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GEOCHEMISTRY

Physicochemical Parameters of the Oldest Boninite Melts

V. A. Simonov[a], Corresponding Member of the RAS E. V. Sklyarov[b], S. V. Kovyazin[a], and V. I. Perelyaev[b]

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Ophiolites of the southeastern Sayan region, the oldest formations in Central Asia (1020 Ma [1]), include unique information on early stages of Paleoasian Ocean evolution. The presence of boninites in the ophiolites indicates that a suprasubduction environment similar to that of the present-day Pacific island-arc systems existed as early as 1 Ga ago. Therefore, investigations of magmatic systems responsible for the formation of such ancient rock complexes are of great scientific interest. In order to elucidate physicochemical parameters of boninite melts of the southeastern Sayan region, we examined melt inclusions in chrome spinels of boninite samples from rock complexes of the "dike-in-dike" type in the Dunzhugursk sector.

We are not able to check the inclusions in the course of heating, because the studied chrome spinels are virtually transparent. Therefore, we developed a special experimental method and designed a microchamber based on a silite heater. The high-temperature experiments were carried out in accordance with the methods of melt inclusion studies [2, 3]. Inclusions detected by the microscopic examination in reflected light were analyzed with a Camebax-Micro microprobe at the United Institute of Geology, Geophysics, and Mineralogy (Novosibirsk). Contents of rare elements (RE), rare earth elements (REE), and water in melt inclusions were determined by secondary ion mass spectrometry using an IMS-4f microprobe at the Institute of Microelectronics of the Russian Academy of Sciences (Yaroslavl), according to the method reported in [4].

Primary melt inclusions (15–50 μm) are uniformly distributed in the chrome spinel grain. Round equilibrium inclusions often show negative faceting and are mainly composed of glass with round gaseous bubbles. Pure homogeneous sectors of the inclusions burn away under the laser beam suggesting their glassy state. Table 1 presents the compositions of glass in heated melt inclusions in boninite-hosted chrome spinels from the southeastern Sayan region.

In terms of the SiO_2 content, the studied homogeneous inclusions make up a series ranging from basalts and basaltic andesites to andesites. This is consistent with data on dikes and volcanics of the Dunzhugursk sector. In the $MgO–SiO_2$ diagram (Fig. 1), data points of chromite-hosted melt inclusions from the eastern

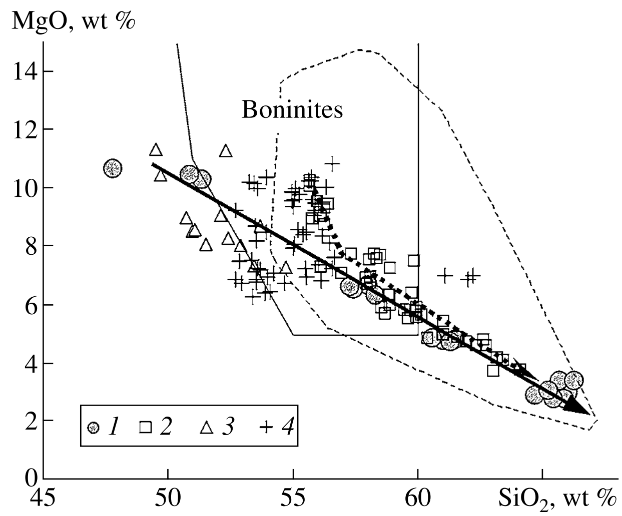

Fig. 1. The $MgO–SiO_2$ diagram for glass from heated melt inclusions in boninite-hosted minerals. (*1–4*) Melt inclusions in (*1*) chrome spinels from ophiolites of the southeastern Sayan region, (*2*) pyroxenes of the Idzu–Bonin island arc, (*3*) pyroxenes from ophiolites of the Gornyi Altai region, and (*4*) pyroxenes from ophiolites of the Dzhida zone. (Boninites) Field of boninites from island arcs of the western Pacific. Dashed line shows the compositional field of dikes and volcanics of the Dunzhugursk sector (ophiolites of the eastern Sayan region). Solid and dotted lines show trends of inclusions in the eastern Sayan region and the Idzu–Bonin island arc, respectively. The diagram is based on original data supplemented with data from [5–7].

[a] *Institute of Geology, Siberian Division, Russian Academy of Sciences, pr. akademika Koptyuga 3, Novosibirsk, 630090 Russia; e-mail: simonov@uiggm.nsc.ru*

[b] *Institute of the Earth's Crust, Siberian Division, Russian Academy of Sciences, ul. Lermontova 128, Irkutsk, 664033 Russia; e-mail: skl@crust.irk.ru*

Table 1. Analyses of glass from heated melt inclusions in boninite-hosted chrome spinels from the southeastern Sayan region, wt %

Analysis no.	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total
50*	65.29	0.13	11.11	0.95	5.95	0.06	3.06	5.99	0.66	0.80	94.01
51	65.48	0.13	11.14	0.60	6.06	0.06	2.93	6.07	0.61	0.83	93.91
52	66.01	0.15	11.26	0.82	6.07	0.04	2.99	6.08	0.62	0.77	94.81
54	65.88	0.14	11.20	1.02	5.58	0.07	2.78	6.14	0.67	0.83	94.31
54-1	65.41	0.11	11.11	0.86	5.73	0.06	2.79	5.96	0.68	0.79	93.50
55	61.02	0.25	13.62	0.54	8.70	0.11	4.81	7.65	1.07	0.07	97.83
56	61.50	0.23	13.98	0.72	8.39	0.10	4.83	7.67	1.05	0.08	98.56
57	61.30	0.25	13.79	0.96	8.35	0.15	4.77	7.68	0.97	0.08	98.28
59	60.58	0.24	13.70	0.84	8.93	0.12	4.89	7.88	1.05	0.07	98.30
65	65.67	0.16	10.10	0.95	6.14	0.06	3.42	6.24	0.61	0.53	93.88
66	66.24	0.15	10.03	0.83	6.19	0.02	3.43	6.34	0.54	0.49	94.27
71	58.01	0.18	14.23	0.68	11.09	0.15	6.66	7.35	0.18	0.05	98.59
72	57.44	0.20	14.07	0.65	11.09	0.20	6.54	7.41	0.15	0.05	97.80
73*	57.28	0.18	14.15	0.64	11.35	0.14	6.61	7.38	0.15	0.04	97.91
74	58.28	0.18	14.09	0.80	10.52	0.14	6.32	7.42	0.17	0.04	97.97
78	47.84	0.22	13.44	0.44	14.83	0.19	10.67	6.55	0.17	0.02	94.37
79*	51.40	0.20	14.23	0.49	14.40	0.19	10.30	6.62	0.17	0.04	98.03
80	50.90	0.21	14.17	0.61	14.37	0.20	10.45	6.74	0.16	0.03	97.84

Note: (*) Inclusions with RE and REE contents determined by the SIMS method.

Sayan region show a decreasing trend in the MgO content (from 10.5 to 2.8 wt %) and a simultaneous increase in the SiO_2 content (from 48–51 to 65–66 wt %) in the boninite field of the island-arc systems of the western Pacific. This trend is consistent with the data on SiO_2 accumulation and simultaneous compositional variations in melt inclusions from boninites of the Gornyi Altai–Dzhida (Mongolia) and Idzu–Bonin island-arc (Pacific) regions. Starting with the SiO_2 and MgO contents of 57.3 and 6.6 wt %, respectively, trends of melt inclusions in the boninite-hosted minerals from the Idzu–Bonin island arc are virtually similar to their counterparts in the ophiolite-hosted chrome spinels from the eastern Sayan region. Melt inclusions from the Idzu–Bonin island-arc and eastern Sayan regions are similarly depleted in Ca, relative to the high-Ca boninite melts of the Gornyi Altai and Dzhida regions. Melt inclusions in chrome spinels of the southeastern Sayan region are characterized by moderate K contents. This is consistent with the data on other boninite series. Therefore, the melt inclusions from the southeastern Sayan region can be divided into low-K (trend **I**) and high-K (trend **II**) series. The first trend shows the evolution from boninites to island-arc tholeiites, whereas the second trend reflects the evolution from boninites to tholeiites and calc-alkaline series (Fig. 2). Thus, magmatic systems of ophiolites of the southeastern Sayan and Dzhida regions show similar evolution patterns, indicating the possibility of simultaneous development of two magma types [7]. In terms of the Ti/K ratio, melt inclusions in chrome spinels from the eastern Sayan region are similar to their counterparts in boninites from island-arc systems of the western Pacific and to melt inclusions in minerals from other boninites in the Idzu–Bonin island-arc, Gornyi Altai, and Dzhida regions.

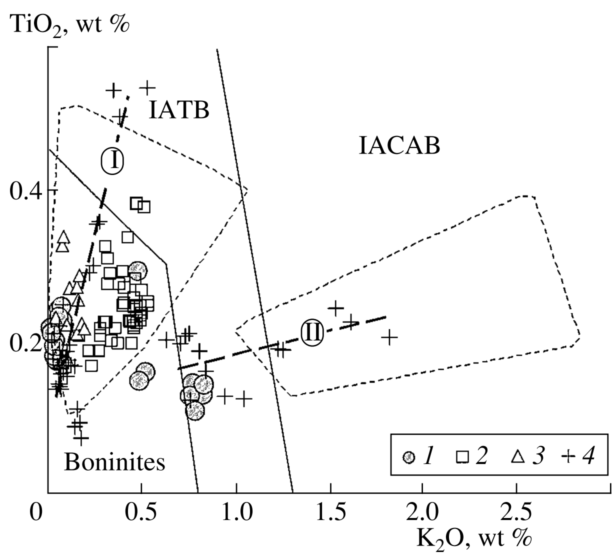

Fig. 2. The TiO_2–K_2O diagram for glass from heated melt inclusions in boninite-hosted minerals. Fields: (Boninites) field of boninites from island arcs of the western Pacific, (IATB) island-arc tholeiitic basalt, (IACAB) island-arc calc-alkaline basalt. Trends of pyroxene-hosted inclusions in boninites from ophiolites of the Dzhida zone: (**I**) low-K and high-Ti inclusions, (**II**) high-K inclusions. See Fig. 1 for other designations.

In contrast to inclusions in boninite-hosted minerals of the Dzhida and Gornyi Altai regions, melt inclusions in chrome spinels of the eastern Sayan region are enriched in Fe (FeO/MgO = 1.4–2.1). This is consistent with data on the boninite-hosted inclusions from the Idzu–Bonin island arc (FeO/MgO up to 1.8) and the composition of dikes and volcanics in the Dunzhugursk sector (FeO/MgO up to 2.3–3 in some areas). Thus, the high Fe content in inclusions in chrome spinels is probably an indicator of natural properties of the old boninite melt rather than an accidental phenomenon. Increase in the Fe content in the course of melt evolution was mainly accompanied by the accumulation of alkali metals and SiO_2, on the one hand, and by the loss of Al and Ca, on the other hand. In terms of the high Fe content, boninite melts of the Idzu–Bonin island arc are the closet analogues of the chrome spinel-hosted inclusions.

The SIMS study of melt inclusions made it possible to determine the contents of RE, REE, and water in boninite magmas of ophiolites in the eastern Sayan region (Fig. 2). Comparison with data on rocks of the boninite series suggests the following conclusions. In terms of the ratio of Y and Zr, which are stable in secondary processes, melt inclusions in the boninite-hosted chrome spinels of the eastern Sayan region are located near their counterparts from the Idzu–Bonin and Tonga arcs in the boninite field of the western Pacific.

With respect to the REE distribution, melt inclusions in the chrome spinels can be divided into two types. The first type is observed in the low-K (K_2O ~0.04 wt %) inclusions associated with trend **I** in boninite-hosted minerals of the Dzhida zone (Fig. 2). The U-shaped morphology of this trend is virtually identical with the trend of island-arc boninites in the western Pacific. The second type is observed in the high-K (K_2O 0.8 wt %) inclusions associated with trend **II** of melt inclusions in minerals of the Dzhida zone grading into the calc-alkaline series. Therefore, such inclusions are enriched in LREEs and their distribution pattern is similar to that of the calk-alkaline rocks.

The SIMS study of chrome spinel-hosted melt inclusions showed that boninite melts of the eastern Sayan region are appreciably enriched with water (up to 4.26 wt %). This value is slighter higher than the water content in the boninite-hosted minerals of the Idzu–Bonin island arc (up to 3.9 wt %).

Calculation of liquidus parameters with the PETROLOG software package [8] using the data on melt inclusions in chrome spinels showed that clinopyroxenes and orthopyroxenes from the ophiolite-hosted boninite melts of the eastern Sayan region crystallized at 1120–1250°C. These values match the earlier data [7, 9] on crystallization temperatures of pyroxenes from boninites of the Gornyi Altai (1160–1230°C), Dzhida (1170–1250°C), Han-Taishirin (1170–1220°C), and Idzu–Bonin (1160–1240°C) regions. They are also consistent with the data on pyroxene-hosted inclusions in boninites of the Tonga arc (1150–1220°C) [3, 10].

Table 2. Contents of RE and REE in glass from heated melt inclusions in boninite-hosted chrome spinels from the southeastern Sayan region, ppm

Element	1	2	3
Th	1.19	0.24	0.42
Rb	18.7	13.8	16.7
Ba	212.4	15.5	12.5
Sr	74.7	9.0	5.9
V	972	1351	645
La	6.38	0.81	1.26
Ce	12.53	2.89	3.20
Nd	5.94	1.14	1.77
Sm	1.18	0.28	0.49
Eu	0.37	0.10	0.08
Gd	0.46	0.52	0.46
Dy	0.68	0.45	0.59
Er	0.56	0.43	0.49
Yb	0.64	0.61	0.77
Y	4.15	2.86	3.68
Zr	27.9	22.7	28.0
Nb	2.84	0.78	1.88
Hf	0.83	0.44	0.72
Ta	0.24	0.08	0.12
U	0.58	0.13	0.22

Note: (1–3) Melt inclusions: (1) analysis 50*, (2) analysis 73*, (3) analysis 79* (see Table 1).

We attempted to define conditions of primary magma generation using the simulation method [11] based on the melt inclusion data. The results obtained (temperature 1400–1570°C, pressure 20–35 kbar, and depth 60–105 km) are consistent with the data on other primary melt inclusions in ophiolites of the Gornyi Altai region (1410–1590°C, 21–35 kbar, 65–105 km), ophiolites of the Dzhida zone (1400–1500°C, 10–30 kbar, 30–90 km), and rocks of the Idzu–Bonin island arc (1440–1600°C, 25–37 kbar, 75–105 km). These results are also consistent with the data on primary boninite melts of the Tonga arc [3].

Thus, the investigation of boninites of different ages shows that their melts were generated under similar constraints in the Neoproterozoic and Phanerozoic.

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