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GEOCHEMISTRY

Variations in Environmental Conditions of Intracontinental Asia over the Past 1 Ma in High-Resolution Geochemical Records from Bottom Sediments of Lake Khubsugul (Mongolia)

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Progress in the study of planetary changes in the environment and climate based on oceanic and glacial records of the Pleistocene provided the basis for further detailed elaboration of spatiotemporal relationships in climate-forming processes. A particular role in this field belongs to continents. In addition to terrestrial sections, bottom sediments of large continental basins provide no less important information about continental variations in the environment. The Asian intracontinental region comprises the two largest freshwater lakes (Baikal and Khubsugul) with different hydrochemical, biological, and hydrological balances. Previous investigations of geochemical records from Baikal sections established that the observed variations were mainly determined by the climatic factor and changes in the biological and hydrological balance of the lake [1–3]. In contrast to Baikal, Khubsugul is a mountain lake (1645 m above sea level) and has much smaller dimensions (136 km long, 39 km wide). Therefore, this lake responds more dramatically to variations in the environment, climate, and, particularly, the humidity regime [4].

The present work reports the first detailed data on the distribution of trace and major elements in Pleistocene sediments of Khubsugul, as well as interpretation of geochemical variations as reflections of environmental variations in Inner Asia.

We studied sediments of core KDP-01 [5] by physical methods. The X-ray spectrometric fluorescence analysis was carried out by a continuous scanning of an undeformed wet core in synchrotron radiation beams (XRF-SR-scan) with a 1-mm step in the Siberian Synchrotron Center. Measured fluorescence fluxes of elements were transformed into concentrations by the method described in [6]. As a result, we obtained records of concentrations for 20 elements (from K to Mo, Pb, U, and Th) for the upper 50 m of the core with a 1-mm step that corresponds to a time resolution of 20–50 yr. In addition, 55 samples taken from core intervals with cardinally different results of scanning were analyzed by standard XRF-SR and INAA methods, as in [7].

As is evident from the comparison of the data on the abundance of elements in the Khubsugul sediments with the typical Baikal sediment (geostandard BIL-1), Khubsugul sediments are anomalously (nearly five times) enriched in Ca (average concentration 6.3 wt %). Consequently, the concentrations of the majority of the remaining elements are slightly lower (Fig. 1). In particular, the concentrations of Mn (960 ppm), U (2.1 ppm), and As (9.0 ppm) are considerably lower relative to Baikal, although these values are rather similar to the clarke concentrations. Mn, U, and As belong to the group of elements with variable valence, and the depletion mentioned above may indicate less active migration in the Khubsugul system than in the Baikal system. Relative depletion in Br is also caused by a low concentration of organic material.

Comparison of horizons of Khubsugul sediments, which were formed in conditionally named glacial and interglacial periods (climatic minimums and optimums) and distinguished by correlation with global glaciations and interglacial events, shows that interglacial horizons are mainly enriched in most elements rel-

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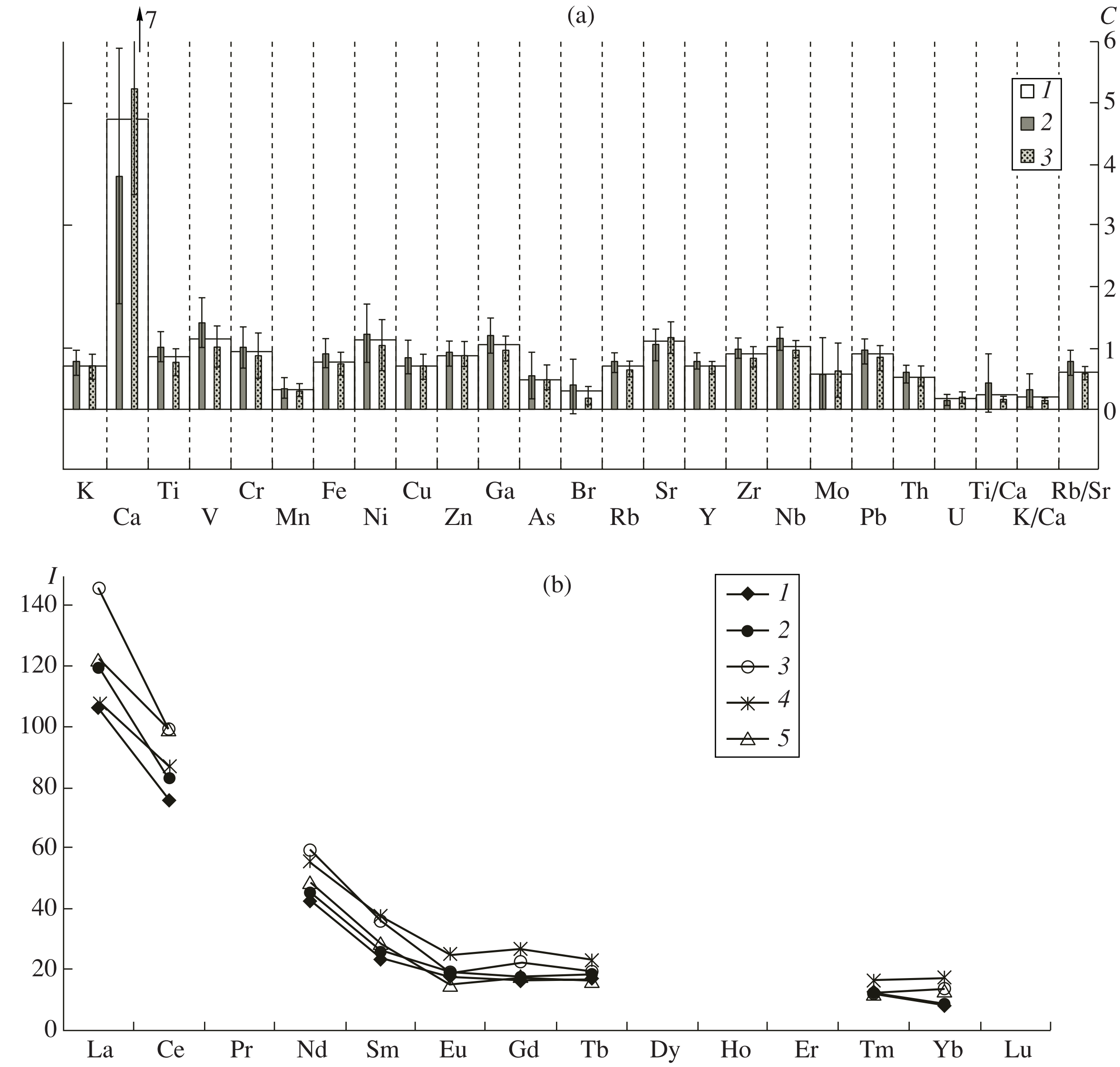

Fig. 1. Average concentrations (*C*) of elements in the 50-m sequence of Pleistocene sediments of Lake Khubsugul: (a) relative to concentrations of the same elements in the Baikal sediment geostandard BIL-1 [8] (*1*), similar ratios of average concentrations in interglacial core horizons (*2*), in glacial intervals (*3*) (values of scatter relative to average values are shown for interglacial and glacial horizons); (b) chondrite-normalized intensities (*I*) of REE in glacial (*1*) and interglacial (*2*) horizons of Khubsugul sediments compared to analogous spectra for the Baikal sediment BIL-1 (*3*), for sediments of Lake Teletskoe (*4*), and for post-Archean Australian schist (PAAS) (*5*).

ative to glacial horizons (average enrichment factor 1.2). Depletion is noticeable only for Ca, Sr, Mo, and U. The high enrichment factor (>1.2) is characteristic of interglacials for V, Br, and some ratios (K/Ca and Ti/Ca). Moreover, the scatter is very high for the As and Br concentrations (within interglacial horizons) and Mo concentrations (within both glacial and interglacial horizons). Of interest is the nearly complete absence of an Eu minimum in the REE distribution. Correlation with similar spectra for sediments from Lake Baikal and Teletskoe Lake [9], as well as with post-Archean Australian schists (PAAS) [10] (as the REE scale of the upper mantle), demonstrates an appreciable depletion of Khubsugul sediments in all REEs, except La and Eu. The distinguished interglacial and glacial horizons of core KDP-1 differ in concentrations of LREEs. Sediments of glacial horizons are depleted in LREEs.

For paleoclimatic interpretation of the records obtained, we chose three main markers: Br, K/Ca, and Ti/Ca. We believe that Br in the Khubsugul sediments is related to the primary bioproductivity of the lake, as in Baikal sediments [11]. Bromine is likely to indicate the trophic nature of the lake. Direct measurements showed that the Br concentration in the present-day organic suspension in Khubsugul water exceeds 0.1 wt %.

It was established previously that the lake lost water during arid periods due to low atmospheric precipita-

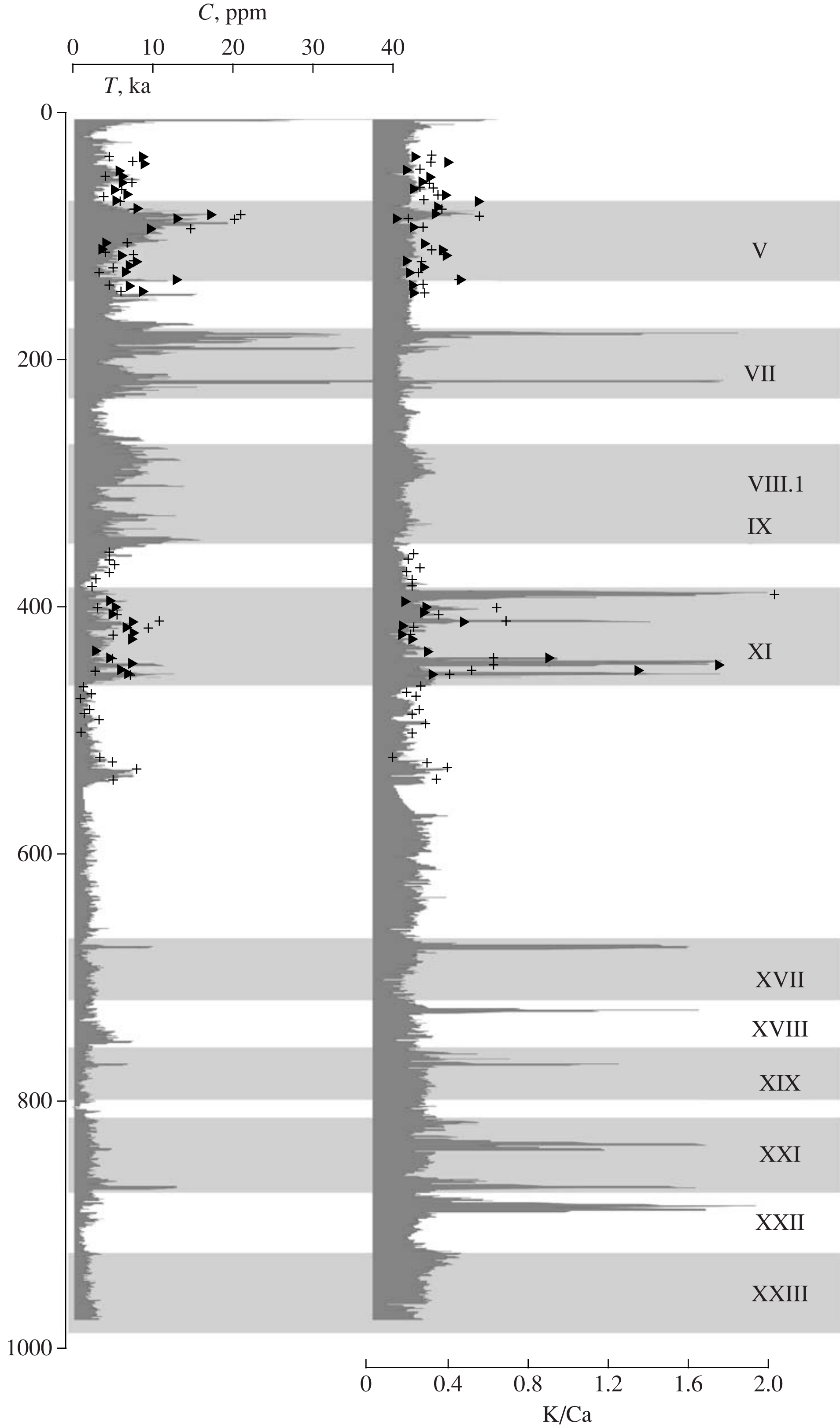

Fig. 2. Records of concentrations (*C*) of Br and K/Ca in Holocene–Pleistocene bottom sediments of Lake Khubsugul. The solid line shaded denotes the results of scanning. Markers indicate data based on standard XRF-SR (crosses) and INAA (triangles) methods. Light gray shaded areas designate adopted correlation with oceanic isotopic stratigraphy and roman figures in them show corresponding OIS (interglacial) numbers. The chronology is based on the five most reliable paleomagnetic events recorded in the core [5].

tion. The consequent negative hydrological balance resulted in carbonatization and sulfatization of bottom sediments [4, 5]. On this basis, K/Ca and Ti/Ca markers are proposed as indicators of the lake flowage. Positive anomalies of K/Ca and Ti/Ca ratios in sediments suggest a decrease in the share of the evaporite component in them and mark episodes of an increase in the regional humidity of the climate. As a consequence, the paleo-Khubsugul basin was filled with water, the discharge threshold was overcome, and the Ca outflow from the lake was activated. The existence of such a peculiar trigger can explain some peculiarities of the Khubsugul record and its distinction from a more calm Baikal record.

The available geochemical records can be divided into three stages. During the first stage spanning from 460 to 8 ka BP (i.e., the period nearest to the present-day one), the Br record comprises contrasting and rhythmic oscillations similar in many respects to variations in the oxygen isotope composition in oceanic sediments related to the growth of ice sheets on the Earth. The Br concentration in older sediments is very low, and the record is not complicated by variations. Such a contrasting Br distribution indicates large-scale reconstruction of the lake biota at another qualitative level at the middle/late Neopleistocene boundary.

The K/Ca ratio (like Ti/Ca) correlates well with Br at the interval of 460–8 ka. Its positive anomalies mark 100-ka-long stages of oceanic stratigraphy (Fig. 2) and indicate interglacial events in the inclination and precession rhythm (cycles with a duration of 41, 23, and 19 ka were established in the spectral analysis of these records). Biogenic (Br) and geochemical (K/Ca) markers exhibit a different time lag (and, probably, a different threshold of response). In particular, if biogenic production is underdeveloped in the lake, the K/Ca ratio clearly marks humidification (see, e.g., OIS XI in Fig. 2). If the correlation with oceanic stratigraphy is direct, climatic optimums of this stage in the Khubsugul record usually turn out to be more prolonged than both minimums and global interglacials. Increase in the duration of optimums can be apparent due to higher rates of sedimentation. However, we cannot also rule out the influence of regional peculiarities of orbitally initiated changes.

At the second stage (670–460 ka BP), traces of Milankovitch oscillations are virtually missing in core KDP-01. We explain this fact by the very low water level of the lake when water exchange intensity was low, chemical characteristics of the water were unsuitable for the vital activity of organisms, and the Ca outflow was low. One of the causes of this phenomenon can be a prolonged aridization of the climate. Nevertheless, the lake still existed: no traces of major lithological unconformities have been found in the core, and signs of eolian mixing are missing in the sediment structure (i.e., the water-mass depth exceeded 20–30 m), although general sedimentation conditions did change (a brief description of the core is given in [5]).

The earliest stage of the Khubsugul record (nearly from 950 to 670 ka BP) was characterized by rhythmic pulsations of humidity and water level in the lake. Bioproductivity considerably exceeded the background level in humidification optimums 890–880 and 680–670 ka BP. Humidification episodes distinguished by K/Ca anomalies also allow us to outline the correlation with oceanic isotopic stratigraphy. Correlation of stages XVII–XXIII is preliminary. Humidification episodes coincide (but not at all everywhere) with planetary interglacial cycles (Fig. 2). We assume that regional factors of the environmental evolution might substantially affect the threshold system of Khubsugul.

The records obtained testify to appreciable reorganizations of the landscape and climate in Inner Asia at 450 ka BP. We also observe traces of such reorganization in the Baikal records. It is reflected in variations of sedimentation rates [3] and diatom dominants [1], the formation of deserts in northern China [14], and so on. The event at ~400 ka BP is also traced in global records. In [13], the mid-Brunhes event was attributed to a considerable increase in dissolution of deep-water carbonates in the ocean. In the Khubsugul region, this process could serve as a powerful trigger leading to reorganization of the whole ecosystem. The second event (about 670 ka BP) is less common in records. However, it should be noted that both rhythmic loess formation [14] and $\delta^{13}C$ variations in marine carbonates [15] involve cycles with a duration of 400–500 ka. Events in the Khubsugul geochemical record described above can also reflect a long cyclic evolution of processes on the land: cycles with a duration of 400–500 ka are present in the frequency spectrum of variations in the Khubsugul records. In [15], the so-called supercycles are attributed to bioactivity of organisms on the planet: the bloom of diatoms in the World Ocean due to increase in the silicate influx from the land (i.e., humidity in continental areas), the burial of huge amounts of organic carbon in oceanic sediments, and $\delta^{13}C$ maximums. The concept of a close relationship between the carbon cycle and the continental landscape complies very well with the observed reorganizations of both the bioproductivity of Asian vast lakes and the reorganization of landscape conditions, including weathering and transportation of the material.

We believe that events in the Khubsugul geochemical record described above might be a component of a common 400- to 500-ka-long cyclic evolution of the environment. At the same time, inner climatic peculiarities of these cycles were extremely diverse in different continental systems.

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