements obtained by autonomous and cable thermographs [29, 30]. Heat flow values are measured from 63 to 81 mW/m^2 at a depth of 88 m. Unfortunately, the temperature recorders could not be placed in the borehole so no initial data are available for determination of the geothermal gradient and heat flow within 88–102.2 m.

DISCUSSION

Although preliminary, the data obtained from the BDP-93-1 core studies will be used as reference to proceed with the project. Magnetic susceptibility measurements showed a good correlation between cores from BH-1 and BH-2 and with materials obtained from piston cores. These data promise that this method can be used to compare and mutually supplement materials from separate boreholes thus providing a sufficiently complete picture of the Baikalian section. Immediately at the site of drilling, the results of studies permit the sedimentation history to be restored and the principal character of changes documented in sediments to be revealed. The lower unit shows higher C/N ratio in the organic substance of sediments which indicates a larger proportion of terrigenous organic material as compared with the upper sediments.

Geological data and specific features of the section suggest that the bulk mass of sediments was transported by terrigenous material of the Buguldeika River. Sediments accumulated in the Post-Manzurka erosional-tectonic stage [14, 16] when an intense transformation of the Buguldeika valley started and when the present appearance of morphotectonic structures of the Baikal depression came into sight. The lower part of the section was formed in the first stage of the Buguldeika thalweg formation which determined transfer of coarse-grained material. The onset of this stage was marked by significant tectonic movements which resulted in uplifting of the continental edge of marginal fault and subsidence of the steps in the water area. Because of depth-dependent geometry of the displacement plane, the surface of the Buguldeika tectonic block and sedimentary beds tilted to the uplifted shoulder of the rift. As the fault scarp was compensated by sediments and the alluvial fan of Buguldeika grew, the dipping beds graded into horizontal ones and then reversed toward the lake axis. Simultaneously, the pattern of sedimentary material changed from primarily riverine to progressively lacustrine. The river flow, however, has exerted an effect on the Buguldeika isthmus sediment composition up to now.

Geophysical data suggest that the Buguldeika drill site is confined to a tilted block bounded by faults

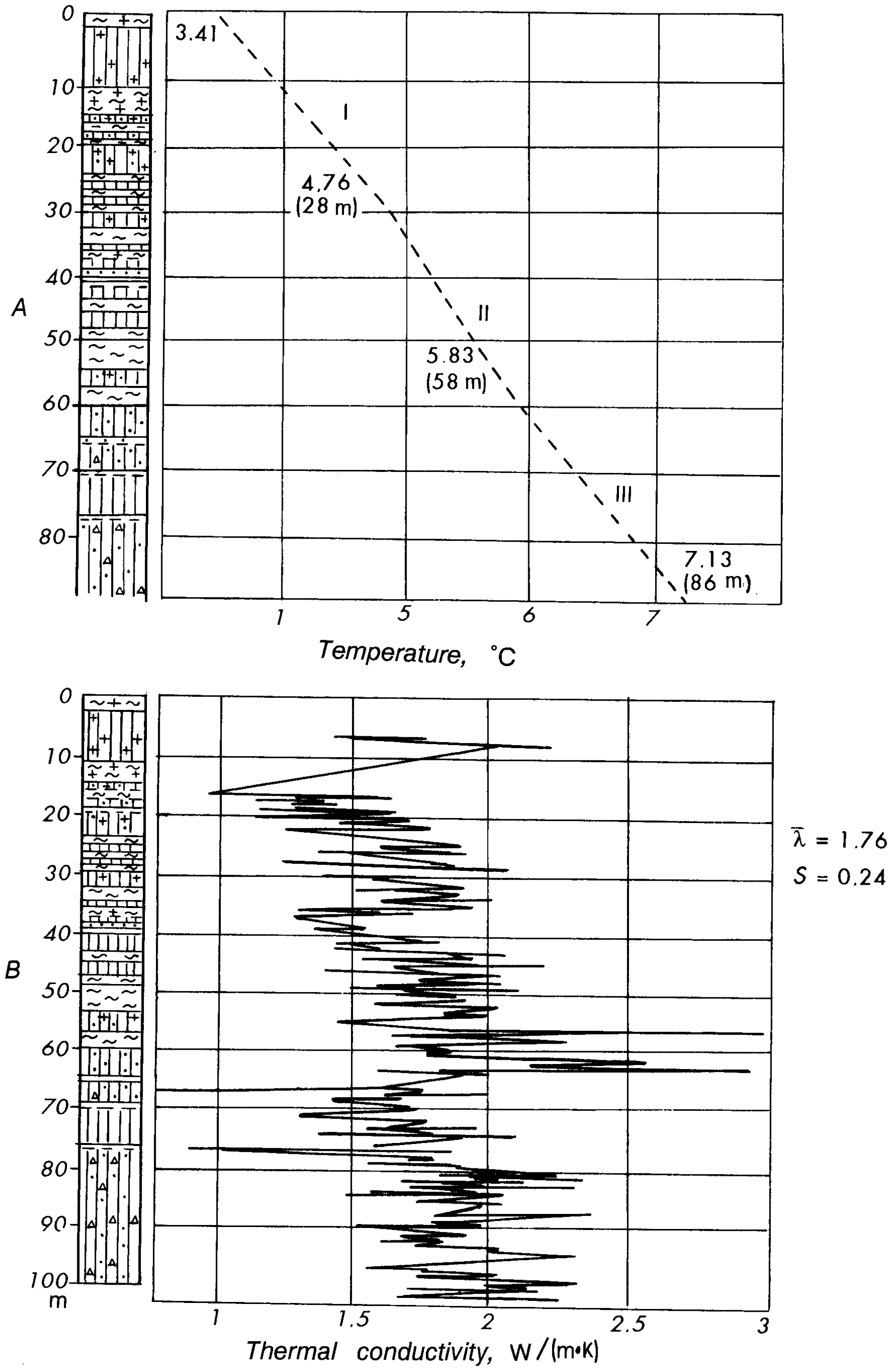

Fig. 19. Distribution of temperatures (*A*) and thermal conductivity values (*B*) across BDP-93-1 borehole.

through which tectonic movements proceeded while the sedimentary sequence was formed. In spite of the tectonic movements sedimentary section formed on the block surface is continuous, different types of sediments regularly replace each other; there are no sharp boundaries (unconformities) between individual horizons of the section. Data obtained by the geophysical method are proved by drilling material. Visual investigation of the core ascertained its uniform structure and predominance of clay material. However, according to the pattern of distribution of interbeds of coarse-grained material, turbidites, biogenic matter, and diatom remains, the section is distinctly subdivided into two portions: upper one to a depth of 50 m and lower, from 50 m to

Table 2

Geothermal measurements in BDP-93-1 borehole

Depth in sediments, m	Thermal conductivity of sediments (λ), W/(m· K)		T, °C	Geothermal gradient (G), mK/m	Heat flow (HF), mW/m^2 (HF = G· λ_2)
	"PATsIT" (λ_1)	"Thermocomparator" (λ_2)			
0			3.41		
	1.03	1.55		48	74
28			4.76		
	1.18	1.75		36	63
58			5.83		
	1.22	1.80		45	81
88			7.19		
		1.86		—	—
102			—		
Average in borehole	1.20	1.76		41	73

the borehole bottom. The deposition of the lower 50 m occurred with the dominant supply of sediments (coarse-grained material) from the Buguldeika basin. The upper portion is dominated by fine-grained sediments. This two-part division is supported by nearly all data of laboratory studies: petrological, mineralogical, geochemical, distribution of biogenic elements, diatom analysis, etc. On the other hand, there are differences in the behavior of some chemical elements: Ti, Mn, Zr and Sr, as well as variations in mineralogy of clay sediments and porosity.

Thus, the data obtained indicate the possibility to use them for evaluation of geologo-tectonic features of the sedimentation region.

Another important conclusion is that the sedimentary section penetrated by borehole may be used for assessment of paleolimnological and paleoclimatic changes. The upper part of the section is the most appropriate for this purpose.

Radiocarbon dating of samples from the upper portion of the core established nearly constant sedimentation rates and provided superb chronology for the last 25–30 ka of the Baikal history. The correlation between the age and the depth of sediments in BH-1 agrees with the previous ratios from nearby piston cores and high-resolution seismic profiles. Coincidence of magnetic susceptibility records for BH-1 and BH-2 and neighboring dated piston cores provides additional stratigraphic and geochronological control, providing thus, for this portion of the section, a safe basis for correlation of paleolimnological and paleoclimatic data. Of particular importance for chronology of sediments is interpretation of the excursion between 25.5 and 27 and around 70 m (see Fig. 11). At present we are inclined to interpret the excursion between 25.5 and 27 m as corresponding to 180,000 years and to double excursion Biwa-1 — Jamaica. Such chronostratigraphic interpretation suggests that the glacial type sediments are equivalent in time to stage 6 on the curve of variation of oxygen isotopes of marine sediments (SPECMAP [22, 31]). Previous results on piston cores are well related to data for BH-1 when correlating with the marine SPECMAP record. It agrees with a frequency of orbital effect after M. Milankovitch [22, 31]. With this in mind, it is feasible to relate the changes in the biogenic silica distribution, pollen, diatoms, as well as mineralogy of clay sediments and variations in petromagnetic parameters of sediments with global processes being external relative to the limnological system of Baikal. However this interpretation is preliminary and requires further research. This is also indicated by radiocarbon dates of core within the range 8–15 m inconsistent with this interpretation.

A good correlation with paleoclimatic changes in the Buguldeika isthmus region is indicated by biogenic characteristics of sediments: biogenic silica content closely associated with the content of diatom remains; zonal distribution of pollen and diatoms; variations of their species composition. Determination of petromagnetic properties of sediments in the upper unit shows that climate changes are associated with variations in concentrations size, and mineral composition of magnetic particle. The variations of mineral composition of clay sediments agree with changes of magnetic properties of rocks. Low concentrations of magnetic particles are associated with interglacial and interstadial periods, while glacial periods are characterized by higher concentrations of magnetic grains. In the warm periods the productivity of the Baikal water column increased which resulted in increased biogenic silica in sediments, and thus abundance of diatoms led to diluted magnetic particle concentrations.

Much more work is required to generalize abundant paleoclimatic and paleolimnological data in order to specify climatic history of Baikal in the Late Pleistocene.

The forthcoming research of BH-2 samples should significantly supplement obtained results of paleoclimatic studies, and drilling of new holes combined with results of geophysical studies [32–34] will throw light upon the tectonic history of the lake as part of the Baikal Rift Zone.

CONCLUSIONS

The first successful drilling from the ice-frozen barge on Lake Baikal has recovered two 100-m long hydraulic piston cores from two holes beneath a 354-m thick water column 5 km offshore of the Buguldeika River in southern Lake Baikal. An average recovery of 72 % and 90 % was obtained in BH-1 and BH-2, respectively, and magnetic susceptibility logging revealed excellent core-to-core correlation of BH-1 and BH-2.

In this report the BDP-93 working group including Russian, American and Japanese scientists described preliminary analytical results from the cores of BDP-93 BH-1. AMS radiocarbon dating provides an accurate chronology for the last 25,000 years of sedimentation. The core possesses a positive (normal) inclination throughout its length, indicating that the sediments were all deposited during the Brunhes magnetic epoch. According to approximate estimates, the borehole section reveals sediments deposited in the late Pleistocene.

Variations in spore-pollen assemblages, diatom microflora, biogenic silica content, rock magnetic properties, clay mineralogy and organic carbon give a detailed record of how climate change impacted the Baikal limnological system over approximately the last 250,000 years. These independent variables alternate in time to follow glacial/interglacial climatic fluctuations. The existing age model suggests that the climatic signals recorded in the Baikal sediments are similar to the Late-Quaternary signals recorded in the Chinese loess sections and in marine sediments.

Not only the climatic record, but also detailed lithological characteristics, rock magnetic properties, and inorganic chemical element distributions of the BDP-93 BH-1 cores distinctly show that the Buguldeika isthmus sediments are subdivided into two portions at a depth of 50 m beneath the lake bottom; this subdivision is due to geologo-tectonic processes.

All the cores recovered from BH-1 and BH-2 at the Buguldeika site are kept on deposit in the core storage facility in Irkutsk. Analytical work is planned for cores of both boreholes in order to establish more reliable geochronology and more precise paleoclimatic records.

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