Composition of Magmatic Melts from the Southern Baikal Volcanic Region: A Study of Inclusions in Olivine from Trachybasalts

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First evidence was obtained on the composition of melt and fluid inclusions in olivine phenocrysts from the trachybasalt of the southern Baikal volcanic region (eastern Tuva lava highland) (Fig1). Inclusions were studied in minerals from the trachybasalts of Kadyr-sug (sample Kd-1) and Sagan volcanoes (sample Be-1) and a lava flow of the protovalley of the B. Yenisei River (sample Be-2). The lavas contain porphyritic grains of olivine and, more rarely, pyroxene. The size of the phenocrysts varies from 1 to 3 mm. The groundmass is usually completely crystallized and consists of plagioclase microlites, small grains of pyroxene, olivine, and opaque minerals, sulfide globules, and apatite needles. Minerals were analyzed on a Camebax Microbeam electron microprobe. The chemical compositions of these rocks and minerals are given in Table 1.

Melt inclusions were studied by the methods of homogenization with subsequent analysis by electron and ion microprobes. Amphibole with high TiO_2 content (up to 9.8 wt %) and clinopyroxene with low SiO_2 (42.3–43.5 wt %) and high Al_2O_3 (12.3–13.4wt %), TiO_2 (4.3–5.1 wt %), and P_2O_5 (up to 0.8 wt %) were detected among the daughter crystals of the melt inclusions (Fig 2, Table 2). The glasses of melt inclusions on the surface were analyzed on a Camebax Microbeam electron Microprobe. The homogenized glasses (16 analyses, Table 3) show small variations in SiO_2 (46.8–50.8 wt %), TiO_2 (2.1–3.6 wt %), MgO (6.3–9.8 wt %), and CaO (6.7–9.4 wt %) and high contents of alkalis (3.1–5.8 wt % Na_2O and 1.8–2.5 wt % K_2O) and P_2O_5 (0.44–0.95 wt %).

The average concentrations of volatiles in the basaltic melts analyzed are (wt %) 0.46 H_2O, 0.09 S, 0.07 F, and 0.04 Cl. Using CO_2 fluid inclusions, the minimum pressure values were estimated for the crystallization of the olivine phenocrysts as 4.6–5.0 kbar, which corresponds to depths of 16.5–18.0 km. The calculation of the minimum CO_2 content in the alkali basalt melt yields a high value of 1.13 to 0.14 wt %.

Trace elements and water were analyzed on an IMS-4f ion microprobe in the Institute of Microelectronics, Russian Academy of Sciences (Yaroslavl, Russia).

The ion microprobe analysis of 17 trace elements in the glasses of melt inclusions (Table 4) demonstrated significant incompatible element enrichment in the magmas of the Baikal rift. The analysis of a great number of trace elements in the melt inclusions allowed us to characterize in detail the geochemistry of the primitive melts of the Baikal rift and constrain a number of specific features of their source. The melts show an increase in the normalized content of trace elements with increasing degree of incompatibility in the processes of mantle melting (Fig. 3). The normalized ratio [La/Yb]N of the melts is close to 10. The highest enrichment relative to the primitive mantle composition was obtained for K and Nb (60–80). In contrast, the normalized contents of other highly incompatible elements (Th, B, and, to a lesser degree, Ba) are somewhat low relative to Nb and K. An intriguing feature of the Baikal rift melts is high [Ba/Th]N = 2.1–2.3, [K/La]N = 2.1–2.2, [Nb/La]N = 1.9–2.1, [Sr/Ce]N = 1.2–1.3, and [P/Zr]N = 1.7–2.2. This can be described in general as a selective enrichment of the melts in Ba, K, Nb, Sr, and P relative to Th and

REE. These element ratios practically do not fractionate in the processes of mantle melting [2] and crystal fractionation of mafic magmas. Consequently, their departure from typical mantle values can be regarded as evidence for either a specific composition of the mantle source or magma contamination by unusual rocks.

The detailed evaluation of the composition and nature of the metasomatic component in the magma source region of the Baikal rift is beyond the scope of this paper. Nonetheless, it can be noted that a number of parameters (high Ba/Th and Sr/Ce) suggest that this component is similar to the high-Sr component of the lavas of Mauna Loa Volcano, Hawaii [4]. It was interpreted [4] as a recycled crustal gabbroid component entrained into the mantle source. Thus, the presence of recycled material in the source of the Baikal rift magmas also cannot be excluded.

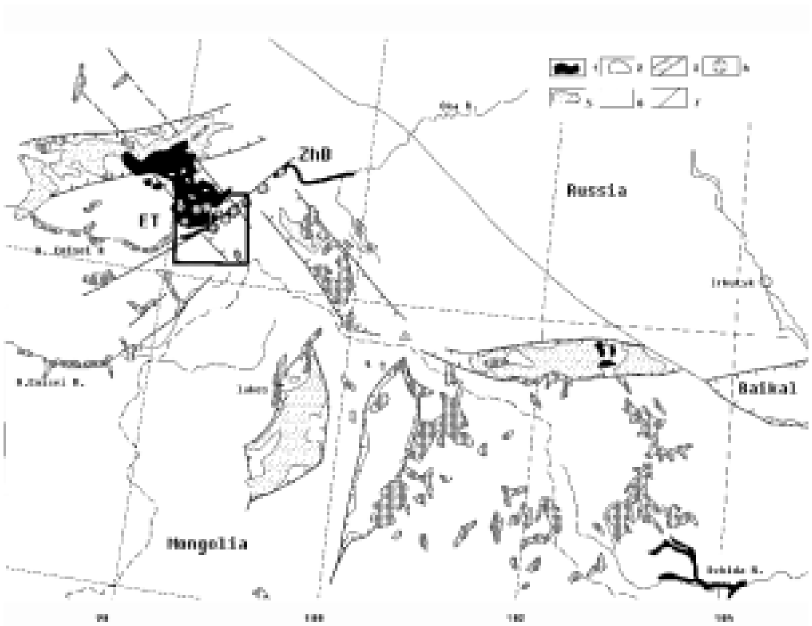

Figure 1. Schematic structure of the Late Cenozoic southern Baikal volcanic region after [22]. (*1*)–(*2*) Basalt fields (*1*—late Pliocene–Holocene and *2*—pre-late Pliocene); (*3*) graben; (*4*) volcano of the Tuva volcanic area; (*5*) Late Cenozoic terrigenous sequences; (*6*) amagmatic domains; and (*7*) fault. Volcanic fields: ET, eastern Tuva; OG, Oka graben; and ZhB, Zhom-Bolok.

Table 1. Chemical compositions of the trachybasalts of the southern Baikal volcanic region and minerals of these rocks, wt %

Component	1 sample Kd-1	2 sample Be-1	3 sample Be-2	4 Be-1	5 Be-2	6 Kd-1	7 Be-1	8 Be-2	9 Be-2	10 Kd-1	11 Kd-1
SiO_2	48.80	45.45	47.42	39.94	35.28	40.35	48.47	47.20	52.28	51.17	52.4
TiO_2	2.37	1.98	2.63	-	-	-	2.60	4.00	1.56	2.26	1.76
Al_2O_3	15.35	13.02	14.76	-	-	-	7.01	5.80	3.14	2.97	3.08
FeO	10.28	11.56	11.43	15.26	43.56	15.81	6.42	11.37	7.48	9.52	8.07
MnO	0.14	0.17	0.15	0.15	0.59	0.23	0.06	0.12	0.07	0.13	0.12
MgO	7.50	13.44	7.40	44.19	20.04	43.51	13.04	10.68	14.32	13.45	13.32
CaO	8.42	7.96	8.68	0.24	0.48	0.25	21.73	20.33	20.96	20.30	20.72

Component	1 sample Kd-1	2 sample Be-1	3 sample Be-2	4 Be-1	5 Be-2	6 Kd-1	7 Be-1	8 Be-2	9 Be-2	10 Kd-1	11 Kd-1
Na_2O	3.96	3.32	3.59	-	-	-	0.49	0.63	0.49	0.55	0.66
K_2O	1.89	1.80	1.88	-	-	-	0.00	0.01	0.00	0.01	0.05
P_2O_5	0.57	0.50	0.52	-	-	-	-	-	-	-	-
Cr_2O_3	-	-	-	–	0.02	–	0.48	0.00	0.28	0.04	0.02
NiO	-	-	-	0.11	–	0.15	-	-	-	-	-
Total	99.28	99.20	98.46	99.89	99.97	100.30	100.30	100.14	100.58	100.40	100.22
Fo	-	-	-	84	45	83	-	-	-	-	-
Fs	-	-	-	-	-	-	11.2	20.1	12.5	16.0	13.8
En	-	-	-	-	-	-	40.4	33.7	42.6	40.3	40.7
Wo	-	-	-	-	-	-	48.4	46.1	44.9	43.7	45.5

Note: 1-3 - rocks, 4-6 - olivine phenocrysts from trachybasalts, 7-11 - clinopyroxene

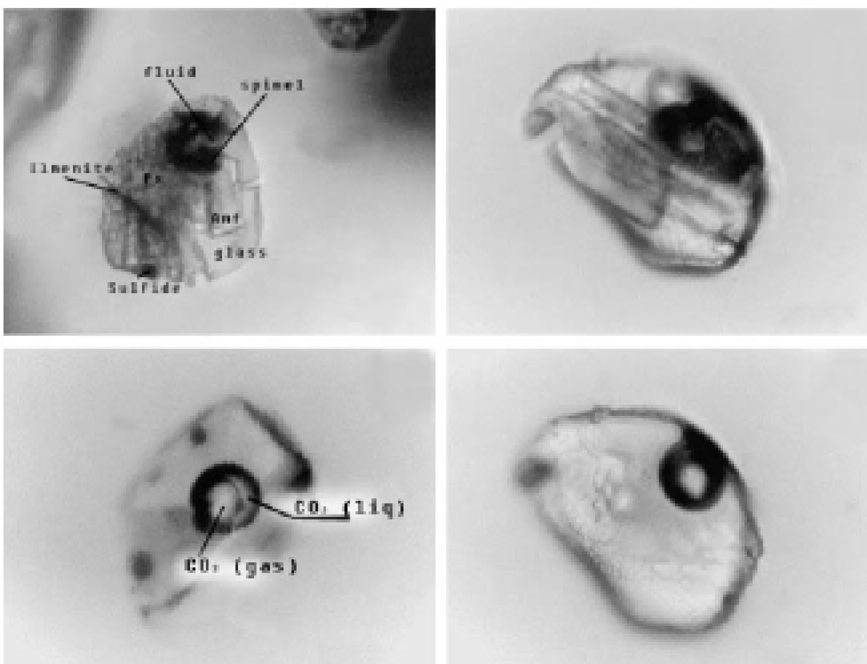

Figure 2. Melt inclusions in olivine from the trachybasalts. Scale bars are 25 ∝m. (a) Partially crystallized inclusion from sample Kd-1; (b) partially crystallized inclusion from sample Be-1 with a CO_2 fluid phase, which is homogenized into gas at 30.2°C; (c) partially crystallized inclusion from sample Be-2 at 20°C; and (d) the same inclusion quenched after heating up to 1200°C.

Table 2. Chemical compositions of daughter crystals and residual glass from melt inclusions in olivine from trachybasalts, wt %

Component	1	2	3	4	5	6	7	8
SiO_2	43.53	42.58	42.29	39.42	0.91	0.54	63.58	71.38
TiO_2	5.06	4.34	5.16	9.57	2.84	50.79	0.26	0.07
Al_2O_3	12.28	12.63	12.48	14.06	39.68	0.32	20.93	20.97
FeO	6.35	6.25	6.15	8.92	23.19	43.01	0.98	0.88
MnO	0.13	0.22	0.19	0.08	0.11	0.32	0.13	0.06
MgO	11.08	10.03	10.4	11.50	14.72	2.17	0.36	0.29
CaO	21.03	22.21	21.26	11.65	0.11	0.16	1.19	0.27
Na_2O	0.86	0.78	0.81	2.62	0.06	0.07	8.17	2.64
K_2O	0.08	0.07	0.06	0.57	0.02	0.06	3.87	3.03
P_2O_5	0.09	0.78	0.49	0.21	0.02	0.00	1.00	0.30
Cr_2O_3	-	-	-	-	17.63	-	-	-
Cl	0.00	0.00	0.01	0.00	0.01	0.02	0.06	0.05
F	-	-	-	0.14	-	-	0.00	0.00
Total	100.49	99.89	99.30	98.74	99.30	97.46	100.53	99.94

Note: 1,2 - pyroxene; 3, 4 - amphibole; 5 - spinel; 6 - ilmenite; and 7,8 - residual glass.

Table 3. Chemical compositions of glasses of melt inclusions in olivine from trachybasalts, wt %

	1, Kd-1	2, Kd-1	3, Kd-1	4, Be-1	5, Be-1	6, Be-1	7, Be-1	8, Be-2	9, Be-2	10, Be-2	11
SiO_2	49.79	50.28	50.78	46.79	49.08	50.15	50.61	47.84	49.08	49.67	49.47
TiO_2	2.43	2.57	2.31	3.58	2.57	2.53	2.52	2.91	2.26	2.42	2.57
Al_2O_3	15.35	16.83	16.28	16.85	15.96	18.68	13.87	15.52	17.35	17.04	16.54
FeO	7.86	6.82	7.07	7.79	7.29	5.40	9.46	7.81	9.58	9.01	7.75
MnO	0.14	0.09	0.09	0.14	0.08	0.06	0.14	0.11	0.15	0.13	0.12
MgO	8.54	7.89	7.48	7.59	7.99	6.32	9.75	7.33	6.96	7.03	7.49
CaO	9.35	6.69	6.73	8.61	8.50	8.27	8.54	7.73	6.92	7.59	8.01
Na_2O	4.65	5.83	5.29	4.82	4.63	5.08	3.09	5.40	5.06	4.64	4.84
K_2O	2.12	2.18	2.01	2.12	2.18	2.49	1.81	1.96	1.85	1.88	2.10
P_2O_5	0.65	0.58	0.76	0.95	0.92	0.81	0.44	0.63	0.75	0.56	0.73
Cl	0.02	0.03	0.05	0.03	0.03	0.06	0.00	0.02	0.04	0.02	0.04
S	0.07	0.03	0.05	0.11	0.16	0.04	0.14	0.05	0.10	0.10	0.09
Total	100.97	99.82	98.90	99.38	99.39	99.89	100.37	97.31	100.10	100.09	99.75
T, °C	1245	1240	1255	1190	1230	1175	1270	1225	1200	1200	–
Fo	84	83	81	83	84	84	84	77	81	81	–
Mg#	66	67	65	63	66	68	65	62	56	58	–

Note: 1–10 - analyses of glasses from inclusions; 11 - average of 16 analyses (together with three analyses from Table 8). *Mg#* = Mg/(Mg + Fe).

Table 4. Concentrations of major, volatile, and trace elements in the homogeneous glasses of melt inclusions in olivine from the trachybasalts.

Component	Be-1, wt%	Be-1, wt%	Be-2, wt%	Component	Be- 1, ppm	Be- 1, ppm	Be- 1, ppm
SiO_2	48.79	49.61	50.78	F	731	578	663
TiO_2	2.71	2.68	2.55	Li	7.3	6.5	11.8
Al_2O_3	18.95	16.57	15.58	B	3.64	4.25	2.40
FeO	6.05	6.74	7.92	Be	1.98	1.67	1.60
MnO	0.09	0.03	0.14	Zr	187	176	177
MgO	6.31	6.99	7.16	Y	18.0	19.3	16.1
CaO	8.73	9.41	6.84	Nb	48.9	37.4	38.7
Na_2O	5.48	4.70	5.66	Th	1.95	1.44	1.61
K_2O	2.35	2.01	2.16	Sr	817	655	646
P_2O_5	0.77	0.81	0.84	Ba	361	278	277
Cl	0.03	0.04	0.06	La	22.8	19.4	19.7
F	0.07	0.06	0.07	Ce	52.0	43.6	46.7
S	0.07	0.10	0.05	Nd	26.3	22.3	24.0
H_2O	0.47	0.45	–	Sm	7.51	5.66	6.20
Total	100.87	100.20	99.81	Eu	2.11	1.28	1.81
T,	°C	1210	1190	1225	Dy	3.84	3.84
Fo	84	84	77	Er	2.00	2.02	1.72
Yb	1.43	1.63	1.42				

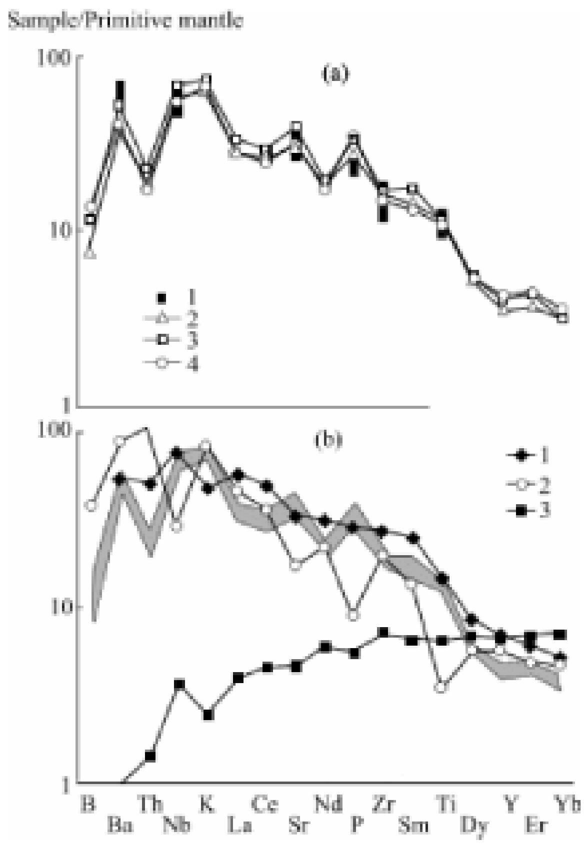

Figure 3. Diagrams showing concentrations of trace elements. (a) Concentrations of trace elements in the (*1*) trachybasalts of the Baikal rift studied and (*2–4*) melt inclusions in olivine from these rocks normalized to the composition of the primitive mantle after [1]. Arrows show the elements that show selective enrichment relative to the elements with similar degrees of incompatibility. Samples: (*2*) Be-2 and (*3*) and (*4*) Be-1. (b) Comparison of the compositions of the primitive melts of the Baikal rift with the average compositions of oceanic island basalts (*1*, after [2]), continental crust (*2*, after [3]), and oceanic rifts (*3*, after [2]).

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