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GEOCHEMISTRY

Strontium Isotope Variations in the Sedimentary Sequence of Lake Baikal

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The study of Sr isotope variations in sedimentary sequences shows that this geochemical parameter is an indicator of both climatic and endogenous processes. It has been established that an increase in $^{87}Sr/^{86}Sr$ values in ocean carbonates over the last 600 Ma correlates with the scale of orogenic movements at the divergent plate margins and global cooling events [1, 2]. In particular, collision of the Indian Eurasian plates 380 Ma ago [3] triggered the growth of the largest mountain systems (the Himalayas and Tibet plateau) and undoubtedly provoked changes in global atmospheric circulation. This mountainous area occupies 4.7 mln km^2 (4.2% of the present-day land area). However, 25% of dissolved salts transported from continents due to weathering are delivered from this region [4]. Significant volumes of rocks exhumed during growth of the Himalayas and Tibet are composed of granitoids and felsic schists.

According to [1], destruction of mountains produces a great volume of clastic material affected by chemical erosion, leading to the growth of the $^{87}Sr/^{86}Sr$ value in seawater and marine authigenic carbonates delivered to bottom sediments; the weathering of silicate minerals is accompanied by consumption of CO_2 from the Earth's atmosphere; this and other geological processes provoked the last global glacial epoch; and this epoch has continued from 37 Ma ago to the present time.

A slightly rugged relief dominated around Baikal 2.5–3 Ma ago [5]. Rocks exposed in the catchment basin at that time were mainly composed of weathering products. The climate was warm and wet. Volcanic activity was interrupted 3–12 Ma ago in the South Baikal volcanic region. Volcanic activity resumed 3–3.5 Ma ago. Intense orogenic processes produced young mountains around Lake Baikal, which were covered by glaciers during glacial periods. Basalts older than 2.5 Ma filled shallow equant depressions. The younger basalts formed extended volcanic rivers, which emphasize the appearance of mountainous relief [6, 7, 2].

The geological evolution of the Baikal rift zone and deep-water Baikal depression has been reconstructed in detail. Its southern and central parts reached great depths about 6.7 Ma ago [2, 8]. This provided the basis for detailed isotopic studies of $^{87}Sr/^{86}Sr$ variations over the entire borehole BDB-96 [9] drilled in Academician Ridge of Lake Baikal (Fig. 1, table). The borehole occupied an age interval of 5 Ma up to the depth of 200 m.

The isotopic composition was determined in terrigenous and diatomaceous sediments. The terrigenous sediment contains 3–8% biogenic silica and 0.2–0.9% total organic carbon. The diatom oozes contain 26–43% biogenic silica and 0.9–1.25% organic carbon. Over the entire borehole, the diatom oozes are depleted in radiogenic Sr relative to the terrigenous rocks of the adjacent horizon because the siliceous valves of diatoms contain Sr extracted during their life from lake water, which is depleted in the radiogenic component as compared to terrigenous material. At a depth of about 110 m corresponding to an age of 2.5 Ma, the $^{87}Sr/^{86}Sr$ ratio demonstrates a sharp decrease both in the terrigenous clays formed during cold glacial periods and in the diatom oozes formed during warm interglacial periods.

At the depths of 110 to 200 m, the $^{87}Sr/^{86}Sr$ value is 0.70972–0.71021 in the diatomaceous oozes and 0.71063–71141 in terrigenous sediments. At depths from 0 to 100 m, the diatomaceous and terrigenous sediments have lower $^{87}Sr/^{86}Sr$ values: 0.70861–0.70956 in the diatom oozes and 0.70983–0.71152 in the terrigenous sediments (Fig. 1, table). This testifies to a change of provenance with time. Global formation of moun-

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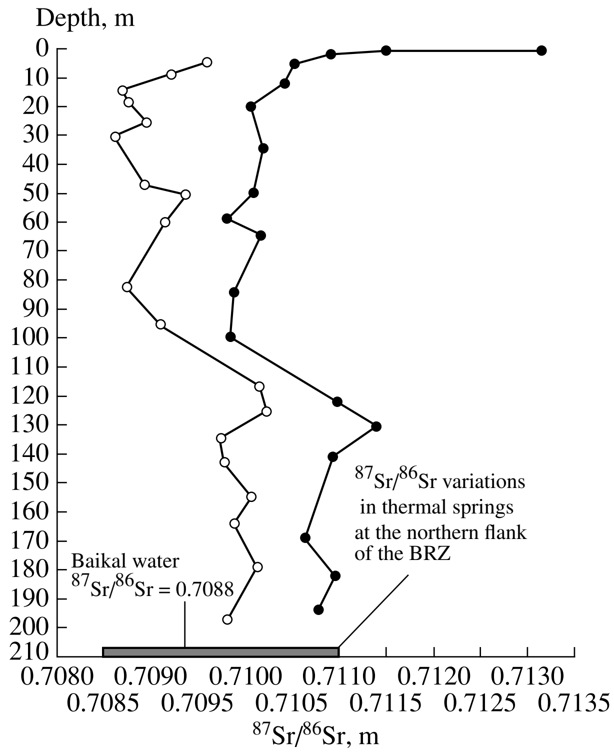

Fig. 1. Sr isotope variations in the Baikalian sediments, borehole BDP-96. Filled and open circles are terrigenous and diatomaceous sediments, respectively. (BRZ) Baikal rift zone.

tains at the divergent plate margins typically leads to increase in the $^{87}Sr/^{86}Sr$ value in sediments, e.g., in the Tibet–Himalaya region. However, this process has the opposite effect on the bottom sediments of Lake Baikal.

The major geochemical sources of material for the formation of Baikal sediments were as follows: (1) bedrock silicate and carbonate rocks exhumed in the catchment basin as the result of mountain growth; (2) weathering crust formed after granites and felsic metamorphic schists, which predominated in the catchment basin prior to the beginning of orogenesis in the Baikal rift zone; and (3) lake waters.

Figure 2 presents summary data on the Sr isotope systematics of sediments, silicate and carbonate rocks, and the weathering crust exposed in the catchment area and lake waters. The Sr isotopic composition of the silicate rocks varies widely depending on rock types and age—from mantle signatures ($^{87}Sr/^{86}Sr = 0.705$) in the Neogene and Quaternary basalts to high radiogenic compositions ($^{87}Sr/^{86}Sr > 1$) in the rapakivi-type peralkaline Early Proterozoic granites of the Primorskii Range. The present-day Sr isotopic composition in the carbonate rocks of the Slyudyanka Group and Ol'khon region varies in a narrow range ($^{87}Sr/^{86}Sr = 0.707$–0.709).

Trends in $^{87}Sr/^{86}Sr$ variations in the studied terrigenous sediments can be related to the mixing of materials from two sources: (i) the weathering crust formed after granites and felsic schists; (ii) products of the disintegration of mafic rocks (Neogene volcanic rocks, Paleozoic basic schists, and sviatonossites first identified in Svyatoi Nos Peninsula) and Paleozoic carbonate rocks. The mixing trend (Fig. 2, line *I*) helps to distinguish geochemical processes responsible for the Sr isotopic composition in the terrigenous components of the Baikal sediments. The Sr isotopic composition in sediments older than 2.5 Ma is close to that in the weathering crust. At the same time, the Sr isotopic composition in the younger sediments is mainly determined by a composition of crystalline schists, carbonate rocks of the Slyudyanka Group, and sviatonossites, i.e., rocks uncovered during orogenesis. In particular, the clastic component in sediments of the Academician Ridge area is dominated by products of disintegration of basic schists and carbonate rocks (Ol'khon Island), as well as sviatonossites and related rocks (Svyatoi Nos Peninsula).

An important feature of the studied section is the systematic difference in Sr isotopic composition between the terrigenous and diatomaceous sediments: the terrigenous sediments are always enriched in the radiogenic Sr relative to the diatomaceous variety at the corresponding depths. At the same time, the diatomaceous and terrigenous sediments deposited before and after the depth of 110 m form different mixing lines (Fig. 2, lines *II* and *III*).

Since the Baikalian sediments contain abundant remains of diatom algae, the skeleton of which is formed from silica dissolved in the Baikalian water, the Sr isotopic composition could change significantly before and after the time boundary of 2.5 Ma.

The terrigenous sediments in the upper part of the section (0.25–1.7 m) are characterized by anomalous Sr isotopic composition (Fig. 1, table). This could be related to a catastrophic phenomenon (evidently, earthquake), which delivered a great amount of material (possibly products of the erosion of granitoids and metamorphic schists) to the lake. This process may explain the shift of data points of the corresponding compositions of terrigenous sediments from mixing line *I* toward felsic compositions of acid silicate rocks (Fig. 2). The catastrophic phenomenon can be exemplified by the formation of Proval Bay in 1861, when several hundred hectares of the Baikal coast were flooded with water. The input of new material changed the composition of terrigenous sediments, but the composition of water and diatom algae remained unchanged. This assumption requires further checking. However, we cannot rule out the possible influence of strong catastrophic earthquakes on the character of sedimentation in the Baikal basin.

Comparison of our data on variations in the Sr isotopic composition in sediments of Lake Baikal with the respective data on long-term global geochemical indicators (distribution of Sr isotopes in marine carbonates)

Sr content and isotopic composition in the terrigenous and diatomaceous sediments of Lake Baikal (borehole BDP-96) and the weathering profile of granitoids from the catchment basin of the lake

Ordinal no.	Depth (m), sample	Sr, μg/g	$^{87}Sr/^{86}Sr$ (present-day)
1*	0.25 (m)	425	0.71312
2*	0.5 (m)	363	0.71148
3*	1.7 (m)	445	0.71089
4	4.91 (m)	320	0.71051
5	11.47 (m)	350	0.71040
6	20.09 (m)	322	0.71005
7	34.81 (m)	350	0.71017
8	49.38 (m)	335	0.71007
9	58.87 (m)	364	0.70980
10	64.53 (m)	383	0.71015
11	84.4 (m)	389	0.70987
12	99.54 (m)	363	0.70983
13	121.65 (m)	325	0.71097
14	130.2 (m)	312	0.71140
15	141.08 (m)	292	0.71093
16	168.98 (m)	306	0.71063
17	182.02 (m)	330	0.71097
18	193.515 (m)	260	0.71078
19	4.43 (m)	260	0.70956
20	8.48 (m)	280	0.70920
21	14.4 (m)	260	0.70868
22	18.1 (m)	277	0.70875
23	25.26 (m)	250	0.70893
24	30.31 (m)	257	0.70860
25	46.97 (m)	263	0.70892
26	50.44 (m)	265	0.70936
27	59.83 (m)	272	0.70913
28	82.37 (m)	281	0.70872
29	95.56 (m)	284	0.70909
30	116.45 (m)	218	0.71014
31	125.225 (m)	220	0.71021
32	134.6 (m)	210	0.70972
33	142.58 (m)	215	0.70977
34	154.45 (m)	205	0.71006
35	164.01 (m)	230	0.70988
36	179.03 (m)	246	0.71012
37	197.06 (m)	197	0.70981
38	Sample AHOC-1	203	0.71469
39	Sample AHOC-2	215	0.71433
40	Sample AHOC-3	199	0.71458
41	K-1	267	0.71167

Note: (1–18) Terrigenous sediment; (19–37) diatom ooze; (38–40) weathering profile of granites (Khamar-Daban); (41) weathering profile of granites (Ol'khon Island). The sedimentary section of borehole BDP-96 was supplemented by three samples of the terrigenous sediments from borehole BDP-98, which are marked by asterisks.

The strontium isotopic composition of the rocks (terrigenous and diatomaceous sediments) was determined on an MI-1201T mass spectrometer at the Vinogradov Institute of Geochemistry and Analytical Chemistry, Siberian Division, Russian Academy of Sciences, and the weathering crust was analyzed on a Finnigan MAT-262 mass spectrometer at the TsKP, Siberian Division, Russian Academy of Sciences. The measurement accuracy of isotope ratios was no worse than 0.018 rel % and 0.004 rel %, respectively. The isotope measurements were controlled by VNIIM standard (recommended value 0.708028 [10]) with the $^{87}Sr/^{86}Sr$ value of 0.70800 ± 13 ($n = 26$) for the MI 1201T mass spectrometer and 0.708019 ± 32 ($n = 21$) for the Finnigan MAT-262 mass spectrometer. The $^{87}Sr/^{86}Sr$ values measured in samples were not normalized to the recommended value in the VNIIM standard.

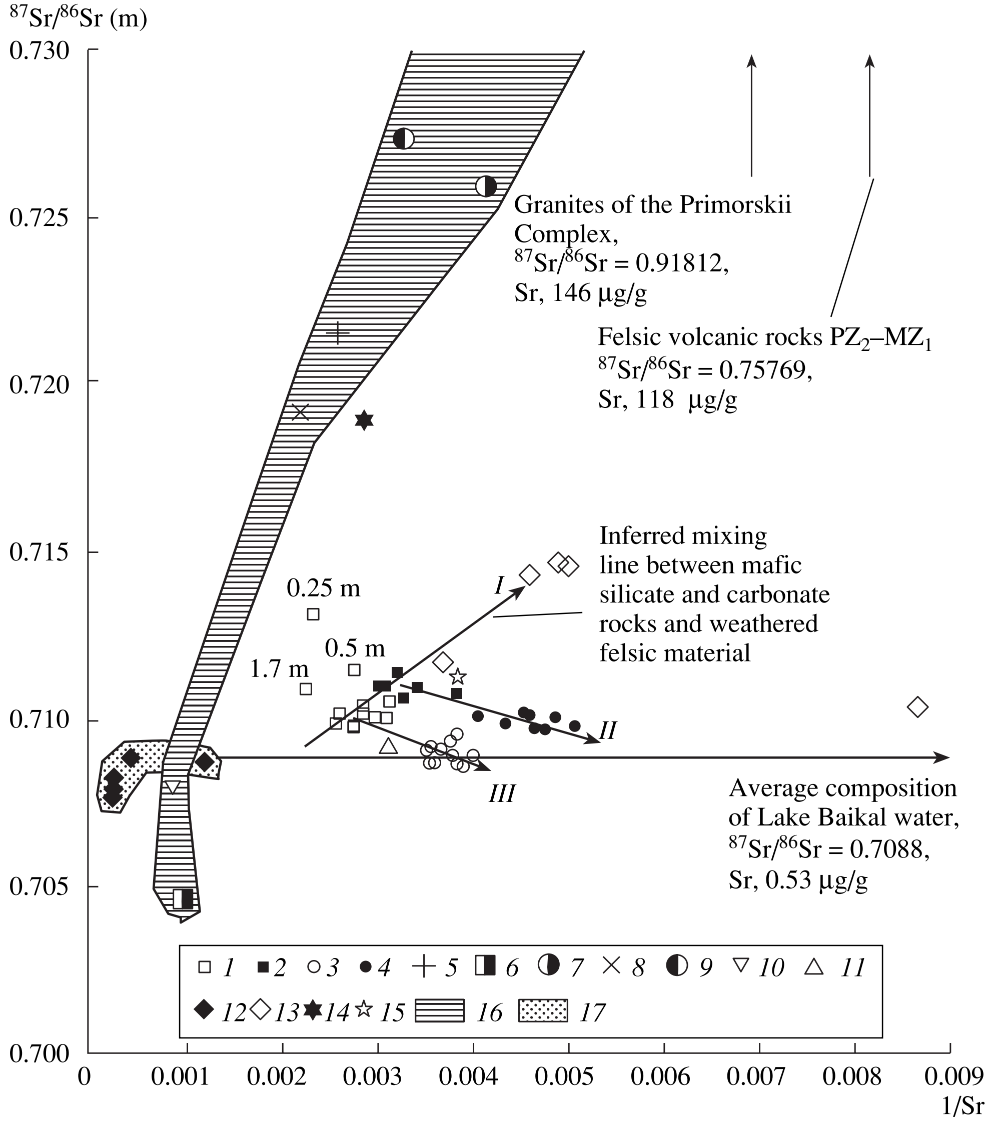

Fig. 2. $^{87}Sr/^{86}Sr$–1/Sr mixing diagram for different sediments from Lake Baikal and possible provenances of terrigenous and authigenic material. Compositions of the major silicate and carbonate rocks developed around the lake, as well as compositions of the terrigenous and diatomaceous sediments of Lake Baikal, are based on the literature data. (*1, 2*) Compositions of the terrigenous sediments from the borehole BDP-96 section (depth <110 m and >110 m, respectively); (*3* and *4*) composition of the diatom ooze from the BDP-96 borehole section (depth <110 m and >110m, respectively); (*5*) average composition of Late Paleozoic granitoids (number of analyses in sampling $n = 79$); (*6*) average composition of riftogenic volcanic rocks of different ages (from Middle Paleozoic to Quaternary) ($n = 95$); (*7*) average composition of metamorphic rocks of the Nyurundukan Formation (without mafic two-pyroxene schists) ($n = 11$); (*8*) average composition of metamorphic schists of the Ol'khon area ($n = 14$); (*10*) average composition of sviatonossites and related rocks ($n = 15$); (*11*) average composition of mafic two-pyroxene schists of the Nyurundukan Formation and Ol'khon area ($n = 4$); (*12*) compositions of carbonate rocks of the Slyudyanka Group; (*13*) weathering profile of granite rocks in the framing of Lake Baikal; (*14*) average composition of the upper continental crust; (*15*) average bulk composition of the continental crust; (*16*) compositional field of the major silicate rocks of Lake Baikal; (*17*) compositional field of the carbonate rocks from complexes in the framing of Lake Baikal. Depths from the bottom surface (0.25, 0.5, and 1.7 m, respectively) are shown for three data points of terrigenous rocks from the upper part of the section.

indicates that variations in isotope indicators can be different on a global scale and on a regional scale. However, in both cases, the Sr isotopic composition of sedimentary rocks can serve as a sensitive indicator of changes in provenances of the sedimentary basin. Hence, this parameter can provide insight into the character of endogenous and orogenic processes.

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