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PRELIMINARY RESULTS OF THE FIRST SCIENTIFIC DRILLING ON LAKE BAIKAL, BUGULDEIKA SITE, SOUTHEASTERN SIBERIA

BDP-93 Baikal Drilling Project Members[*][†]

The Baikal Drilling Project (BDP) is a multinational effort to investigate the paleoclimatic history and tectonic evolution of the Baikal sedimentary basin during the Late Neogene. In March 1993 the Baikal drilling system was successfuly deployed from a barge frozen into position over a topographic high, termed the Buguldeika saddle, in the southern basin of Lake Baikal. The BDP-93 scientific team, made up of Russian, American and Japanese scientists, successfully recovered the first long (>100 m) hydraulic piston cores from two holes in 354 m of water. High quality cores of 98 m (Hole 1) and 102 m (Hole 2), representing sedimentation over the last 500,000 years, were collected in 78 mm diameter plastic liners with an average recovery of 72% and 90%, respectively. Magnetic susceptibility logging reveals an excellent hole-to-hole correlation. In this report the scientific team describes the preliminary analytical results from BDP-93 hole 1 cores. Radiocarbon dating by accelerator mass spectrometry provides an accurate chronology for the upper portion of Hole 1. Detailed lithologic characteristics, rock magnetic properties and inorganic element distributions show a significant change to the depositional environment occuring at 50 m subbottom depth, approximately 250,000 BP. This change may be due to uplift and rotation of the horst block in the Buguldeika saddle. The sedimentary section above 50 m is pelitic with varve-like laminae, whereas the section below 50 m contains a high proportion of sand and gravel horizons often organized into turbidite sequences. Accordingly, high resolution seismic records reveal a change in sonic velocity at this depth. It is inferred that sedimentation prior to 250 ka BP was from the west via the Buguldeika river system. After 250 ka BP the Buguldeika saddle reflects an increase in hemipelagic sediments admixed with fine-grained material from the Selenga River drainage basin, east of Lake Baikal. Variations in the spore-pollen assemblage, diatoms, biogenic silica content, rock magnetic properties, clay mineralogy and organic carbon in the upper 50 m of BDP-93-1 reveal a detailed record of climate change over approximately the last 250,000 years. These variables alternate in a pattern characteristic of glacial/interglacial climatic fluctuations. The present age model suggests that the climate signal recorded in Lake Baikal sediments is similar to Late Quaternary signals recorded in Chinese loess sections and in marine sediments. Copyright © 1996 INQUA/ Elsevier Science Ltd

INTRODUCTION

Scientific Goals

The Baikal Drilling Project is a multinational investigation of the paleoclimatic history and tectonic evolution of the Lake Baikal sedimentary basin. Lake Baikal occupies the largest basin in the Baikal Rift Zone (BRZ), one of the two major continental rift zones 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 20 million years. This record is continuous because the deep basins of Baikal, which range in depth from 800 to 1640 m, were not glaciated by Siberian-ice sheets during the Pleistocene. Sedimentation was therefore uninterrupted in Baikal while movement of ice sheets disrupted and scoured much of the sediments of Europe, northwestern Siberia and North America (Grosswald, 1980). The Baikal watershed was and is sensitive to past and present climate change processes. For example, during the last glacial maximum glaciers existed in the mountains surrounding the northern shores of Lake 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 (Lydolph, 1977). The seasonal interplay of these centers of action significantly influences global climate and produces the highest degree of continentality (seasonal contrast) observed on Earth. Comprehensive studies of Baikal sediments therefore provide an opportunity to understand how the global climate system has influenced long-term climatic change in central Asia, including such phenomena as the

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intensification of northern hemisphere glaciation during the Plio-Pleistocene and the influences of Tibetan Plateau uplift on the Siberian atmospheric high and climate of southeastern Siberia (Molnar and Tapponnier, 1975; Zhongli *et al.*, 1992). In addition, Baikal sediments contain a record of the recent evolution of one of the most important active intracontinental rifts of the world. Tectonic signals should be preserved in the sedimentary record as changes in turbidite frequency, mineralogy and other parameters influenced by characteristics of the watershed drainage pattern.

Organization of BDP

Initial discussions included the Soviet Academy of Sciences (SAS) and Ministry of Geology (MINGEO), the U.S. Geological Survey (USGS), a number of U.S. universities and the University of Kyoto (Japan; Williams, 1993). In 1990 BDP became an important part of the Baikal International Center for Ecological Research (BICER) headquartered in the Limnological Institute, Irkutsk. Most recently, components of the BDP objectives became part of the IGB.P. program of Past Global Changes (PAGES).

Prior to the first BDP drilling at Buguldeika in 1993, several piston coring and high resolution seismic expeditions were sponsored by the USGS, BICER and the Japan Baikal Association (JABIRP). These 1990–1992 expeditions provided (1) 3600 km of high-resolution seismic-reflection profiles to delineate the sedimentary environments and facies beneath the lake, to define how those environments have responded to climate change, and to locate and correlate appropriate sites for coring; and (2) a set of 209 cores of various types at 38 sites that provide the raw materials for analyses aimed at detailed reconstructions of paleoenvironmental conditions (Bezrukova *et al.*, 1991; Lake Baikal Paleoclimate Project Members, 1992; Kuzmin and Williams, 1993).

During 1992–1993, participation in BDP has expanded to include a large, multidisciplinary team of Russian, American and Japanese scientists who study the geochronological, geochemical, micropaleontological, and sedimentological characteristics of Baikal sediments. Costs for the site-selection surveys, drilling/coring and subsequent analytical work are borne equally among the BDP partners. Planning, financing and scientific objectives are determined by BDP Steering, Technology, and Scientific Advisory committees.

Technological Requirements

Due to Baikal's great depth, intense weather changes and high level of tectonic activity, certain technical problems of drilling lacustrine sediments in Baikal needed solving in order to realize the scientific tasks posed. To accomplish the objectives of BDP, a specialized lightweight drilling system, using aluminum drill pipe to reduce the overall weight of the system, was developed by the Nedra Drilling Enterprise based in Yaroslavl, Russia. To maximize recovery of undisturbed sediment, Nedra engineers 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, vibracorer and rotary corer for use under different conditions. In 1992, this drilling rig was tested by the NEDRA enterprise from the surface of Slyudinsky Lake, a small nearshore lagoon in the coastal zone of Northern Baikal. These tests confirmed that the equipment would perform within the designed specifications in full-scale drilling scheduled for the following year. In January 1993 the Baikal drilling system was deployed from a 15×30 m barge frozen into position using two ships, satellite navigation and the aid of high resolution seismic (see next section on site selection).

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 liners with an average recovery of 72% and 90% in Holes 1 and 2, respectively. Magnetic susceptibility and thermal conductivity measurements were made prior to splitting of the BDP-93-1 cores, and core descriptions and photographs were taken prior to sampling. From Hole 1 a suite of approximately 200 reconnaissance samples were taken and distributed among Russian, Japanese, and U.S. scientists. Following ODP protocols, a BDP sampling protocol identified the analytical teams to be involved in the reconnaissance BW-931 cores. The key properties to be measured included radiocarbon dating by accelerator mass spectrometry, rock magnetic parameters, organic constituents (biogenic silica and total C, H, N, S), diatom and spore/pollen contents, 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 that will utilize samples from both boreholes. Cores from both boreholes are archived in a refrigerated (~4°C) core storage facility at the Institute of the Earth's Crust in Irkutsk.

CHARACTERISTICS OF THE BDP-93 DRILLING SITE

General Geologic and Tectonic Setting of the Buguldeika Site

The latest phase of rifting in the Baikal Rift Zone began at about 30–35 Ma, after almost 150 Ma of tectonic quiescence (Zonenshain and Savostin, 1981; Lipman *et al.*, 1989). Lake Baikal occupies the deepest part of the Baikal Rift Zone. The Baikal depression is divided into the northern, central and southern basins (Zorin, 1966; Zorin *et al.*, 1977). The Buguldeika Site lies on the western margin between the central and southern depressions, offshore of the Buguldeika River and directly across from the Selenga Delta (Fig. 1). The Buguldeika River basin drains territory comprised of

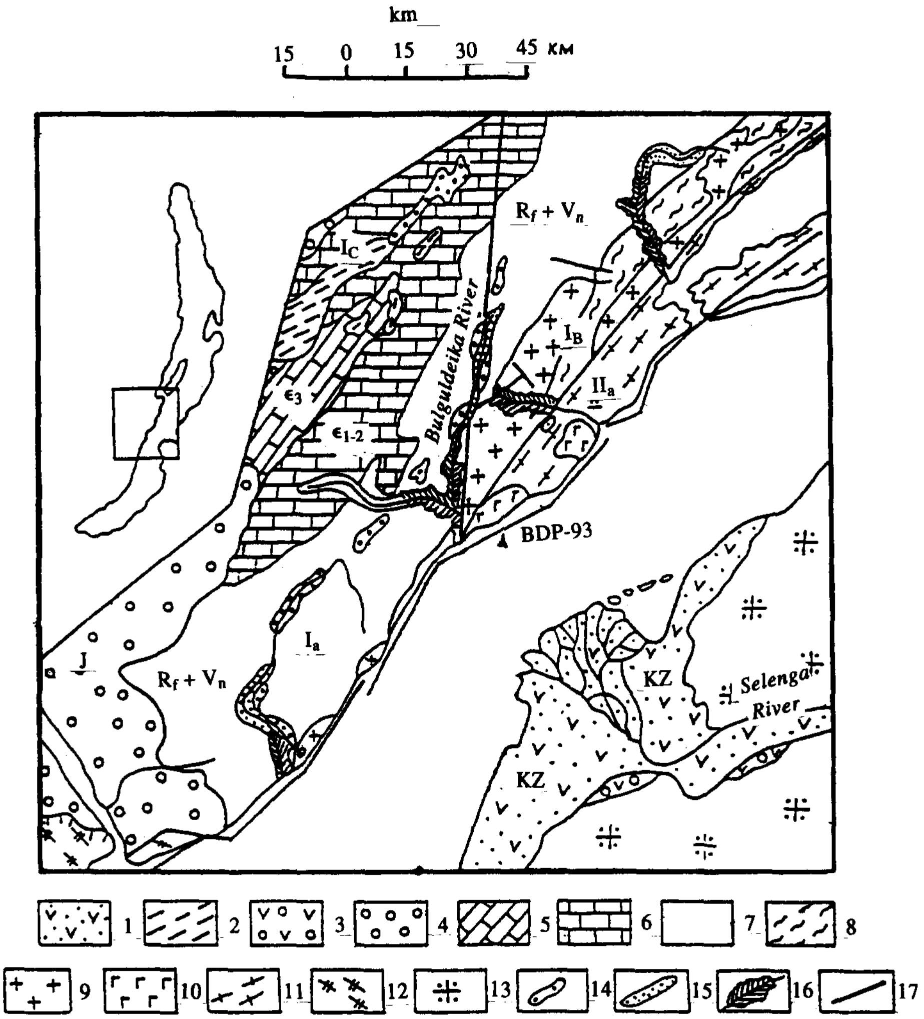

FIG. 1. Schematic geological map of BDP-93 Drill Site. Inset: location map of Lake Baikal, BDP-93 Drill Site. Main structures: I — Siberian Platform; Ia — Olkha-Goloustnaya plateau with relics of laterite-kaolinite weathering crust; Ib — Primorsky Ridge; Ic — Near-Baikal trough; II — Baikal folded-mountain region; IIa — Near-Ol'khon plateau with relics of laterite-kaolinite weathering crust; IIb — Ust-Selenga Zone. 1 — Cenozoic sediments of Selenga river delta; 2 — Paleogene and Neogene: clays, sands, brown coal; 3 — Mesozoic: terrigenous-volcanogenic sediments, acid and basic intrusions; 4 — Jurassic: conglomerates, sandstones, tuffs, coals; 5 — Upper Cambrian: carbonate-terrigenous gypsum-bearing sediments; 6 — Lower and Middle Cambrian: salt-bearing-carbonate sediments; 7 — Riphean-Vendian: carbonate-terrigenous (with phosphorites) sediments; 8–10 Proterozoic: 8 — Metasands, chlorite schists, chlorite-biotite schists with granite, disthene, chloritoid, metabasalts and meta-andesites; 9 — granite-gneisses; chloritizated, epidotized granites; 10 — diorites, basites, hyperbasites; 11 — Upper Archean-Paleozoic (Ol'khon complex): gneisses, granite-gneisses, crystalline schists, amphibolites, marbles, pegmatites; 12 — Lower Archean (Sharyzhalgai complex): gneisses, crystalline schists, granite-gneisses; 13 — Precambrian-Paleozoic (non-segmented): mainly granitoids; 14 — Ancient valleys of the Manzurka stage (Late Pliocene–Eopleistocene); 15 — Middle Pleistocene–Holocene valleys of the Angara-Lena system; 16 — Late Pleistocene–Holocene valleys of the Baikal system; 17 — main faults. Triangle denotes BDP-93 Drill Site.

different tectonic blocks of different geological structure which are separated by faults (Fig. 1; Logachov, 1968; Logachov *et al.*, 1974; Mats, 1993). Deposition at the Buguldeika site was likely influenced by the erosional-tectonic stages (Manzurka, Neobaikalian) that are related to formation of the Baikal rift depression. In the Manzurka stage the valley of pre-Manzurka River was the outlet when Baikal water flowed into the Lena River (Logachov *et al.*, 1974; Kononov and Mats, 1986). In the Neobaikalian stage (Late Pleistocene–Recent time) the Buguldeika River developed its thalweg towards Baikal in two parts. The first phase was one of downcutting and transportation of coarser material. The second phase from the end of the Middle Pleistocene to recent time is characterized by quieter stream-like flow and transfer of fine-grained material into Baikal. Although the primary objectives involved the paleoclimate record, it was hoped that the BDP-93 drilling of the Buguldeika site would also reveal the development of the Buguldeika erosional-tectonic regime.

Use of Geophysical Profiles for Site Selection at the Buguldeika Site

An array of high-resolution water-gun and 3.5 kHz seismic-reflection profiles were used in the selection of the Buguldeika Drill Site on top of a tilted fault block that forms a small horst within the Baikal Rift Zone (Figs 2 and 3). Foremost in the selection was the continuous, subparallel reflections in the upper 50 m of sediment which suggested a thick hemipelagic sequence of

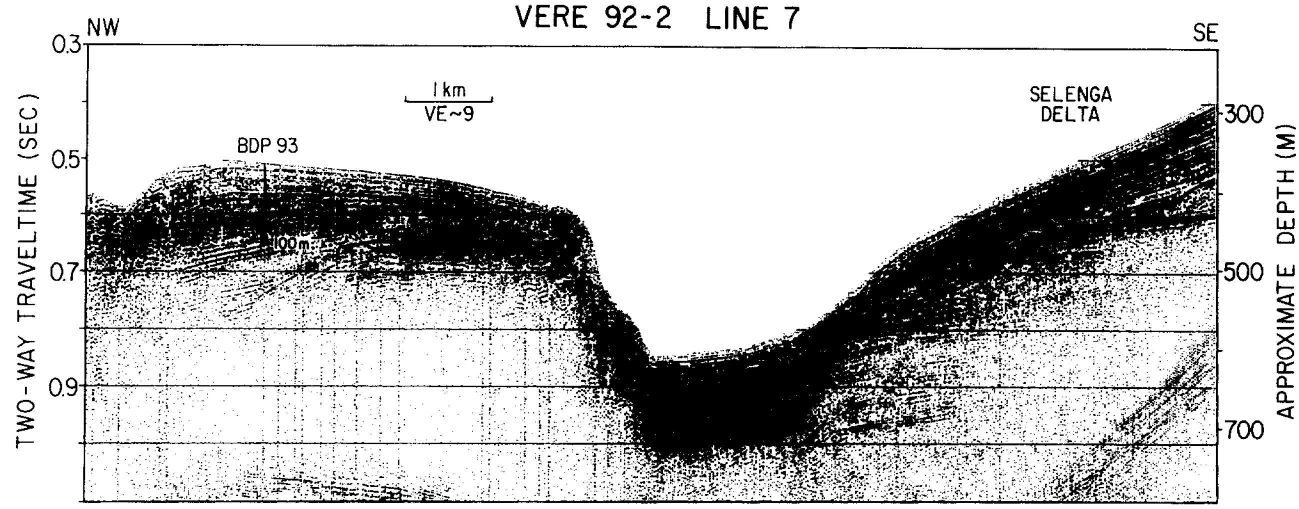

FIG. 2. Seismic-reflection profile (15 cubic inch water gun) from northwest to southeast, perpendicular to the axis of the rift and parallel to the slope of the Selenga Delta.

sediments suitable for paleoclimatic studies. Other considerations were technological and scientific. For example, the drilling system at that time was limited to waters less than 400 m. An additional consideration was the opportunity to recover the palynological and mineralogical signals originating from the most important part of the Baikal watershed (the Selenga). We also chose the site to avoid direct influence from deposits of the Buguldeika subaqueous fan which, just south of the drill site, are marked by irregular reflections and mounded surface morphology that appear to interfinger with the hemipelagic sediments. The fault block on which the drill site was located is tilted to the southwest and is raised above the slope of the adjacent Selenga Delta.

A major change in the lithologic character of the sediments in BDP-93 Hole 1 occurs at a depth of about 50 m and is marked by a prominent reflection. Other reflection characteristics generally correlate with lithologic variations in the core. Below 100 m depth at the drill site, several prominent reflections and a distinct unconformity may be related to changes in tectonic activity. In addition, one of these horizons may relate to a diversion of the take outlet from the Buguldeika River (and thence to the Lena River) to the Angara River. A gradual reversal in dip direction upsection implies changes in the rate of tectonic movement on several faults which bound the Buguldeika block.

RESULTS

Lithological Characteristics of BDP-93 Hole 1

Over 900 smear slides have been examined to characterize the major lithological parameters of the BDP-93 Hole 1. Figure 4 depicts the sedimentary record of the BDP-93 borehole based on the primary core description. The sediments of this core primarily have a silt-pelite composition. Lenses and interbeds of sand and silt increase in abundance downcore, as does the proportion of fine gravel. Based on a smear slide calculation the diatom content of some silt or sand

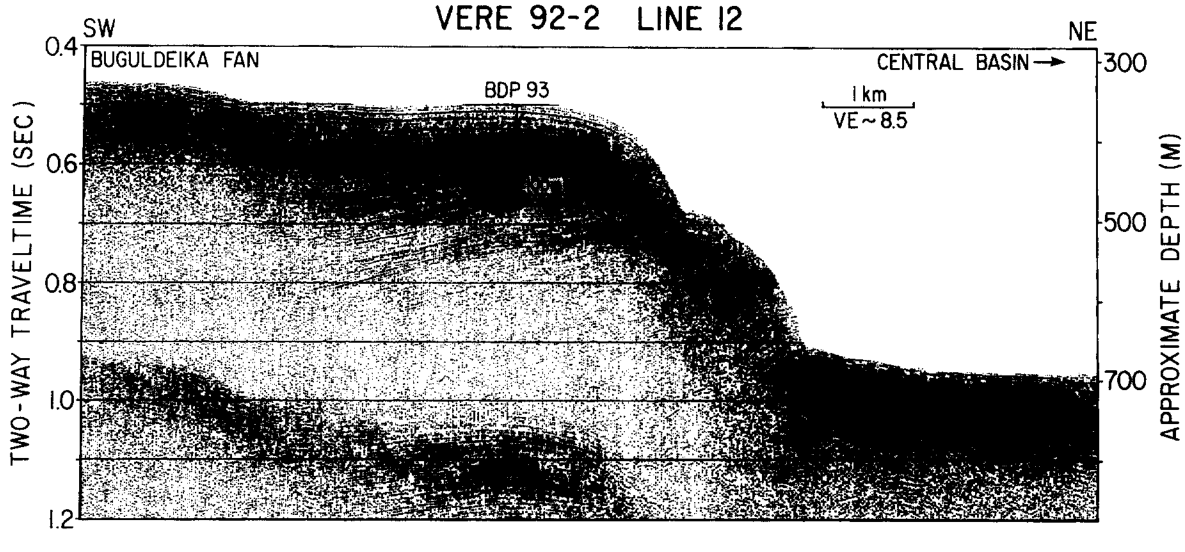

FIG. 3. Seismic-reflection profile (15 cubic inch water gun) from northeast to southwest, parallel to the axis of the rift.

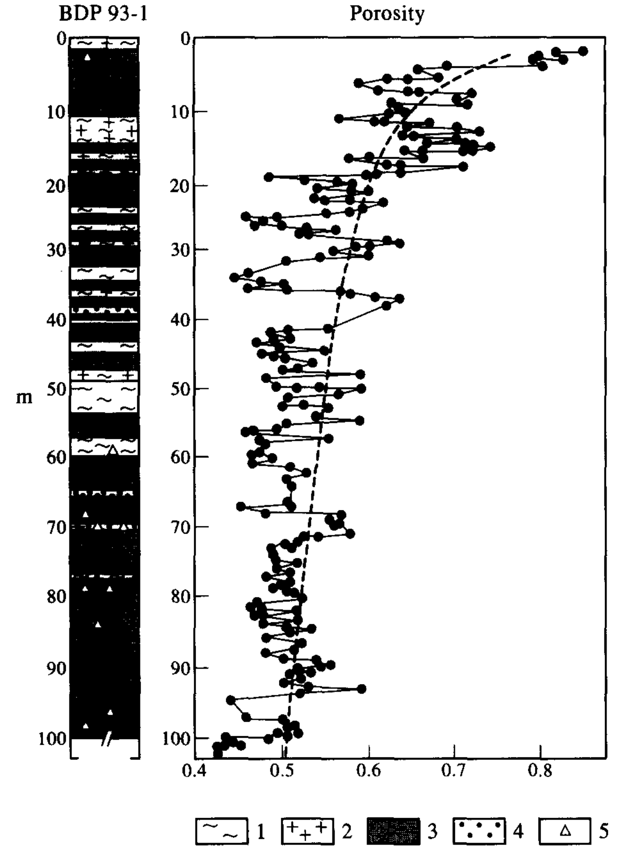

FIG. 4. Lithological column of BDP-93 hole 1 with porosity. 1 — silt-clay mud; 2 — diatom ooze; 3 — clay; 4 — sand; 5 — gravel.

interbeds varies from 3 to 90% and diminishes sharply in the lower part of the BDP-93-1 cross-section.

The texture of the sediments range from massive to laminated, thin-laminated and lenslike with some layers exhibiting gradational layering. The frequency of turbidites increases downcore. Turbidites are typically 3–5 cm thick and commonly consist of silt-pelite or aleurite. The underlying surface of some turbidites are uneven, a result of erosion of the underlying sequence by suspension flow. Deposition from suspension flow is likely to be related to phases of river flooding. Thus, the textural features of the BDP-93-1 cores indicate various modes of sedimentation. In addition to pelagic sedimentation and turbidites, the sedimentary sequence was affected by ice rafting as indicated by dropped granules and pebbles.

The lithologic column of BDP-93-1 (Fig. 4) displays a rhythmic structure, each rhythm consisting of two units. The first layer is composed of silt-pelite mud with a high content of diatoms (25–30%), as well as biogenic silica (5–15%) and carbon (1–1.5%). The second layer commonly consists of clay with low amounts of diatom frustules (<3%) and biogenic silica (1–2%). Seven rhythms are evident and are particularly distinct in the upper part of the core (Fig. 4). Thus, the lithologic column suggests that the BDP-93-1 sequence at the Buguideika site experienced a fairly continuous sediment accumulation consisting of finegrained sediments from a combination of riverine and water column sources with periods of suspension flow and ice rafting.

The pattern of sedimentation and composition clearly shows two sequences. The first, from the top to 50 m, is more fine-grained, contains a large amount of diatom material and displays a pronounced rhythmic structure. This upper section apparently formed under relatively quiet conditions of facustrine-pelagic sedimentation. The lower sequence, below 50 m, is more coarse-grained with abundant turbidites interspersed with pelite material and more interbeds of sand and silt relative to the upper 50 m. The lower sequence was apparently formed by input of river material brought from the coast, possibly by discharge through the Buguldeika River.

Figure 4 illustrates the variation in effective porosity of bottom sediments throughout the core. The porosity steadily diminishes from 0.855 at 0.03 m depth to 0.428 in the borehole shaft (102.5 m). In the upper part of the cross-section (0–10 m) the variation in porosity is well correlated with observed changes in bottom sediment porosity from 10 m piston cores. Thus, it can be inferred that this pattern of porosity variation in the upper (100 m) layer of sediments at the Buguldeika saddle is common for Baikal. As seen on the plot, the porosity values that deviate from the average 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 was comprised of fine-grained (<62.5 μm), silty-clay ooze. Only at 39, 61 and 66 m, where sand interbeds of a few tens of centimeters occur, do coarser-grained fractions dominate. The sand and silt grains are poorly rounded and sorted. These granulometric characteristics suggest that the bulk of the suspended material was transported into a sedimentary basin that had an average depth comparable to the present average.

Over 90% of the light minerals in the core are quartz, plagioclase, K-feldspar, micas (biotite, muscovite) and clay aggregates. Clay aggregates consist of poorly cemented quartz, K-feldspar and clay minerals, mainly smectites. Plagioclase is more abundant than K-feldspar. Biotite mica is several times more abundant than muscovite. The fight fraction also contains lesser amounts of chlorite, graphite, rock fragments, carbonized plant remains and diatoms.

Heavy minerals constitute a small fraction of the composition (a few grams per ton of sediment). Only in a few horizons do the concentration of heavy fractions reach as high as 30 gm to 76 gm per ton. 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. These minerals, as a rule, accommodate about 50% of the total weight of the heavy fraction. Authigenic minerals pyrite and marcasite are also present.

In the BDP-93-1 drill core the relative proportions of illite, smectite, chlorite and kaolinite in the <2 um size fraction vary with depth. Previous work on clay minerals in the 1990–1992 piston cores showed little differentia-

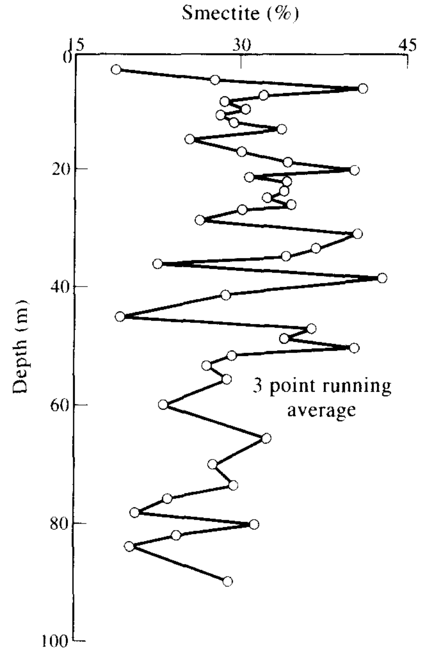

FIG. 5. Smectite and quartz/plagioclase variations in BDP-93 Hole 1.

tion of these clays geographically, implying that they should be sensitive to changes in weathering conditions in the sediment source area. Although the smectite abundance varies considerably in BDP-93-1, two patterns are evident (Fig. 5). First, a noticeable and persistent decrease in smectite abundance occurs below about 50 m. This agrees with most of the lithologic evidence (e.g. quartz to plagioclase ratio, clay minerals, the amount of rock fragments and plant remains, etc.) which also shows that BDP93-1 may be divided into two parts: above and below 45–50 m. Secondly, in the upper 50 m there are several high-amplitude changes in smectite abundance that will be investigated for climatic significance.

Kaolinite abundance (not shown) fluctuates around a slightly increasing mean to a depth of approximately 35 m, after which it undergoes a large decrease and remains relatively constant to the bottom of the core. Chlorite (not shown) tends to increase gradually down-core. A comprehensive environmental interpretation of this data await correlation with other climate proxy data. However, a preliminary examination of piston cores 305 (Selenga Delta) and 333 (Academician Ridge) demonstrate a distinct correlation between the abundance of smectite and biogenic silica. This suggests that, in some instances, smectite may have been produced in soils around Lake Baikal during the same (warmer?) episodes which stimulated the productivity of siliceous microorganisms.

Inorganic Geochemical Parameters

Inorganic geochemical data, primarily the distribution of Al_2O_3, TiO_2, K_2O, MnO, Zr, Sr, Co, V, Zn, Pb, Ni, Cu, and S indicates that the sedimentary sequence of BDP-93-1 borehole is divided into an upper (<50 m) and lower (>50 m) section. We have chosen to illustrate this geochemical division in Fig. 6, using the distribution of Ti, Zr, and Sr. The top section of the core displays an asymmetric distribution of TiO_2. This implies that marked changes to the geological setting must have occurred such as changes in the level of erosion and the amount runoff to the Buguldeika river; both of which could affect sedimentation in the vicinity of the drill site. In addition the chemical composition of the upper and lower parts of the core differ from the average composition of bottom sediments of Baikal and stream sediments of river tributaries (Pampura *et al.*, 1993). Further research may make it possible to identify fluctuations in element abundance that are related to climate change. Finally, elements such as Si, P, Fe, Cd, and Mg which experience diagenetic migration or biogenic accumulation do not differ significantly between the upper and lower parts of the core.

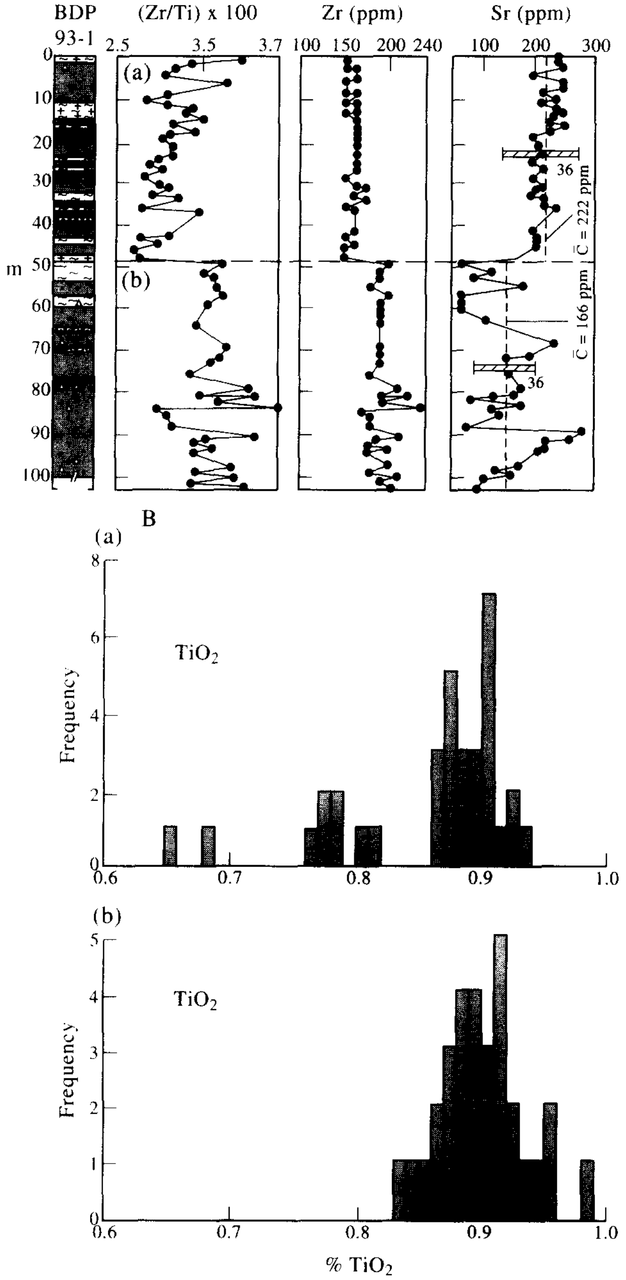

FIG. 6. A — Distribution of (Zr/Ti) × 100 and Zr and Sr contents downcore; B — histogram of TiO_2 distributions in the upper (a) and lower (b) parts of BDP-93 core.

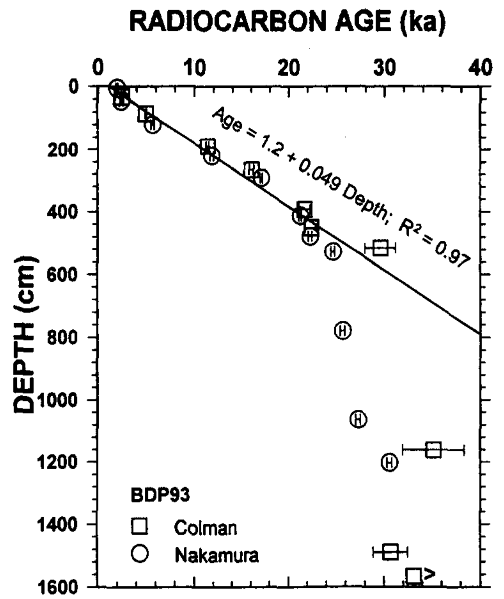

FIG. 7. Accelerator mass spectrometry (AMS) radiocarbon ages for BDP-93-1. Uppermost sample is wood; the remaining samples are total organic carbon. Analytical error bars (one sigma) are shown. The linear regression line is for the upper 15 ages.

Radiocarbon Dating

A total of 21 samples from the upper part of the BDP-93-1 drill hole have been dated using standard accelerator mass spectrometry (AMS) methods at the Woods Hole AMS Facility and the tandetron AMS facility at Nagoya University. All of the samples are total organic carbon except for one wood sample at a depth of 25 cm. There is good agreement among the ages in the upper 500 cm (Fig. 7), spanning the last 25,000 years and giving a linear, constant sedimentation rate of approximately 20 cm per thousand years. A regression line for the uppermost 15 ages provides an extremely good linear fit (r^2=0.97). The lowest age is infinite.

Below 500 cm, the data appear to indicate a change to a more rapid sedimentation rate. However, a variety of evidence suggests that this apparent increase is spurious, due to slight contamination of the samples, probably by modern bacteria. First, the samples below 500 cm have very low organic carbon contents and are thus easily contaminated. Contamination by one to two percent of modern carbon is enough to explain the deviation of these samples from the regression line. Second, a change in sedimentation at 25,000 BP in the midst of a glacial period is unlikely comparable to the change at 13,000 BP during the transition from glacial to interglacial conditions. Finally, initial ages from the second drill core at the Buguldeika site fall almost exactly on the regression line to an age of 35,000 BP. Thus, it appears that the net sedimentation rate at the Buguldeika site was nearly constant throughout the period covered by radiocarbon dating. Radiocarbon data from other sites in the lake suggest that the comparison between glacial and interglacial sedimentation rates depends on a balance between biogenic and terrigenous flux, the former being greater during interglacials and the latter being greater during glacial periods.

The ages for the upper part of BDP-93-1 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 take (Lake Baikal Paleoclimate Project Members, 1992; Colman *et al.*, 1993). For example, AMS radiocarbon ages from core PC2 site 339, less than one km away from the BDP-93-1 core, are remarkably consistent with those from depths correlated by means of magnetic susceptibility for the two sites.

Whole-Core Magnetic Susceptibility Logging of BDP-93 Holes 1 and 2

Low-field, whole-core magnetic susceptibility (K) of all cores from both BDP-93 holes were measured at 3 cm intervals, rapidly and non-destructively, using a susceptibility meter with a pass through loop sensor (King *et al.*, 1983, 1993). Magnetic susceptibility is primarily a measure of the magnetic mineral concentration in the sediment (higher values indicate increased magnetic mineral concentration). Whole-core measurements can be used in several ways. First, magnetic susceptibility provides accurate core correlation between the two holes to a depth of 84 m (Fig. 8). This correlation enables a more complete composite section to be obtained because gaps in one core can be filled with correlative sediment recovered in the other core.

Second, magnetic susceptibility can be used to correlate the upper meter of sediment in Holes 1 and 2 to gravity cores from nearby stations 305 and 339. This correlation indicates that the drilling procedure recovered undisturbed surficial sediment in both holes because gravity cores also preserved the surficial sediment. Although Hole 2 was located only 3 m away from Hole 1, the movement of the drill casing did not greatly disturb the lakefloor because Hole 2 also recovered undisturbed surficial sediment.

Third, magnetic susceptibility can help identify con-

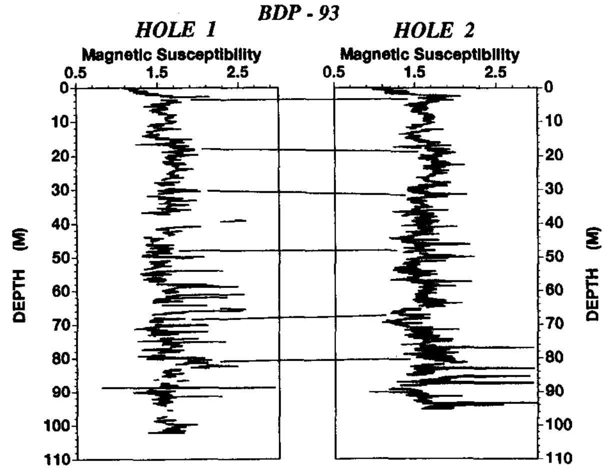

FIG. 8. Whole-core magnetic susceptibility [Log K (relative CGS units)] profiles for BDP-93 Holes 1 and 2. Magnetic susceptibility is a measure of the concentration of magnetic minerals in the sediment. The log of susceptibility was taken to reduce large K values for display purposes.

tamination from the drilling process. The presence of unusually high K values at the top of a core is the result of contamination from the accumulation of sediment, grease, and metal filings in the drill casing between successive hydraulic piston coring runs. This contaminated sediment fills the core catcher and core cutter of the APC prior to the actual coring stroke and is incorporated into the core top by the coring stroke. The K profiles suggest that the intervals (cm) 1959–1971, 2564–2680, 3169–3171, 3270–3324, 3871–3933, 5392–5402, 6092–6120, 6192–6214, 7510–7520, 8848–8850, and 9133–9145 cm in Hole 1 and the intervals (cm) 1224–1232, 3596–3602, 4583–4620, 5107–5116, 8526–8532, and 9336–9358 cm in Hole 2 may contain contaminated sediment. These intervals warrant close examination of lithology and sedimentary structures to corroborate the presence of contaminated sediment.

Fourth, the K profile for Hole 1 shows a high degree of correlation to the lithology of the upper 50 m. Diatomaceous sediment is characterized by low K values reflecting the dilution effect of diamagnetic biogenic silica. Clayey sediment is characterized by relatively high K values. This same relationship has been seen in previously collected cores from other parts of Lake Baikal (Lake Baikal Paleoclimate Project Members, 1992; King *et al.*, 1993).

Initial Paleomagnetic and Rock-Magnetic Results of BDP-93 Hole 1

Oriented paleomagnetic subsamples in 5 cm^3 plastic boxes were taken at 30 cm intervals from Hole 1. These samples were measured for paleomagnetic properties (declination, inclination and intensity) and a subset of samples were measured for rock-magnetic properties (concentration, grain size, and mineralogy).

Step-wise alternating field (AF) demagnetization was performed on a small subset of samples. The results indicate that the sediment contains a stable primary remanence, an extremely small secondary viscous remanence, and a relatively high intensity of magnetization. These characteristics make the Baikal sediments well suited for paleomagnetic investigation. The inclination record for BDP-93 Hole 1 indicates that the sediment record is entirely Brunhes in age (Fig. 9). The inclination record displays secular variations and excursions. Shallow or negative inclinations observed in single samples from depths of (cm) 455, 1476, 2001, 5262, 7715.5, and 9358 cm are not found in neighboring samples and are not likely to reflect excursions in the earth's magnetic field. Two intervals of shallow or negative inclinations are represented in multiple samples and are likely to reflect excursions in the earth's magnetic field. The first excursion is located between 25.5 and 27 m (Fig. 9). The interpretation of the rock-magnetic parameters (see next section) indicates that this interval represents glacial conditions, possibly marine Oxygen Isotope Stage 6. This BDP Hole 1 excursion correlates to an excursion identified in core 287 K-2 from the Academician Ridge region of Lake Baikal. The excursion present in core 287 K-2 is also located within inferred stage 6 sediments (King *et al.*, 1993). If this climatic interpretation is correct then the excursion would be approximately 180,000 ka, corresponding to the Biwa 1–Jamaica double excursion. On the other hand, if this excursion is related to the Blake excursion then the climatic interpretation is wrong. At this time we stress the need to measure additional samples from this interval. In addition, the compilation of multiple climate proxy data (e.g. biogenic silica, diatoms, pollen, clay mineralogy) is required in order to better define the climate signal and thereby confidently place this excursion within a time-frame. It is premature to identify this excursion at this time.

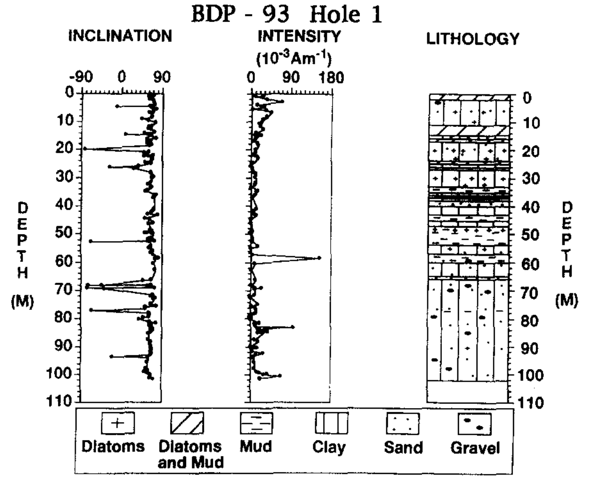

FIG. 9. Inclination and intensity of magnetization after AF demagnetization at peak field of 5.0 and 10.0 mT. Two excursions are present between 25.5–27 m and 67–71 m.

The deeper 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 a major change in depositional environment at about 50 m.

Rock-magnetic measurements (concentration, grain size, and mineralogy of the magnetic component of the sediment) of the 72 American subsamples and 20 Russian subsamples indicate that in the upper 50 m of sediment, rock-magnetic parameters appear to be related to climate change. Inferred interglacial and interstadial periods are characterized by low magnetic concentrations (K, KARM, SIRM) and a composition that is predominantly low coercivity minerals (HIRM, S ratio; Fig. 10). Inferred glacial periods are characterized by higher magnetic concentrations (K, KARM, SIRM) and increased amounts of high coercivity minerals (HIRM, S ratio; Fig. 10). We infer that during warm periods increased diatomaceous sedimentation, resulting from increased lake productivity, diluted the magnetic concentration. In addition, during warm periods enhanced soil development in the Selenga and Buguldeika River catchments yielded 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. 10). This change in magnetic parameters and lithology suggests a

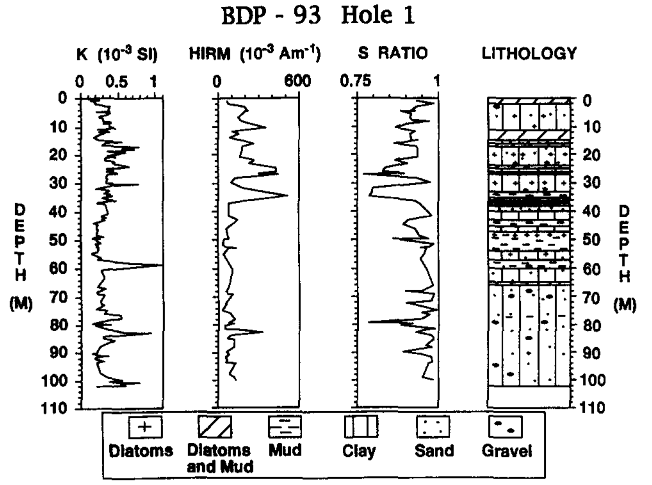

FIG. 10. Selected rock-magnetic parameters for BDP-93 Hole 1. Magnetic susceptibility (K) is primarily a measure of magnetic concentration within the sediment. HIRM and the S ratio reflect variations in magnetic mineralogy. Higher values of HIRM [(IRM-0.3T + SIRM)12] indicate increased amounts of high coercivity minerals (i.e. hematite, geothite). The S ratio [IRM-0.3TISIRM] is the ratio of higher coercivity minerals to lower coercivity minerals (i.e. magnetite, maghemite). S values of 1 indicate 100% low coercivity minerals, whereas lower values indicate an increasing proportion of high coercivity minerals.

change in deposition environment at the site to one dominated by fluvial inputs below 50 m.

Results of Palynological Analysis of BDP-93-1 Core

Seventy-seven samples were analyzed using standard procedures to obtain a sporepollen spectra (SPS) for the BDP-93-1 core. Fluctuations in the abundance of 74 taxa (families, genera and species) record changes in the terrestrial vegetation of the Lake Baikal area. Nearly 85% of the samples contain some portion of terrigenous material consisting predominantly of plant tissue. The pollen material exhibits variable preservation, but in general the SPS is very diverse with elements from present-day plants as well as some reworked pollen of Paleogene–Neogene age and some Jurassic species.

Palynological analysis identified three different types of SPS: 'forest', 'forest–steppe', and 'steppe'. SPS 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 infrequently. Pollen of small-leafed species, *Betula, Alnus, Duschekia fruticosa*, and *Salix* make up 5–29% of the pollen sum. Pollen of thermophyllic genera *Corylus, Carpinus, Quercus*, and *Ulmus* are abundant.

SPS 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 Cyperceae, Asteraceae, and Graminese, and from the genus *Artemisia*. SPS of these types almost always include pollen grains of thermophyllic genera: *Ulmus, Corylus, Quercus, Carpinus*, and sometimes *liex*.

As evident from the spore-pollen diagram (Fig. 11), the total composition of pollen and spores reflect intervals of SPS alternation of 'forest' type with that of 'steppe' and 'forest–steppe' types. Based on this evidence, 13 palynologic zones correlative with variations in the sedimentary environment have been distinguished (Fig. 11). The zones display an alternation of moderately dry and warm epochs with moderately cold, damp epochs throughout the core. Zones II, IV, IX, XI, and XIII contain floras dominated by elms and dark conifers like cedar and some pine. These floras are characteristic of moderately cold, damp climate conditions. Zones I, III, V, VI, and XII are characterized by floras of relatively dry climates (pollen of wood species). Zones VII, VIII, and X should be considered transitional because their flora is common for damp, cool environments, and they show a low content of wood species. Shrub and herb floras are present.

Within the range 30–104 m a very interesting relationship is noted: the intervals containing moderately cold damp taxa of SPS are followed by a sharp increase of 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. This phenomenon may be explained as a result of both tectonic and climatic conditions. The combined effects of tectonic lowering of the level of erosion and climate change led to more intense washout of ancient sediments. Peaks in the concentration of spore-pollen material reflect intervals of dark-coniferous forest vegetation; high pollen productivity is characteristic of these conifers.

The core sediments are interpreted to represent a fairly high sedimentation rate. The bulk of the sediment was derived from the Buguldeika River and, to a lesser extent, from the Selenga River. SPS of zone III contain pollen of the group 'mixed oak' (Quercetum mixture). These species constitute a warmth-loving flora, which in warm periods of the Lower–Middle Pleistocene grew in the Trans-Baikal area, mid-Siberian lowland, and possibly in the Tunka depression. In our opinion, pollen of these plants were brought by the Selenga River flowing through the steppes and forest–steppes of Trans-Baikal. It is not likely that this assemblage was transported by the Buguldeika River since the Quercetum mix group was not growing in the Buguldeika River basin.

Diatom Studies

Preliminary observations of the diatom assemblages in BDP-93-1 show large changes in the abundance and type of diatoms (Fig. 12a). Some sections of the core are apparently barren of diatoms with less than one frustule per 100 mg of dry sediment. Diatoms were recovered using the technique described in Bezrukova *et al.* (1991). Presently, it is not clear if these zones represent periods of extreme sediment dilution, lack of diatom productivity, or both. In samples that contain diatoms, species endemic to Lake Baikal dominate the assemblages. A significant number of species, common in boreal lakes outside the Baikal region, are restricted to surficial sediments; (<300

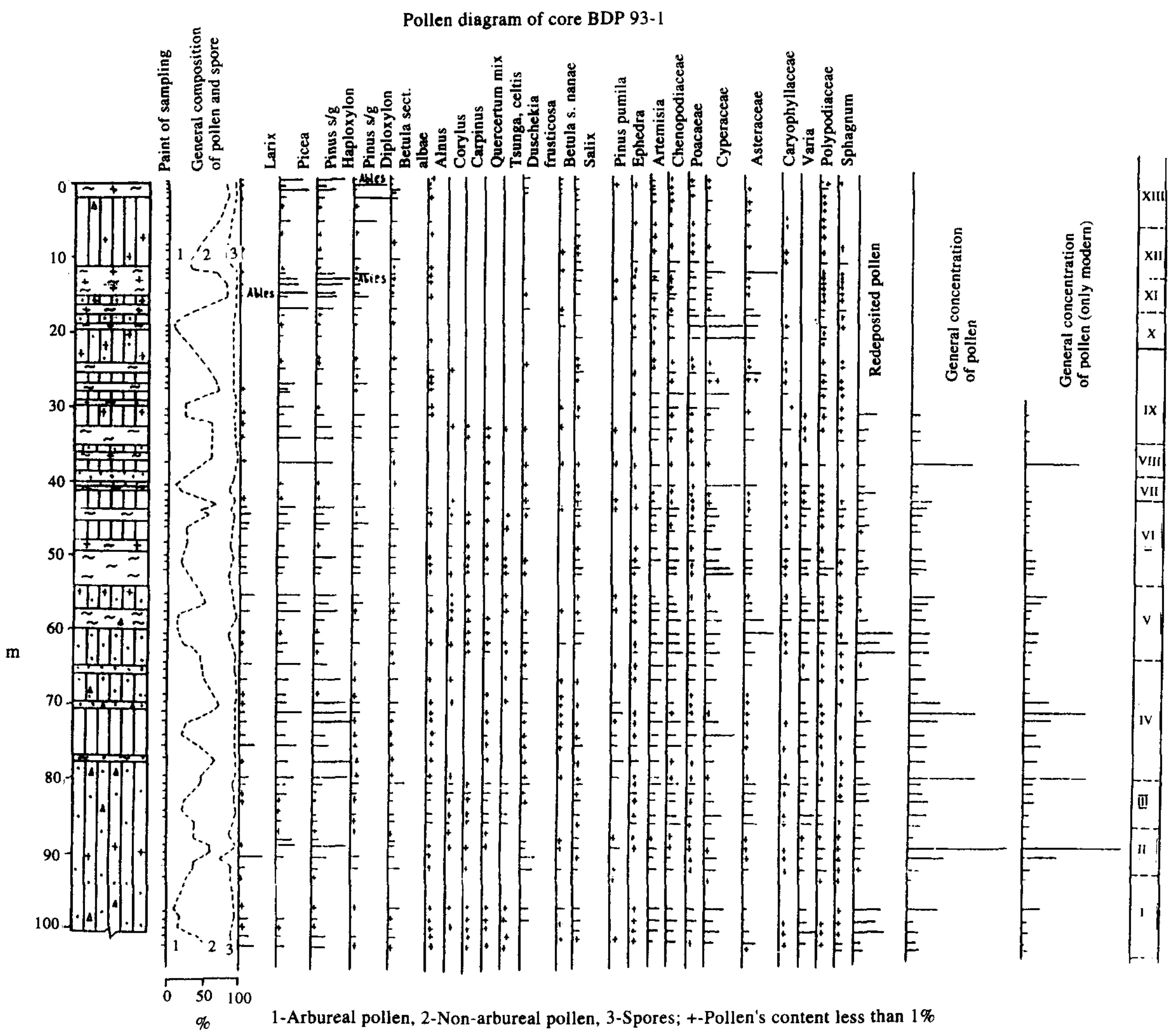

FIG. 11. Palynological zones based on major floral compositions: XIII — 0–0.50 m *Picea, Abies, Pinus sibirica, Pinus silvestris*; XII — 5.50–13.0 m — Asteraceae, Cyperaceae, Poaceae; XI — 13.0–19.0 m — *Picea, Pinus sibirica*; X — 19.0–23.5 m — Cyperaceae, Asteraceae, Poaceae; IX — 23.5–35.5 m — *Picea, 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 sibirica, Betula*; Asteraceae, Polypodiaceae; IV — 64.0–80.0 m *Pinus sibirica, Picea, Larix; Salix*; Cyperaceae; III — 80.0–86.0 m — Broad-leaved wood; 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*.

years). As would be expected, planktonic species are overwhelmingly abundant, although elements of a very rich benthic assemblage are also present in most samples. The upper sections contain species found in modern flora, including *Cyclotella baicalensis, C. ornata, C. minuta, Aulacoseira baicalensis*, and *Aulacoseira* spores.

Two significant departures in species composition occur in some samples: the occurrence of a very large and morphologically unusual species *Stephanodiscus grandis* and the periodic occurrence of the so-called archaic *Stephanodiscus* complex. Our current hypothesis is that alternations between *Aulacoseira/Cyclotelia*-dominated assemblages and *Stephanodiscus*-dominated assemblages reflect climatic transitions. By analogy, sections with *Aulacoseira/Cyclotelia* dominated assemblages should most closely approximate modern conditions. By reasonable inference, *Stephanodiscus* dominated assemblages may reflect enhanced turbidity and circulation associated with periglacial conditions. More information on this record will become available as more detailed counts are tabulated and the apparently barren sections are investigated further.

The qualitative analysis of diatom distributions shows that to a depth 2098 m sediments contain diatom complexes similar to those described in an 11 m piston core from the Academician Ridge (Loginova and Khursevich, 1990). In lower horizons, within the range 2103 to 6320 cm, diatoms are less frequent. Species of the fossil group *Stephanodiscus* are dominant at horizons 2776, 2872, 3677, and 4401 cm. The same fossil species of *Stephanodiscus* along with *C. baicalensis, C. minuta* and frustules of *A. islandica* are found at 5452 cm depth. A new *Stephanodiscus* complex never previously described in Baikal sediments was found at 6682–7098 cm (Fig. 12b). Further downcore diatoms occur very infrequently (Fig. 12a). The low abundance of diatoms may be due to: (1) essential dilution by coastal terrigenous material, and (2) post-depositional dissolution of diatoms, as shown by the presence of disk-like forms 30–40 mm in diameter at 7098 cm depth and lower.

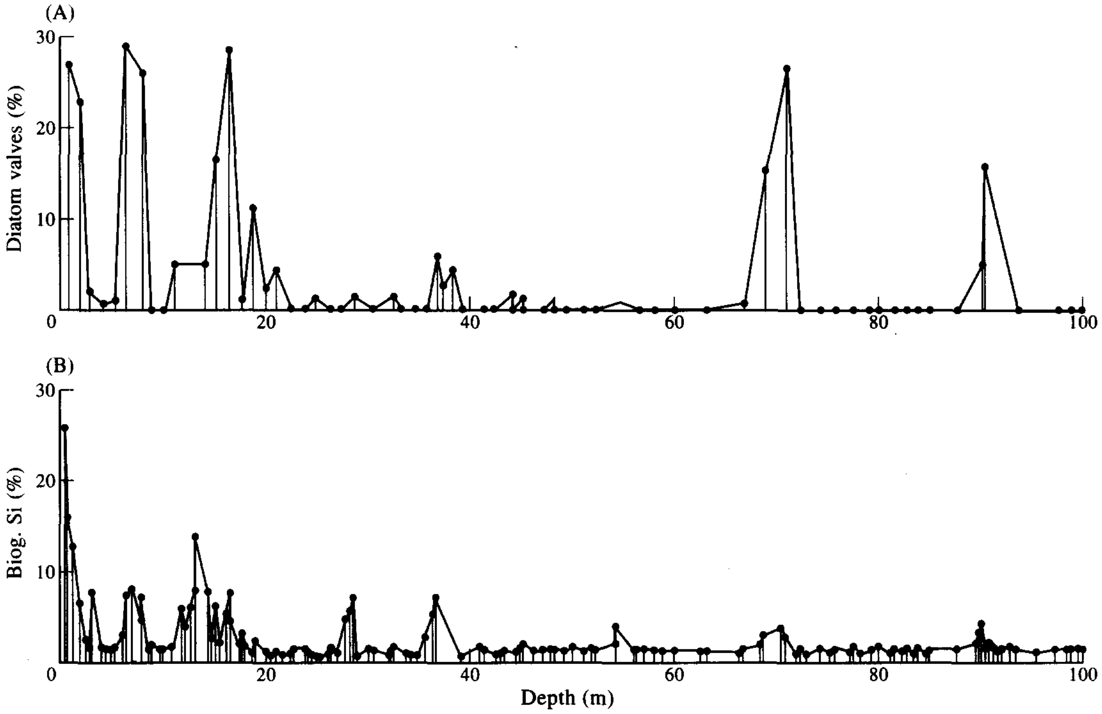

FIG. 12. (a) Distribution of diatom valve amounts (A) and biogenic silica (B).

Although a highly endemic flora is present, it is clear that a wealth of biostratigraphic and paleoecological information is potentially available. The quantitative distribution of diatom frustules in the core correlates well with the percentage of biogenic silica. A few cases of discordance may be explained by a discrepancy in the depth of the layers analyzed in both cases. Additional subsampling and further refinement of taxonomic separation should sharpen interpretations and reveal additional detail.

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 core (Fig. 12b). The sediments in the upper 2 m of the core, radiocarbon dated as Holocene, have maximum BSi contents of 20–25%. The sediments that represent the last glacial maximum (2–5 m) generally have BSi contents of a few percent or less. By analogy, we infer that previous interglacial sediments had high diatom productivity, and that previous glacial periods are marked by low diatom productivity. This inference depends on the assumption that BSi has not been significantly altered by diagenetic processes.

The first subsurface maximum in BSi occurs at about 7 m, but it is relatively small, less than 15%. Extrapolation of the sedimentation rates for the first 30,000 years from the upper part of the core suggests an age of about 36,000 years for this peak. The next subsurface maximum is from about 11 to 17 m and has multiple peaks, the largest of which is more than 20% at about 14 m. This interval is the one that is most like the Holocene in the entire core. Although the similarity of this peak to that of the Holocene suggests correlation to the fast interglacial, detailed correlation of the BSi record to glacial and interglacial periods awaits better dating control.

Most of the clearly delineated peaks in BSi occur in the upper 50 m of the core, above the change in lithology and inorganic geochemistry noted earlier. However, small but significant BSi peaks also occur in the lower lithologic unit, at approximately 55, 68–71, and 90 m. Most of the peaks below 15 m are less than 10%; the reason these peaks are less than those in the Holocene and at 14 m is not known at present.

Concentrations of organic carbon and total nitrogen in sediments from BDP-93-1 range from 0.4–3.4%, and 0.06–0.3%, respectively (Fig. 13). A maximum in organic carbon, observed in the first meter of the core, corresponds to the Holocene organic carbon maximum (6000 BP) observed in piston cores throughout Lake Baikal. Numerous peaks in organic carbon are observed downcore but not all of these peaks correspond to peaks in biogenic silica. Total nitrogen concentrations downcore show a pattern generally parallel to that for organic carbon. Atomic C/N values range from 7 to 18, with a whole core average of 10, indicating aquatic productivity as the primary source of organic matter for the sediments at the Buguldeika site. Higher than average atomic C/N values occur from 44 to 80 m, suggesting a time of increased terrigenous runoff to the lake. Microscopic examination of the sediments also show increased woody debris over this depth range. Organic carbon contents and atomic C/N values are highly correlated. This may suggest that high organic carbon values are the result of increased organic input from terrigenous runoff, superimposed on a steady rain of organic matter from aquatic production.

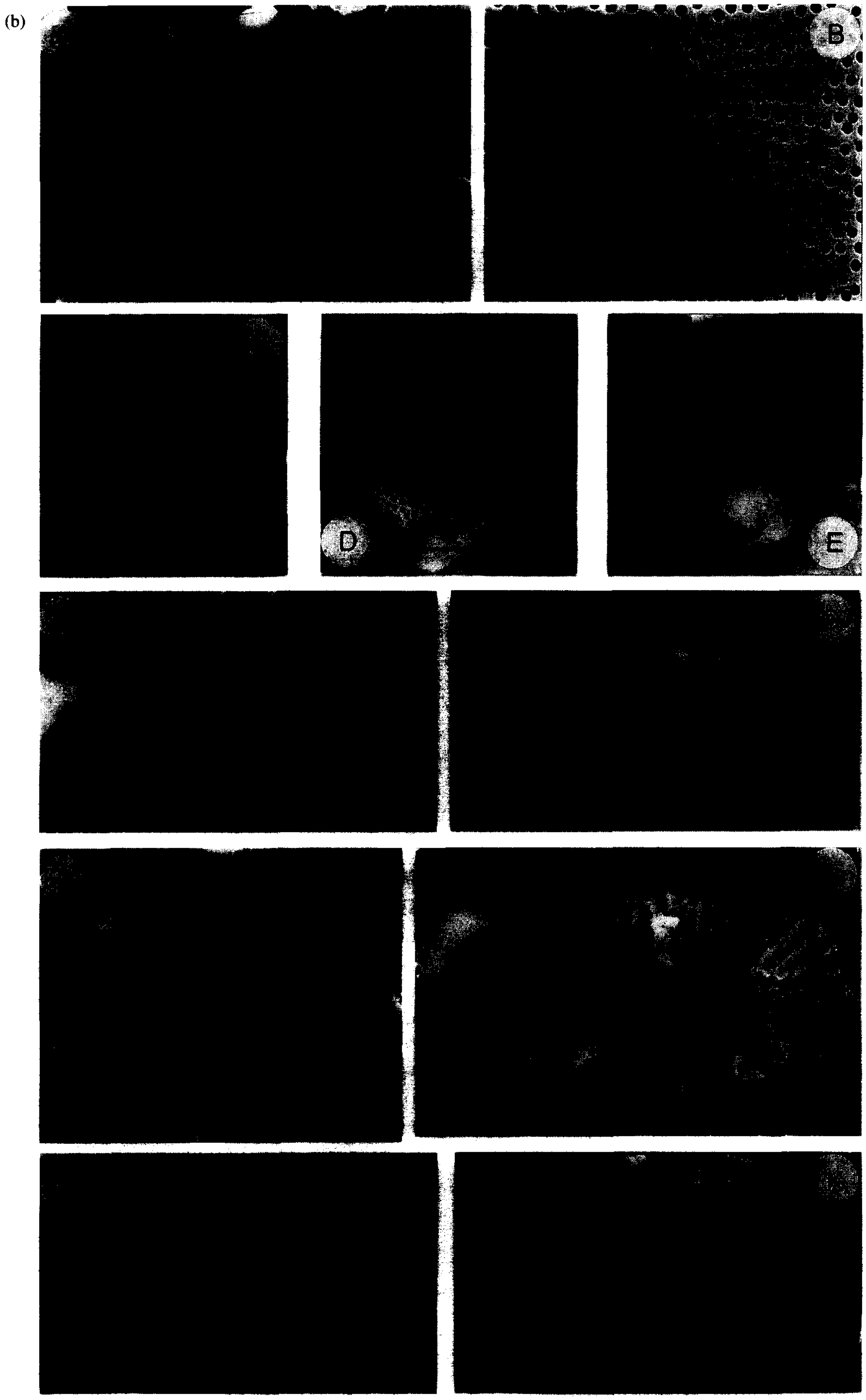

FIG. 12. (b) Relics of diatom algae from 6682–7098 cm depth. (A–B) the general view of sediments from 6685 cm depth; (C–K) photomicrographs of a potentially new species of *Stephanodiscus*. Scale: (A–B) 100 mm; (C–E, G) 10 mm; (F, H, K) 1 mm.

DISCUSSION

Preliminary Evidence for Paleolimnological and Paleoclimatic Changes

The AMS radiocarbon dates in the upper part of Hole 1 yield fairly constant sedimentation rates and an excellent chronology for the last 25 to 30 BP. Age–depth relations in Hole 1 are consistent with those predicted from nearby conventional piston cores and high resolution seismic profiles. Additional stratigraphic and geochronologic control is provided by the magnetic susceptibility records of Holes 1 and 2 as compared to nearby radiometrically

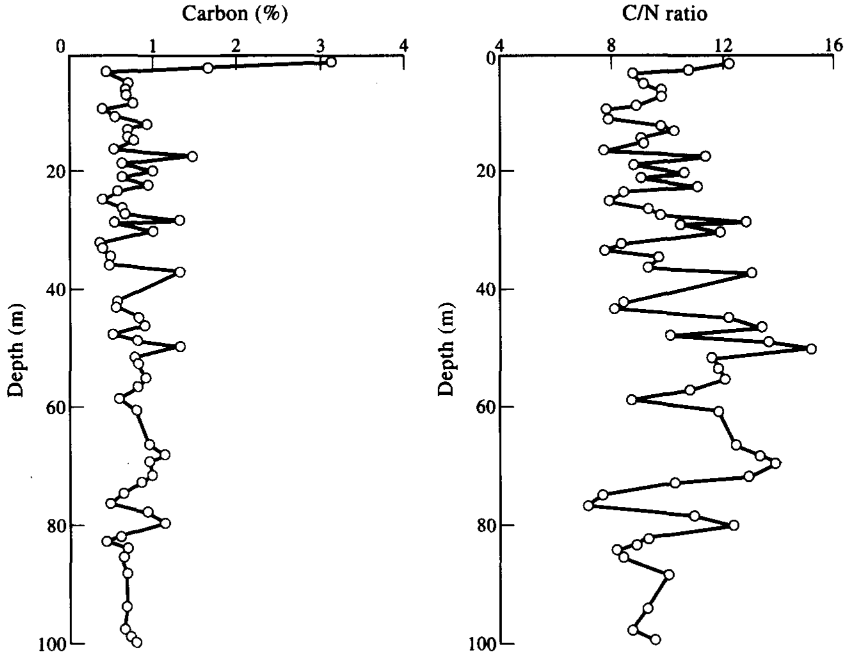

FIG. 13. Total organic carbon (weight %) and Carbon/Nitrogen (C/N) measurements for BDP-93-1.

dated piston cores. The resolution of the two excursions in the inclination record between 25.5 and 27 m and at about 70 m (Fig. 9) will aid correlation. At the present time we favor the interpretation that the excursion between 25.5 and 27 m corresponds to the 180,000 ka Biwa–1 Jamaica double excursion. This chronostratigraphic interpretation would place the glacial-type sediments of Hole 1 equivalent in time to marine Oxygen Isotope Stage 6. At this point it is possible to relate the changes in biogenic silica, pollen, diatoms, clay mineralogy and variations in rock magnetic parameters in BDP-93 cores from Hole 1 to processes external to the limnological system of Baikal. As stated earlier however, this interpretation may change once additional samples are measured from this interval. Work is underway to compile multiple climate proxy data at higher resolution in order to refine the character of Baikal's response to climate forcing over the last 250,000 years.

Patterns of biogenic silica, zonations in pollen and diatoms, clay mineralogy and variations in rock magnetic parameters in BDP-93 cores from Hole 1 show excellent evidence for paleolimnological and paleoclimatic changes at the Buguldeika site in southern Baikal (Fig. 14). Climatically driven changes are particularly evident in the upper 50 m of Hole 1. Below this depth climatic signals may also be present, but they are less apparent due to increased fluvial input of coarse materials from a Buguideika river drainage source. Rock magnetic measurements in the upper 50 m of BDP-93 Hole 1 indicate that variations in magnetic concentration, grain size and mineralogy appear to be related to climate change. These rock magnetic variations are also consistent with those observed in the clay mineralogy suite. Low magnetic concentrations and a predominance of low coercivity minerals appear to be associated with interglacial and interstadial periods while, as would be expected, glacial periods are characterized by higher concentrations of magnetic grains and increased amounts of high coercivity minerals. During warm periods, therefore, Lake Baikal's overall aquatic productivity became higher, resulting in increased biogenic silica and abundance of diatoms which dilute the magnetic concentration. Additional sampling of Hole 2 will supplement the existing reconnaissance data set and may lead to a better understanding of the nature of soil development in the Selenga and Buguldeika River catchments. Work on previously collected Baikal piston cores indicates that it will be relatively straightforward to date the BDP-93 cores by correlation to the SPECMAP marine record (Imbrie *et al.*, 1984). The SPECMAP record has been tuned to Milankovitch orbital forcing frequencies (Peck *et al.*, 1994).

Preliminary Evidence of a Change in Depositional Environment at the Buguldeika Site

Several independent parameters provide evidence that the sedimentary section at the Buguideika site was gradually affected by uplift and biting of the Buguldeika block. Episodes of coarse sand deposition within some

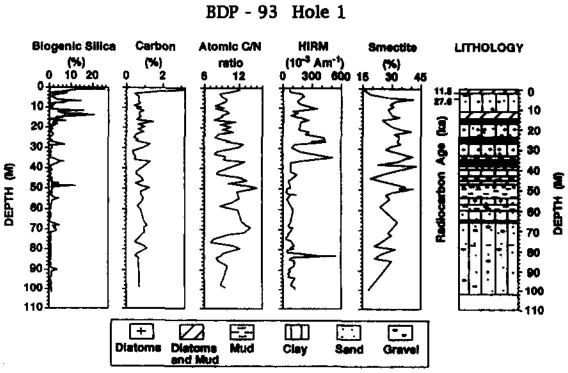

FIG. 14. Summary figure of evidence for a change in depositional environment and paleoclimatic–paleolimnologic changes at the Buguldeika site. Radiocarbon ages determined by linear regression based on 15 radiocarbon dated samples.

hemipelagic sections indicate that deposition of the lower 50 m of the BDP-93 site is dominated by sedimentation from the Buguideika River system.

Deposition of the upper 50 m is dominated by hemipelagic sedimentation and fine-grained input from the Selenga River system to the east. Sedimentation rates are lower in the upper 50 m and the radiocarbon dates currently available show that sedimentation was fairly uniform.

Below 50 m the magnetic concentration generally increases, low coercivity minerals predominate throughout, and increased amounts of sand and gravel are present (Fig. 8). This change in magnetic parameters and lithology suggests that the depositional environment at the site below 50 m was dominated by fluvial input. This interpretation is corroborated by the shift in chemical elemental data as well as clay mineralogy, porosity, grain size etc. Even the carbon to nitrogen ratios of the organic matter become higher below 50 m, indicating more terrestrial input versus aquatic production. These combined results, while preliminary, clearly show the exciting potential of distinguishing climatically driven changes in Baikal sediments versus those which reflect episodes of tectonic processes. They also confirm the earlier interpretation of the Manzurka and Neobaikalian erosional-tectonic stages in the Buguldeika region by Logachov *et al.* (1974) and Kononov and Mats (1986). Furthermore, the present chronostratigraphy of the BDP-93 cores places the cut-off of the pre-Manzurka River valley as an outlet of Baikal water at the time when Baikal water flowed into the Lena River. Future drilling may produce a better understanding of the tectonic history of Lake Baikal and its portion of the Baikal Rift Zone, especially when combined with results from multichannel seismic and other geophysical studies (Hutchinson *et al.*, 1992, 1993; Klitgord *et al.*, 1993a, 1993b; Scholz *et al.*, 1993).

SUMMARY AND CONCLUSIONS

The first successful drilling from a barge frozen in the winter ice of Lake Baikal has recovered two 100 m hydraulic piston cores from two holes in 354 m of water, approximately 5 km offshore of the Buguldeika River in southern Lake Baikal. An average recovery of 72% and 90% was obtained in Holes 1 and 2, respectively. Magnetic susceptibility logging reveals excellent core-to-core correlation of Holes 1 and 2. In this report the BDP-93 scientific team, made up of Russian, American and Japanese scientists, describes the preliminary analytical results from the cores of BDP-93 Hole 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 entire length, indicating that the sediments were all deposited during the Brunhes magnetic epoch. Current estimates are that the sediments represent deposition over the last 500,000 years.

Variations in spore-pollen assemblages, diatom microflora, biogenic silica content, rock magnetic properties, clay mineralogy and organic carbon reveal a detailed record of how climate change impacted the Baikal limnological system over approximately the last 250,000 years. These independent variables alternate in a pattern characteristic of glacial/interglacial climatic fluctuations. The present age model suggests that the climatic signal recorded in the Baikal sediments at Buguldeika is similar to late Quaternary signals recorded in Chinese loess sections and in marine sediments. In addition to the climate record, detailed lithologic characteristics, rock magnetic properties and inorganic element distributions in BDP-93 Hole 1 cores all reflect a significant change in character at 50 m subbottom depth. In the upper 50 m, low values of magnetic susceptibility are coincident with diatom-rich zones, whereas higher values are found in clay-rich layers. The change in these parameters appears to be related to tectonic uplift and tilting of the Buguldeika saddle as well as a change from Buguldeika-dominated sedimentation to a more hemipelagic Selenga River source(s). This change is estimated to occur approximately 250,000 years before present.

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