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GEOCHEMISTRY

Sr–Nd Isotopic Heterogeneity of Basalts of the Sierra Leone Test Site, Mid-Atlantic Ridge, 5°–7° S

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Mid-ocean ridge basalts (MORBs) provide important information on the composition and structure of the upper mantle. Isotope–geochemical data are essential for their studies, though their interpretation is still controversial. Observed regularities in the variation of Sr and Nd isotopic composition of MORBs can be regarded either as a result of mixing of different homogeneous isotope reservoirs (depleted mantle, enriched mantle, oceanic island basalt source, and others) [1] or as an isotope heterogeneity of depleted mantle on the kilometer or meter scale [2]. The choice between these hypotheses can only be based on a detailed study of the character and scale of isotope heterogeneity in basalts and other magmatic rocks of the oceanic crust.

When studying MORBs, special attention is traditionally given to chilled volcanic glasses that form a crust at the surface of pillow lavas outpouring onto the ocean floor [3, 4]. In addition, the question remains as to whether or not there is a difference in isotopic characteristics between the volcanic glass crust, which is formed in the course of interaction with seawater, and basalts separated from water by this crust. Moreover, no isotope data are available on basalts and associated rocks of the third layer of the oceanic crust or on metasomatites developed after the latter rocks. To solve this problem, we studied the collection of samples dredged during Cruise 10 of the R/V *Akademik Ioffe* (2001–2002) in the axial (7°10′–5°00′ N) zone of the Mid-Atlantic Ridge[4].

The studied MAR segment is located between the Bogdanov fault (7°10′) and 5°00′ N in the Sierra Leone fault zone (Fig. 1). Since the geological structure of the area is comprehensively described in [4], we give only general information. The ridge is strongly rugged. The rift valley consists of echelons of deep-water depressions, including the Markov Deep with a depth of 5 km. Dredging showed that the slopes of the depressions over a distance of more than 300 km are composed of abyssal rocks, including serpentinized peridotites and various gabbroids. Strongly altered and tectonized basalts and dolerites are exposed at the floor of the rift valley, on its northern and southern walls, as well as on the upper parts of slopes. Unaltered basalts with volcanic glass crust are found on the valley floor and slopes of the neovolcanic rises at the ridge crest.

In terms of the chemical composition, the unaltered basalts of the test site and primitive leucotroctolite (sample I1068/72) are similar to the MOR tholeiites. Gabbronorite (sample I1069/35) is characterized by elevated contents of Ti, Fe, P, Nb, Ta, and Cu but lower contents of Cr, Ni, and Sr. Mineralized metasomatites have low contents of Si, Ti, Fe, Nb, and Ca but higher contents of Mg, Ni, and Sr (sample I1069/107). Detailed petrographic and geochemical data on the studied rocks are reported in [7, 8].

To study variations in the Nd and Sr isotopic composition of major rock types of the test site, we took ten samples of unaltered basalts with volcanic glass crusts and four samples of plutonic rocks represented by gabbroids (primitive and hornblende varieties), trondhjemite, and metasomatite formed after crushed gabbroids. After splitting volcanic rocks into basalt and chilled glass, the samples were studied separately.

To decrease the possible surface effect of seawater contamination, all samples were preliminarily leached with 2.3M HCl in an ultrasonic bath for 10 min and then rinsed in deionized water. This procedure was used for powdered samples of granular rocks (gabbroids, plagiogranite, and metasomatite) and the grain size fraction of 0.2–0.5 mm in the case of basalts and glasses. Isotopic analysis of primary material, acid leachate, and residue performed for some samples

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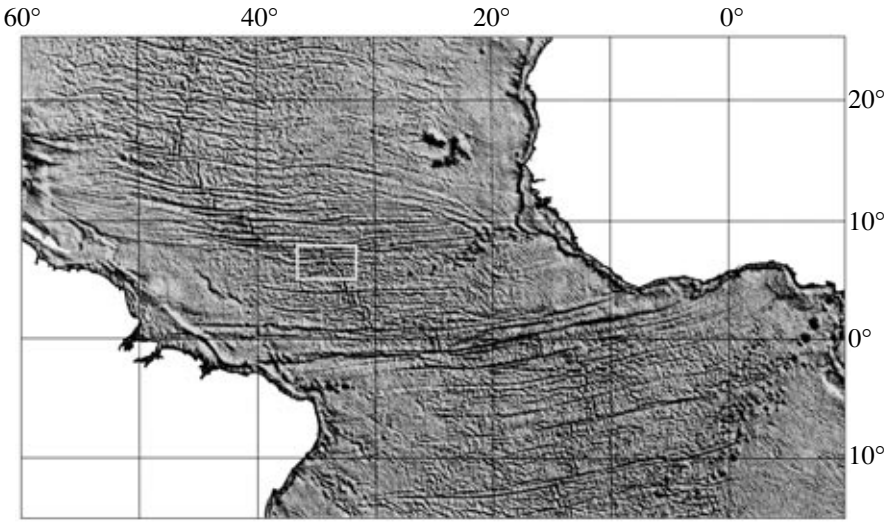

Fig. 1. Map showing position of the study area in structures of the oceanic floor of the Central Atlantic. Based on satellite altimetry data [6].

showed insignificant contamination by seawater Sr. The $^{87}Sr/^{86}Sr$ values in the initial material and residue were similar within analytical error.

Isotope ratios were determined on a Micromass Sector 54 (England) multichannel mass spectrometer at the Laboratory of Isotope Geochemistry and Geochronology of the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry (Moscow). The Rb, Sm, and Nd isotopic measurements were carried out on triple filament, while Sr was loaded on a single filament. The concentrations of elements and values of $^{87}Rb/^{86}Sr$ and $^{147}Sm/^{144}Nd$ ratios were determined by isotope dilution with ^{85}Rb–^{84}Sr and ^{149}Sm–^{150}Nd spikes added to the samples before the chemical decomposition. The fractions of elements were separated using the technique described in [9]. Errors in isotope analysis are given in the note to the table.

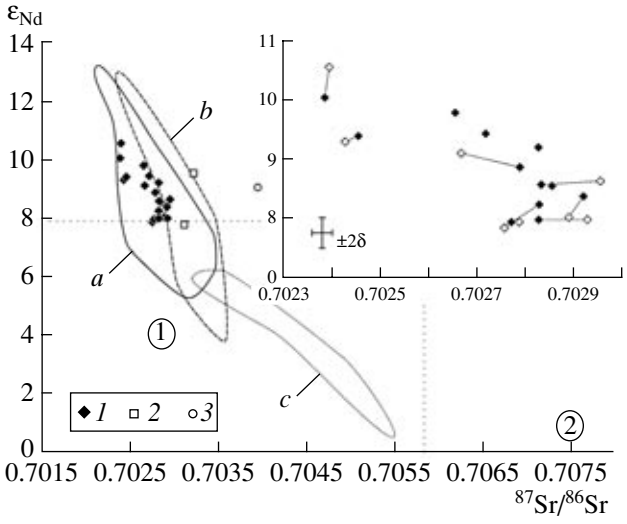

Fig. 2. $^{87}Sr/^{86}Sr$–ε_{Nd} correlation diagram for the studied basalts and their glasses dredged on the Sierra Leone test site, Mid-Atlantic Ridge, 5°–7° N. (*1*) Basalts and their glasses (open symbols in the inset), (*2*) gabbroids, (*3*) trondhjemite; dashed lines show the position of data points of metasomatite formed after gabbro; encircled numbers designate hypothetical sources: (*1*) HIMU, (2) EM2; contours: (*a*) MAR basalts between 3 and 46° S [10], (*b*) MAR basalts between 30° and 50° N [11], (*c*) basalts of Sao Migel and Azores islands [12].

The results are demonstrated in the table and Fig. 2. In terms of isotope characteristics, the studied basalts of the Sierra Leone test site are plotted in the MORB field of the Southern Hemisphere. They occupy an intermediate position between the most depleted basalts ($^{87}Sr/^{86}Sr < 0.7025$, $\varepsilon_{Nd} > 12$) and high-latitude basalts ($^{87}Sr/^{86}Sr > 0.7030$, $\varepsilon_{Nd} < 8$). No signs of isotopic similarity to oceanic island basalts are observed. It is seen in the Sr–Nd diagram (Fig. 2) that isotope variations within the comparatively small test site (less than 2° in the sublongitudinal direction) are comparable with the variations along segments of MAR 15–20 times longer.

In general, the data points of basalts and their glasses define a single trend extended along mantle array in the Sr–Nd diagram. However, two pairs of basalt–glass data points (samples I1003/11 and I1052/38) are plotted well apart from main cluster, with a gap in $^{87}Sr/^{86}Sr$ ratio exceeding the analytical error by several times (Fig. 2, inset). In terms of petrogarphy and geochemistry, these basalts show no significant differences and represent typical MOR tholeiites, probably because the studied collection does not include rocks with intermediate isotope characteristics as a result of random sampling.

Results of study of Rb–Sr and Sm–Nd isotope systems in basalts, their glasses, and underlying holocrystalline rocks dredged from the Markov Deep, Sierra Leone test site, Mid-Atlantic Ridge, 5°–7°S

Sample no.	Rock[1]	Rb	Sr	$^{87}Rb/^{86}Sr$[2]	$^{87}Sr/^{86}Sr$[3]	Nd	Sm	$^{147}Sm/^{144}Nd$[4]	$^{143}Nd/^{144}Nd$[5]	ε_{Nd}[6]
		μg/g				μg/g				
I1003/11	Glass (b)	1.6	173	0.0273	0.70239	17.2	5.3	0.1874	0.513177	10.5
	Basalt	0.87	175	0.0144	0.70238	17.2	5.3	0.1877	0.513151	10.0
I1011/1	Glass (br)	1.6	127	0.0373	0.70270	–	–	–	–	–
I1016/5	Glass (b)	2.6	144	0.0513	0.70269	–	–	–	–	–
	Basalt	1.6	148	0.0314	0.70265	8.3	2.9	0.2079	0.513138	9.8
I1026/21	Basalt	3.4	176	0.0566	0.70271	6.0	2.2	0.2216	0.513120	9.4
I1026/3	Basalt	4.3	116	0.1073	0.70282	10.5	3.6	0.2084	0.513108	9.2
	Glass (b)	2.8	116	0.0686	0.70279	–	–	–	–	–
I1027/5	Glass (bg)	1.9	131	0.0424	0.70266	11.6	3.9	0.2006	0.513103	9.1
	Basalt	6.9	130	0.1518	0.70278	9.3	3.2	0.2100	0.513091	8.8
I1030/1	Glass (br)	1.9	157	0.0355	0.70274	–	–	–	–	–
	Basalt	2.7	120	0.0651	0.70284	8.3	2.9	0.2115	0.513075	8.5
I1031/1	Glass (bg)	1.8	118	0.0447	0.70288	10.2	3.3	0.1972	0.513048	8.0
	Basalt	2.0	119	0.0475	0.70291	9.6	3.2	0.2004	0.513066	8.3
I1036/4	Glass (br)	4.3	178	0.0695	0.70275	11.1	3.3	0.1818	0.513039	7.8
	Basalt	4.2	183	0.0668	0.70282	10.5	3.3	0.1868	0.513059	8.2
I1037/2	Glass (b)	4.1	150	0.0780	0.70278	12.9	4.0	0.1893	0.513044	7.9
	Basalt	5.5	155	0.1019	0.70276	10.1	3.3	0.1953	0.513044	7.9
I1052/38	Glass (b)	0.40	143	0.0082	0.70242	9.1	3.2	0.2134	0.513113	9.3
	Basalt	0.70	208	0.0097	0.70245	9.0	3.2	0.2120	0.513118	9.4
I1069/1	Glass (b)	2.6	119	0.0638	0.70286	–	–	–	–	–
	Glass (bg)	2.6	119	0.0641	0.70292	16.0	5.2	0.1956	0.513046	8.0
	Basalt	3.2	128	0.0725	0.70282	8.4	3.0	0.2165	0.513046	8.0
I1072/1	Glass (bg)	3.1	101	0.0880	0.70294	7.9	2.7	0.2050	0.513079	8.6
	Basalt	1.5	157	0.0283	0.70282	9.2	3.2	0.2080	0.513076	8.5
I1060/57	Trondhjemite	2.4	68	0.1020	0.70393	45	11	0.1480	0.513100	9.0
I1068/27	Leucotroctolite	1.6	126	0.0378	0.70311	28	8.9	0.1940	0.513035	7.7
I1069/107	Metasomatite	0.74	205	0.0105	0.70580	0.3	0.1	0.1691	0.513043	7.9
I1069/35	Gabbronorite	5.2	83	0.1801	0.70321	9.2	3.1	0.2040	0.513125	9.5

Note: ([1]) Parenthesized letters denote characteristics of glasses: (b) black, (bg) black with gray disseminations, (g) gray, (br) brown; ([2]) error is no more than ±1% ($2\sigma_{av}$); ([3]) error is no more than ±0.002% ($2\sigma_{single}$) based on replicate measurements of isotope standard SRM-987 ($^{87}Sr/^{86}Sr = 0.710247 \pm 14$); ([4]) error is no more than ±0.2% ($2\sigma_{single}$) based on replicate measurements in BCR-1standard and replicate analyses of samples; ([5]) error is ±0.0015% ($2\sigma_{single}$) based on replicate measurements of laboratory standard Nd_2O_3 ($^{143}Nd/^{144}Nd = 0.512407 \pm 8$); ([6]) values were calculated relative to uniform chondrite reservoir with $^{143}Nd/^{144}Nd = 0.512638$. (–) Not analyzed.

Comparison of the obtained data indicates that the volcanic basalts and plutonic rocks of the test site are very similar in ε_{Nd}. However, the plutonic rocks have a higher $^{87}Sr/^{86}Sr$ ratio. The highest values of this parameter are recorded in metasomatite, while trondhjemite occupies an intermediate position between the metasomatite and gabbroids.

In some cases, the obtained isotope data on basalts and chilled glasses significantly differ. The differences in ε_{Nd} are overlapped by analytical error, but the discrepancy in Sr can be significant (Fig. 2, inset). In addition, the scale of this heterogeneity in individual samples is comparable with the scatter over the entire test site. No common regularity was found in the distribution of Sr isotopes between basalts and coexisting chilled glasses: high $^{87}Sr/^{86}Sr$ ratios are observed in both glasses and basalts.

The Sr–Nd isotope variations could be caused by different factors: heterogeneity of the basaltic melt source; contamination of the primary melt by wall rocks in the intermediate chambers and channel; or postmagmatic alterations by interaction with seawater. One of these factors or their combination could lead to the isotope heterogeneity of basalts within the Sierra Leone test site.

The analyzed basalts, their glasses, and holocrystalline rocks of the third layer (except metasomatite) bear no evidence of postmagmatic alteration [8]. Hence, this factor can be ruled out as the cause of isotope heterogeneity of the samples. The surface contamination of the rocks by seawater Sr is also excluded, because all samples were specially treated before isotope analysis. The contamination of basaltic magma by seawater during outpouring onto the ocean floor is also hardly possible, because this process should produce a systematic and unioriented shift in the $^{87}Sr/^{86}Sr$ ratio. No seawater was found in fluid inclusions in the chilled glasses of MAR basalts [13], indirectly confirming the conclusion based on isotope data.

The irregular variations in the $^{87}Sr/^{86}Sr$ ratio in the basalt–glass system could be explained by irregular contamination of basaltic melt by rocks on the walls of intermediate chamber and conduits immediately before eruption. The rapid eruption of unevenly contaminated magma could prevent its homogenization with respect to the Sr isotopic composition. This mechanism could explain the absence of regularities in the distribution of Sr isotopes between glass and basalt, because any part of the lava flow could be chilled during effusion onto the seafloor.

Dissolved xenocrysts of plagioclase compositionally similar to those of gabbroids from the test site were found in both basalts and glasses of the analyzed samples. This indicates that basaltic melt entrained and assimilated the older gabbroids of the third layer of the oceanic crust [14] and, possibly, metasomatic rocks and scarce trondhjemites. As compared to basalts, all these rocks have higher $^{87}Sr/^{86}Sr$ values and similar ε_{Nd} values. The assimilation of such a contaminant must lead to irregular variations in the $^{87}Sr/^{86}Sr$ value, with no change in the ε_{Nd} value.

Heterogeneous contamination of basaltic melt immediately before effusion onto the seafloor cannot provide the correlation observed between ε_{Nd} and $^{87}Sr/^{86}Sr$ in the studied basalts. The local petrogenetic processes, which mainly affect the Sr isotopic composition, only partially disturb but do not obliterate this correlation. Evidently, the isotopic heterogeneity existed in the basaltic melts before the contamination, which preceded eruption. Two hypotheses can be proposed to explain this heterogeneity: (i) the primary homogeneous melt was contaminated at a great depth by material with distinct ε_{Nd} and $^{87}Sr/^{86}Sr$ values; (ii) the source of primary melt was isotopically heterogeneous.

Taking into consideration the high petrographic and geochemical homogeneity of basalts [8], the second assumption seems to be more realistic.

It should be noted in conclusion that the scatter in $^{87}Sr/^{86}Sr$ and ε_{Nd} values in basalts from the Sierra Leone test site is comparable with the Sr–Nd isotope heterogeneity in MAR segments 15–20 times longer.

Based on the isotope study of the rocks of Sierra Leone test site, we can draw two conclusions concerning the nature of this heterogeneity:

(1) Small-scale nonsystematic differences detected in Sr isotopic composition between unaltered basalts and their chilled glasses are related to the contamination of basaltic melt by a material with higher $^{87}Sr/^{86}Sr$ values and incomplete mixing of rapidly ascending contaminated melt before effusion on the oceanic floor. The most possible contaminants of the basaltic melt are gabbroids of the third layer of the oceanic crust.

(2) Local petrogenetic processes cannot completely explain the observed correlation between ε_{Nd} and $^{87}Sr/^{87}Sr$ in the studied basalts. Therefore, we are forced to conclude that the basaltic melt was generated from an isotopically heterogeneous source. The possibility of correlated Sr–Nd isotope variations in basalts owing to the contamination of primary homogeneous melt by deep-seated rocks seems to be less probable.

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