Melt inclusions in minerals of allivalites of the Kuril–Kamchatka island arc

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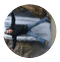

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Melt Inclusions in Minerals of Allivalites of the Kuril–Kamchatka Island Arc

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Abstract—The genesis of low-silica (generally olivine–anorthite) inclusions in volcanic rocks of the low-K tholeiitic island-arc series is a matter of active discussion. The study of melt inclusions in the major minerals of allivalites from three volcanoes of the Kuril–Kamchatka island arc proved the previously suggested genetic affinity between the allivalites and host lavas and the cumulative origin of these rocks. The composition of the parent melt was determined by two independent methods: by calculation and by temperature measurement during experiments. The temperature of coeval crystallization of olivine and plagioclase in allivalites is estimated at 1050–1100°C at an H_2O content of 1.5–2.0 wt % in the parent melt. Similar results were obtained for different volcanoes, which indicates a correspondence of the determined melt composition to the composition of the parent magma of low-K tholeiite for the Kuril–Kamchatka area. According to calculations, the formation of basaltic melt results from the separation of 7–8% of olivine–plagioclase cumulate from the parent magma.

INTRODUCTION

Over the past decades, much attention has been given to the studies of holocrystalline inclusions in various volcanic rocks. Understanding their origin is very important for solving the genetic problems of volcanic associations. This paper is devoted to the origin of low-silica olivine–anorthite (with minor clinopyroxene) inclusions abundant in volcanic rocks of the low-K tholeiitic island-arc series.

Since these inclusions are comprehensively described in the literature, we will characterize them and their host volcanics only briefly and present the main arguments for their close affinity. We studied holocrystalline inclusions and their host rocks from many volcanoes of the Kuril–Kamchatka island arc. The data obtained for Ksudach, Mutnovskii, Zavaritskii, Mendeleev, and Golovin volcanoes (Fig. 1) are discussed in this paper. Inclusions of this type are also found in the rocks of some other volcanoes in the forearc zone (Kikhpinych, Koshelevskii, Kambal'nyi, Malyi Semyachik, Nemo, etc.). The dominant inclusion type transported during the eruptions of these volcanoes are low-silica olivine–anorthite rocks (allivalites) with minor clinopyroxene, whose mineral composition is described in [1]. However, allivalites are associated with higher silica rocks, such as olivine-bearing and olivine-free gabbro and gabbronorites, quartz gabbro, and, rarely, quartz diorites and plagiogranites. This fact points to a differentiated series of holocrystalline rocks, whose fragments are transported as inclusions in lavas. We studied the allivalites more comprehensively, because they are dominant among the inclusions and have the lowest SiO_2 contents.

The allivalites are coarse-grained equigranular (or rarely porphyritic) rocks, locally containing minor interstitial glass. Their modal mineral proportions vary significantly. The rocks have massive, porous, banded, or taxitic structures, which are normally cut by inclusion edges. Therefore, most inclusions were captured in the solid or ductile state. The rocks normally exhibit evidence of brecciation, high-temperature recrystallization, and blastic deformation. Some inclusions are rimmed by fine-grained mineral aggregates and show evidence of partial melting (brown porous transparent glass around relics of melted grains, usually clinopyroxene). Rounded inclusions with a radiating texture similar to orbicules in orbicular gabbro are scarce.

The volcanic rocks hosting the inclusions compose a low-K tholeiite basalt–andesibasalt–andesite–dacite series, which is dominated by basalts and andesibasalts (Table 1). The inclusions are most abundant in dacitic and andesidacitic pyroclastic rocks.

The volcanic rocks of this series are rich in phenocrysts (20–50%), 60–80% of which are plagioclase. Pyroxenes are the most abundant mafic minerals. Olivine occurs in basic rocks, whereas amphibole and biotite (2–3% of the total phenocryst amount) occur in silicic rocks. Basalts and andesibasalts contain phenocrysts of olivine $Fo_{66–75}$, plagioclase $An_{41–81}$, augite $En_{40–42}Fs_{18–22}Wo_{37–39}$, hypersthene $En_{63–68}Fs_{28–33}Wo_{3–4}$, and partially corroded xenocrysts of olivine $Fo_{77–79}$ and plagioclase $An_{90–94}$. Andesites include phenocrysts of olivine $Fo_{70–72}$, plagioclase $An_{50–73}$, clinopyroxene $En_{36–41}Fs_{18–25}Wo_{38–41}$, and orthopyroxene $En_{46–62}Fs_{35–51}Wo_{3–4}$. Andesitic dacites and dacites contain xenocrysts of olivine, phenocrysts of plagioclase with 33–59% anorthite end-member, clinopyroxene $En_{35–37}Fs_{24–26}Wo_{38–39}$, and orthopyroxene $En_{60–62}Fs_{34–36}Wo_{3–4}$. The proportions between clino- and orthopyroxene phenocrysts are highly variable.

We studied allivalite samples from basalts of Mutnovskii, Ksudach, and Golovin volcanoes. The allivalites are massive or taxitic rocks with cumulative and locally hypidiomorphic textures. Allivalites have small amounts of interstitial glass (<10–15%) and are comprised of 60–95% plagioclase ($An_{96–89}$), 5–35% olivine ($Fo_{76–81}$) and minor clinopyroxene. Minor orthopyroxene is found only in allivalite inclusions from Mutnovskii Volcano.

The mineral composition of allivalites is listed in Table 2. Olivine forms euhedral or subhedral equant crystals 0.5–1.5 mm in size. Olivine in the samples is rather uniform in composition and contains 76–81% *Fo*. Plagioclase composes prismatic euhedral or subhedral crystals up to 5 mm in size (1.5–2.0 mm, on the average). The compositions of plagioclase in allivalites from Mutnovskii and Ksudach volcanoes are rather similar ($An_{89–94}$), whereas those from Golovin Volcano are more calcic ($An_{93.4–95}$). The allivalite plagioclases are comparable with early-generation plagioclases in the corresponding host volcanics. The magnesium numbers of ortho- and clinopyroxenes in allivalites from Mutnovskii Volcano range from 82.7–84.6 and 80.4–81.0, respectively. Clinopyroxene is usual in allivalites, whereas orthopyroxene is very rare in such Ca-rich parageneses. The spinellids are magnetite and chromian magnetite with low Al contents.

The composition of the allivalites and host volcanics is presented in Table 1. Allivalites have low SiO_2 (39–45%), alkali (<1%), TiO_2, and P_2O_5 contents, a low iron proportion (*f* = 25–55), and high Al_2O_3 (20–27%) and CaO (up to 14%) contents (Table 1). They represent a series of rocks highly enriched in CaO with a distinct tholeiitic differentiation trend. This trend results from the cotectic crystallization of plagioclase and olivine. Therefore, the compositional diversity of inclusions is probably related to the fractionation of these minerals. The host volcanic rocks are also CaO-rich members of the tholeiitic series and have higher SiO_2, TiO_2, MnO, P_2O_5, and alkali and lower Al_2O_3, MgO, and CaO contents as compared to the allivalites. The trend of enrichment in iron, typical of the inclusions, gives way to a trend of enrichment in alkalis in the volcanic rocks (Fig. 2a), whose depletion in iron is related to the crystallization of Fe–Ti oxides and mafic silicates. Although classified within the same series, the rocks indicate compositional differences in different volcanoes (Figs. 2a–2c). For example, the alkali contents are higher in the rocks from Kamchatka (Ksudach and Mutnovskii volcanoes) than in those of the Kuril Islands (Zavaritskii and Mendeleev volcanoes), and the rocks of Mendeleev Volcano are higher in iron. Allivalites from different volcanoes also vary in their major-element contents due to variable proportions of olivine and plagioclase in the inclusions.

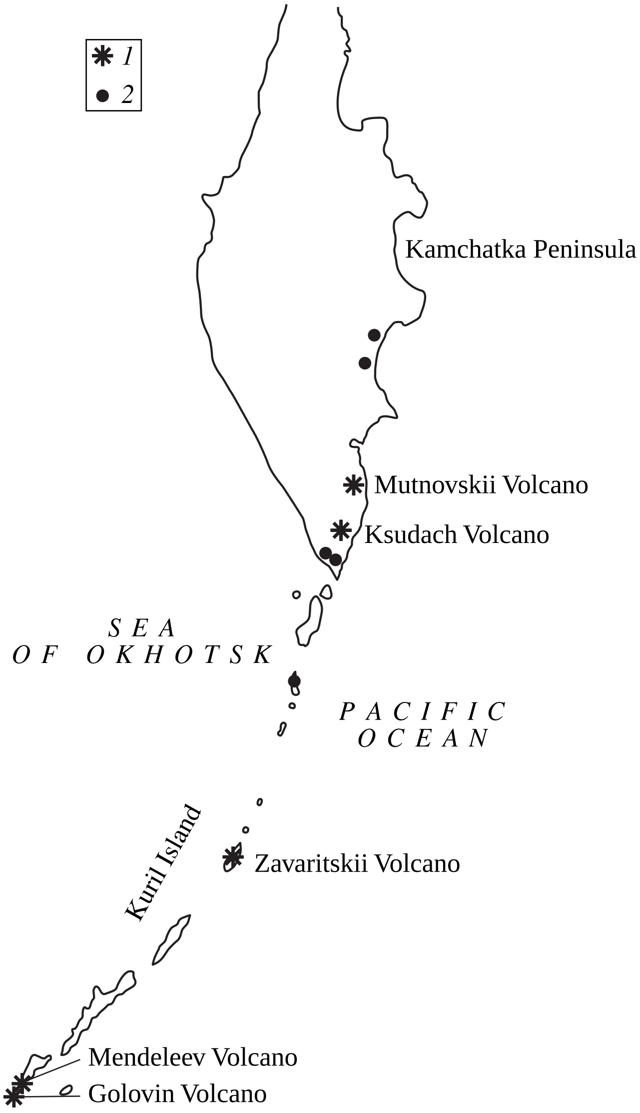

Fig. 1. Location map for the studied volcanoes of the Kuril–Kamchatka island arc. (*1*) Volcanoes discussed in this paper, (*2*) other volcanoes transporting allivalite inclusions.

Both the inclusions and the host volcanics have trace-element concentrations typical of CaO-rich rocks of the tholeiitic series. The volcanics are richer in K, Rb, and Ba, and poorer in HFSE (Ti, Zr, and Hf) compared to MORB [5] (Table 3, Fig. 3a). The REE contents in the volcanics are approximately one order of magnitude higher than in chondrites [6] and have a rather gentle distribution pattern that is free of distinct anomalies (Fig. 3b). Allivalites are poorer in trace elements of the above-mentioned groups. The REE contents in these rocks are comparable to those in chondrites. Positive Eu and Sr anomalies are typical of allivalites, because of the high plagioclase contents, but are normally absent in volcanics. Initial $^{87}Sr/^{86}Sr$ ratios

Table 1. Major-element concentrations (wt %) in volcanic rocks and olivine–plagioclase inclusions

Number	Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O
Volcanic rocks													
Mendeleev Volcano													
1	G-94/5	43.90	0.24	23.82	1.79	7.28	0.12	8.93	12.74	0.88	0.07	0.02	1.00
2	G-76/2	55.63	0.76	17.32	6.08	3.67	0.17	4.31	8.05	2.73	0.41	0.08	2.12
3	G-77/1	57.12	0.79	16.21	3.27	6.25	0.17	3.81	8.13	2.79	0.45	0.08	2.41
4	G-94/1	57.38	0.77	16.20	5.53	3.99	0.17	4.05	7.85	2.80	0.45	0.06	2.21
5	G-81/1	57.90	0.79	15.78	1.63	7.90	0.17	3.76	7.81	2.84	0.44	0.09	2.49
6	G-94/4	58.49	0.79	15.87	2.62	6.93	0.17	3.65	7.59	3.00	0.47	0.09	2.54
Zavaritskii Volcano													
7	C-314/20	53.63	0.83	17.11	3.84	6.99	0.20	4.69	9.22	2.74	0.36	0.09	2.23
8	C-310/1	54.90	0.85	18.15	3.23	6.42	0.18	2.87	9.21	3.11	0.40	0.10	3.25
9	C-310/2	54.91	0.85	18.09	3.83	5.93	0.18	2.88	9.08	3.00	0.43	0.11	3.26
10	C-314/5	54.92	0.82	18.52	2.29	7.43	0.18	2.37	9.14	3.23	0.41	0.10	4.00
11	C-314/3	54.94	0.81	18.49	2.28	7.39	0.18	2.38	9.17	3.23	0.41	0.10	3.97
12	C-310/3	54.94	0.84	18.22	2.55	6.95	0.18	2.88	9.30	3.11	0.40	0.11	3.21
13	C-314/16	55.35	0.87	17.12	1.73	8.37	0.02	3.23	8.64	3.15	0.46	0.11	3.07
14	C-314/15	55.56	0.88	17.11	2.25	7.90	0.19	3.39	8.60	3.11	0.42	0.11	2.93
15	C-314/1	55.84	0.85	18.18	2.11	7.09	0.18	2.24	8.97	3.36	0.44	0.11	4.01
16	C-307/5	56.30	0.90	17.14	2.38	7.28	0.18	3.04	8.47	3.29	0.48	0.13	3.10
17	C-314/13	57.33	0.91	16.59	2.59	7.15	0.20	2.56	7.84	3.51	0.49	0.12	3.70
18	C-314/19	57.36	0.92	16.50	2.96	6.94	0.20	2.58	7.70	3.41	0.54	0.13	3.72
19	C-314/10	57.42	0.92	16.44	3.18	6.81	0.20	2.59	7.63	3.36	0.55	0.13	3.73
20	C-314/14	57.45	0.92	16.36	1.52	8.40	0.21	2.61	7.71	3.52	0.58	0.13	3.74
21	C-314/9	57.50	0.93	16.35	2.90	7.17	0.20	2.58	7.64	3.40	0.50	0.13	3.79
22	C-307/7	59.45	0.93	15.08	2.56	7.33	0.21	2.69	6.53	3.81	0.66	0.15	3.58
23	C-312	61.64	0.76	15.57	3.44	4.48	0.19	1.98	5.92	4.13	0.64	0.16	3.83
24	C-321	63.86	0.61	15.08	2.42	4.34	0.19	1.84	5.25	4.31	0.64	0.14	3.54
25	C-308/1	64.11	0.50	14.75	3.30	4.41	0.18	1.86	5.00	4.33	0.66	0.14	3.97
Ksudach Volcano													
26	Ka-39/7	48.21	0.67	18.03	2.72	7.10	0.19	7.86	12.02	1.92	0.19	0.06	1.21
27	Ka-38a/7	49.35	0.75	21.00	2.30	6.46	0.17	4.78	12.46	2.11	0.22	0.07	1.78
28	Ka-1/7	56.79	0.84	16.33	6.55	2.83	0.22	3.55	7.38	4.02	0.64	0.19	2.46
29	Ka-17/7	57.50	0.87	16.46	1.55	7.70	0.22	3.04	7.26	3.92	0.66	0.16	2.99
30	Ka-110/7	58.68	0.81	16.32	1.71	6.85	0.21	2.72	6.84	4.09	0.77	0.16	3.08
31	Ka-113/7	58.75	0.86	16.11	2.50	5.71	0.19	3.10	6.49	4.29	0.91	0.18	2.57
Mutnovskii Volcano													
32	M-01	50.02	0.96	19.30	2.63	7.21	0.18	4.73	10.80	2.68	0.37	0.16	2.02
33	M-02	50.15	0.97	19.20	2.65	6.98	0.18	4.76	10.79	2.70	0.36	0.16	1.97
34	M-03	50.37	0.97	18.99	2.20	7.19	0.18	4.58	10.51	2.73	0.36	0.16	2.00
35	M-04	50.63	1.11	17.89	4.18	7.35	0.21	5.20	9.70	2.89	0.35	0.20	2.14
36	M-05	51.52	0.90	19.11	3.78	5.11	0.17	4.46	10.02	2.76	0.53	0.17	1.91
37	M-06	54.00	0.82	17.24	1.31	7.24	0.16	5.38	8.83	2.93	1.00	0.19	1.56
38	M-07	54.48	0.92	16.98	2.57	6.13	0.16	4.82	8.59	2.87	1.09	0.19	1.75
39	M-08	56.71	1.14	16.57	3.46	5.84	0.20	3.22	6.74	3.98	0.83	0.25	2.78
Inclusions													
Mendeleev Volcano													
40	G-94/8	43.61	0.08	26.59	0.96	5.62	0.10	7.76	14.14	0.72	0.05	0.02	0.84
41	G-94/9	44.41	0.61	19.89	3.80	7.60	0.16	7.78	14.60	0.67	0.20	0.01	1.42
42	G-94/10	44.70	0.18	26.61	3.10	3.05	0.09	6.50	14.45	0.86	0.05	0.02	0.90
Zavaritskii Volcano													
43	C-320/2g	44.00	0.31	19.74	2.85	6.33	0.13	10.08	15.57	0.53	0.01	0.01	0.88
44	C-320/1	44.40	0.13	25.88	1.42	4.40	0.09	7.68	14.52	0.79	0.04	0.01	0.74
Ksudach Volcano													
45	Ka-77/7	44.28	0.07	29.97	0.83	2.64	0.05	4.51	16.56	0.74	0.03	0.00	0.75
46	Ka-139/7	45.06	0.19	17.55	1.30	5.66	0.11	13.69	15.65	0.45	0.01	0.00	0.50
47	Ka-3/7	45.35	0.15	23.26	1.32	3.31	0.08	7.88	17.63	0.27	0.01	0.00	0.57

Table 2. Compositions of minerals in allivalites of the low-K tholeiite series from the Kuril–Kamchatka island arc

Volcano	Number of samples	SiO_2	Al_2O_3	FeO	MnO	MgO	CaO	NiO			*Fo*, %
Olivine											
Mutnovskii	16	$\frac{38.30}{0.08}$	$\frac{0.07}{<0.01}$	$\frac{20.32}{2.24}$	$\frac{0.35}{0.01}$	$\frac{40.50}{1.49}$	$\frac{0.22}{<0.01}$	$\frac{0.16}{0.01}$			$\frac{78.20}{3.24}$
Ksudach	15	$\frac{38.65}{0.08}$	$\frac{0.09}{<0.01}$	$\frac{19.32}{1.08}$	$\frac{0.34}{0.01}$	$\frac{41.02}{0.47}$	$\frac{0.25}{0.01}$	$\frac{0.14}{0.02}$			$\frac{79.26}{2.26}$
Golovin	12	$\frac{38.38}{0.22}$	$\frac{0.07}{<0.01}$	$\frac{21.16}{2.56}$	$\frac{0.36}{<0.01}$	$\frac{39.23}{1.35}$	$\frac{0.23}{<0.01}$	$\frac{0.26}{0.02}$			$\frac{76.94}{5.61}$
Plagioclase											
		SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O			*An*, %
Mutnovskii	12	$\frac{47.09}{2.68}$	$\frac{33.01}{1.94}$	$\frac{1.14}{0.06}$	$\frac{0.19}{0.01}$	$\frac{16.76}{1.03}$	$\frac{1.81}{0.44}$	$\frac{0.02}{<0.01}$			$\frac{91.11}{4.56}$
Ksudach	10	$\frac{47.06}{3.32}$	$\frac{33.45}{1.63}$	$\frac{0.70}{0.02}$	$\frac{0.17}{0.02}$	$\frac{16.97}{1.35}$	$\frac{1.60}{0.39}$	$\frac{0.03}{<0.01}$			$\frac{92.15}{1.07}$
Golovin	8	$\frac{46.47}{0.31}$	$\frac{33.30}{1.50}$	$\frac{0.89}{0.10}$	$\frac{0.25}{0.02}$	$\frac{17.73}{0.14}$	$\frac{1.46}{0.12}$	$\frac{0.03}{<0.01}$			$\frac{93.08}{2.77}$
Clinopyroxene											
		SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	NiO	Cr_2O_3	Mg/(Fe + Mg), %
Mutnovskii	6	$\frac{48.49}{0.27}$	$\frac{0.39}{<0.01}$	$\frac{2.35}{0.17}$	$\frac{11.19}{1.05}$	$\frac{0.33}{<0.01}$	$\frac{27.40}{7.02}$	$\frac{9.62}{10.51}$	$\frac{<0.01}{<0.01}$	$\frac{0.08}{0.02}$	$\frac{81.06}{0.37}$
Orthopyroxene											
		SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	NiO	Cr_2O_3	*En*, %
Mutnovskii	7	$\frac{48.37}{0.12}$	$\frac{0.21}{<0.01}$	$\frac{1.33}{0.11}$	$\frac{12.37}{0.32}$	$\frac{0.37}{<0.01}$	$\frac{35.30}{0.32}$	$\frac{1.74}{0.01}$	$\frac{0.12}{0.01}$	$\frac{0.04}{<0.01}$	$\frac{83.70}{1.35}$
Spinellids											
		SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO		NiO	Cr_2O_3	
Mutnovskii (inclusions in olivine)	19	$\frac{0.12}{0.01}$	$\frac{5.44}{6.35}$	$\frac{10.09}{12.30}$	$\frac{63.77}{57.91}$	$\frac{0.23}{0.02}$	$\frac{6.56}{2.21}$		$\frac{0.32}{0.02}$	$\frac{13.09}{31.92}$	
Mutnovskii (inclusion in plagioclase)	6	$\frac{0.02}{<0.01}$	$\frac{4.53}{1.94}$	$\frac{12.09}{11.49}$	$\frac{60.73}{35.19}$	$\frac{0.66}{0.82}$	$\frac{7.68}{1.75}$		$\frac{0.05}{0.01}$	$\frac{13.94}{55.66}$	

Note: Numerator denotes the mean concentration (wt %), denominator shows dispersion. The analyses were conducted at the Laboratory of Microanalytical Techniques, Department of Petrology, Moscow State University. Analysts E.V. Guseva and N.N. Korotaeva. CamScan-4DV electron microscope, equipped with a Link-10 000 analytical system.

are similar in volcanic rocks and olivine–plagioclase inclusions (0.7033–0.7035). The trace-element contents are different in inclusions and their host rocks. However, inclusions and volcanic rocks within individual volcanoes have some similar geochemical features [1].

Similar mineral assemblages in the inclusions and host volcanics, smooth evolutionary trends, volcano-specific mineralogic composition of inclusions and volcanic rocks, trace-element distribution, and similar Sr isotope ratios suggest a close genetic relation between the inclusions and host rocks [1, 7]. The inclusions show evidence of a higher crystallization temperature: they are rich in olivine and rarely contain orthopyroxene, whereas the proportions of these minerals are the opposite in the volcanic rocks. Relics of disintegrated inclusions are present in volcanic rocks as xenocrysts or mineral aggregates that are not in equilibrium with the host magma and are normally strongly corroded.

Thus, a comparison between the compositional features of inclusions and host volcanics shows their close genetic relationship. Many researchers have reached a similar conclusion [1, 8–13]. The ubiquitous cumula-

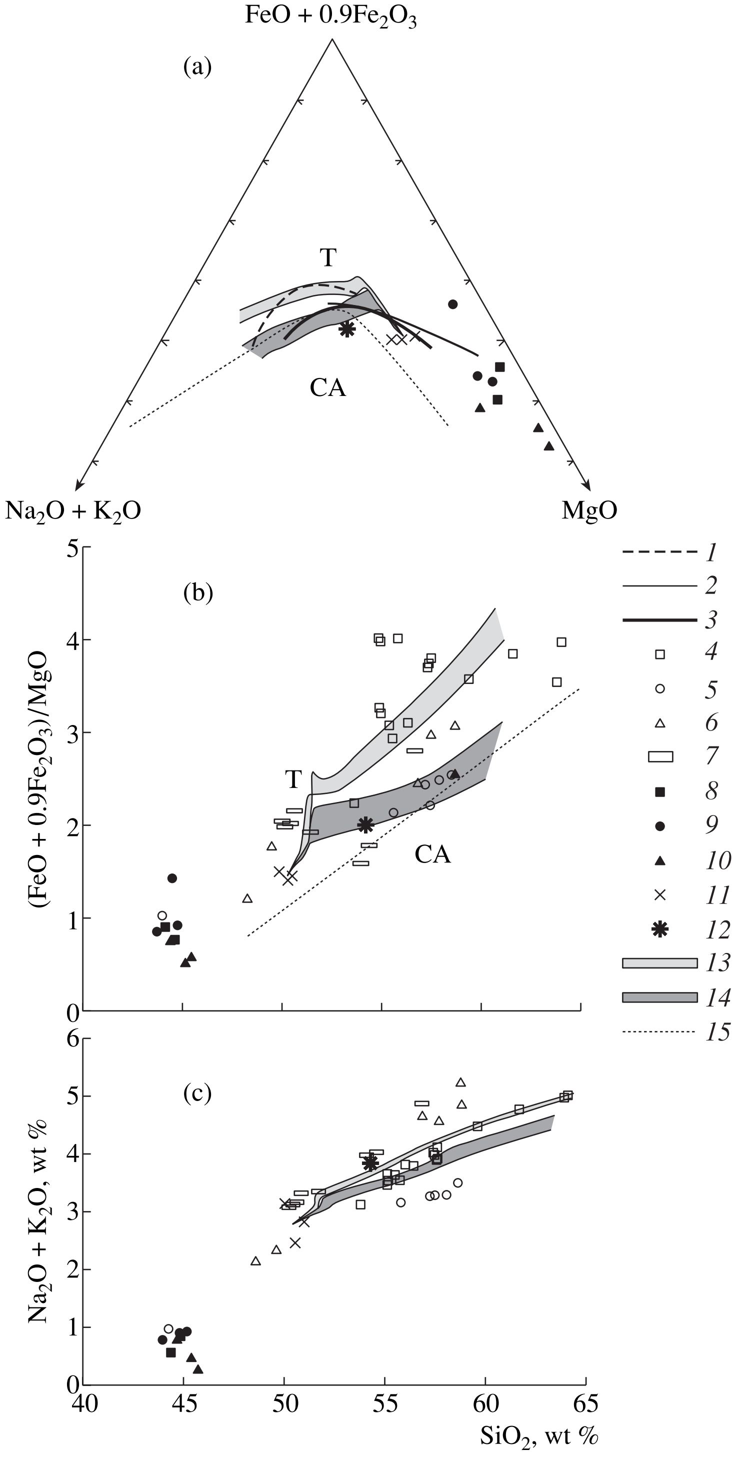

Fig. 2. Petrochemical diagrams for volcanic rocks and olivine–plagioclase inclusions: (a) AFM [2], (b) SiO_2–($0.9Fe_2O_3$ + FeO)/MgO [3], (c) SiO_2–K_2O + Na_2O.

(a) (*1–3*) Differentiation trends for volcanoes: (*1*) Mendeleev, (*2*) Zavaritskii, (*3*) Ksudach. (b, c) (*4–7*) Compositions of volcanic rocks, volcanoes: (*4*) Mendeleev, (*5*) Zavaritskii, (*6*) Ksudach, (*7*) Mutnovskii; (*8–10*) compositions of olivine–plagioclase inclusions, volcanoes: (*8*) Mendeleev, (*9*) Zavaritskii, (*10*) Ksudach; (*11*) composition of parent melt for allivalites obtained during the thermometric experiments; (*12*) calculated composition of parent melt for allivalites of Mutnovskii Volcano; (*13–14*) differentiation trends calculated using the COMAGMAT program [4] for the parent melt of allivalites at lithostatic pressure of 1 kbar: (*13*) H_2O content of 2% and oxygen fugacity of 0.4–0.6 logarithmic units above the NNO buffer, (*14*) H_2O contents of 1.0–1.2% and oxygen fugacity of 1.0–1.2 logarithmic units above the NNO buffer; (*15*) boundary separating the rocks of the tholeiitic (T) and calc-alkaline (CA) series.

tive textures, high proportions of high-temperature minerals (olivine and anorthite) in inclusions, and their depletion in incompatible elements are consistent with an origin of the inclusions by the accumulation of early minerals from the parent magma. Numerical modeling of magma evolution in the low-K tholeiitic series validates this hypothesis for the origin of many allivalites [14].

MELT INCLUSIONS IN ALLIVALITE MINERALS

The studies of melt inclusions in minerals began a new era in solving the problem of the origin of low-silica inclusions in island-arc volcanic rocks. The data on melt inclusions have been used since the 1970s for calculating the *P*–*T* conditions of magma crystallization and estimating the melt compositions at different stages of its evolution [15, 16]. The minerals of allivalites from the Kuril–Kamchatka island arc contain many glassy melt inclusions appropriate for such comprehensive investigations.

The composition of inclusions and host minerals was determined at the Department of Petrology of the Moscow State University using a Camscan-4DV electron microscope with a LinkSystem-10 000 (analysts E.V. Guseva and N.N. Korotaeva). In order to avoid boundary effects [17], the glass compositions were determined for inclusions ≥2 μm in size. The rock compositions were determined in 1985 at Copenhagen University with the assistance of J. Bailey. The major element determination with XRF analysis was supplemented by atomic absorption measurements of Na and Mg and ferrous iron measurements by titration. REE, Cs, U, Th, Hf, Co, and Sc contents were determined using INAA, and the other trace elements were analyzed by XRF (Philips PW 1400).

Melt inclusions were found in all rock-forming minerals of the inclusions: olivine, plagioclase, and pyroxene. Data on melt inclusions in olivine and plagioclase of allivalites from Mutnovskii, Ksudach, and Golovin volcanoes are discussed in this paper.

Most of the melt inclusions were represented by naturally quenched glasses and consisted of cream-white glass and a gas phase (10–15 vol % of the inclusion). The inclusions are more abundant in plagioclases than in olivines and are normally oriented along the elongated crystal axis. Melt inclusions in olivine are usually equant. Partially recrystallized inclusions are predominant in plagioclases with >91% *An* and in olivines with a magnesian number >79. The inclusions are 10–40 and 10–50 μm in size in plagioclase and olivine, respectively. They are normally confined to growth zones in plagioclase crystals and are irregularly distributed over the olivine grains. According to Roedder [15], these features characterize primary melt inclusions.

Along with glassy inclusions, olivines and plagioclase also contain partly recrystallized inclusions. The latter are not appropriate for estimating the parent melt composition, because they are rich in dispersed opaque phases and contain secondary minerals replacing glass. They are normally confined to some linear trails in the crystals and vary in morphology and composition. Allivalite minerals (both olivine and plagioclase) contain rare primary fluid inclusions in the central parts of the grains. This confirms that the minerals crystallized from a fluid-saturated magma.

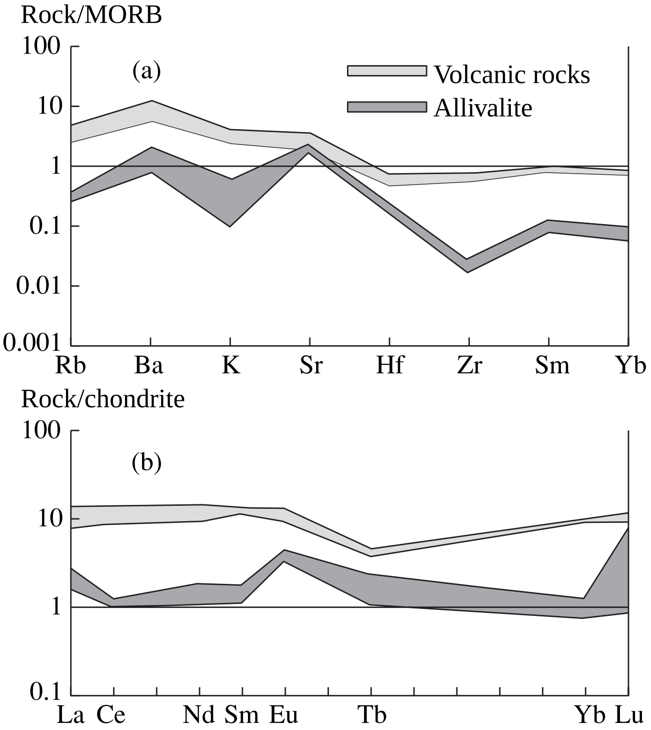

Fig. 3. MORB-normalized [5] trace-element patterns (a) and chondrite-normalized [6] REE patterns (b) for volcanic rocks and allivalites.

MELT COMPOSITION ESTIMATED BY GLASSY MELT INCLUSIONS

The relatively simple mineralogy of allivalites with a dominant composition of olivine and plagioclase allows an estimation of the parent magma composition to be made. The calculations are based on the compositions of primary glass inclusions (Table 4) in plagioclases ($An_{90–91}$) and olivines ($Fo_{79–80}$). Primary inclusions in olivines are depleted in olivine components and those in plagioclases are depleted in plagioclase components because of crystallization of minerals on the walls of inclusions after their entrapment. Thus, we can constrain the melt composition from which the allivalites crystallized. The MgO contents are underestimated for inclusions in olivine and overestimated for inclusions in plagioclase. Thus, the MgO content in the magma was 3.5–4.9 wt %. Using this technique, we also estimated the Al_2O_3 and CaO contents in the parent magma to be 15.2–17.7 and 8.6–9.4%, respectively.

Table 3. Trace-element concentrations (ppm) in volcanic rocks and olivine–plagioclase inclusions

Number	Sample	Cs	Rb	Ba	Pb	Sr	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu	Y	Th	U
Volcanic rocks																	
Ksudach Volcano																	
1	Ka-1/7	0.2	7.2	198	14	303	4	13.7	13.3	3.9	1.28	0.8	3.2	0.5	34	0.7	0.2
2	Ka-38a/7	0.2	2.6	118	3	355	1.7	7	5.5	1.6	0.69	0.4	1.2	0.2	14	0.7	0.1
3	Ka-17/7	0.8	9.6	182	5	328	3.7	11.7	11.5	3.5	1.25	0.8	2.7	0.5	32	0.8	0.3
Golovin Volcano																	
4	G-10	0.8	7.5	168	6	219	2.6	7.8	7.7	2.5	0.82	0.6	2.3	0.4	27	0.2	0.3
5	G-12	0.3	6.9	152	5	228	3.3	9.5	6.7	3.2	0.85	0.7	2.9	0.4	30	0.1	0.3
Mutnovskii Volcano																	
6	M-04	0.22	3.4	172	1	441	3.7	9.8	7.9	2.74	0.93	0.6	2.2	0.4	23	0.4	0.1
7	M-08	0.4	11.7	293	3	390	6.6	17.5	12.8	4.15	1.53	0.9	3.5	0.5	35	0.9	0.4
8	M-06	1.02	17.8	303	4	384	6.6	16.2	10.7	3.09	1.04	0.7	2.5	0.4	23	1.3	0.6
9	M-03	0.29	4.2	153	2	445	3.5	9	7.3	2.56	1.05	0.6	2.1	0.3	22	0.3	0.2
10	M-01	0.27	4.3	164	1	445	3.5	9.7	7.5	2.55	1.06	0.6	2.1	0.3	24	0.2	0.2
11	M-07	1.15	19.7	322	6	359	6.8	16.2	11.2	3.36	1.08	0.6	2.4	0.4	24	1.4	0.7
12	M-05	0.64	8.9	216	2	430	6.4	16.3	11.5	3.56	1.28	0.9	2.6	0.4	35	0.6	0.3
13	M-02	0.48	3.9	160	3	437	3.5	9.8	7.6	2.59	1	0.7	2	0.3	20	0.2	0.2
Mendeleev Volcano																	
14	G-76/2	0.3	6.3	141	3	265	2.6	8.6	6.7	2.2	0.78	0.5	1.8	0.3	20	0.1	0.2
15	G-77/1	0.3	6.9	152	5	228	3.3	9.5	6.7	3.2	0.85	0.7	2.9	0.4	30	0.1	0.3
Zavaritskii Volcano																	
16	C-314/1	0.2	5.4	118	5	279	3.1	8.6	9.7	3	1.01	0.6	2.7	0.5	28	0.1	0.3
17	C-314/3	0.2	5.4	110	5	286	3.1	8.7	9.1	2.6	0.93	0.6	2.5	0.5	27	0.1	0.2
18	C-314/5	0.2	4.6	111	5	276	3	9.1	9	3	1.01	0.6	2.4	0.4	27	0.1	0.2
Inclusions																	
Ksudach Volcano																	
19	Ka-3/7	0.8	0.5	19	1	279	1	1	1	0.3	0.38	0.15	0.28	0.04	2.9	0.7	0.03
20	Ka-77/7	0.3	0.6	13	1	387	1	1	1	0.2	0.16	0.56	0.08	0.01	0.8	0.2	0.03
21	Ka-139/7	0.3	0.5	18	1	206	1	1	1	0.3	0.62	0.24	0.29	0.05	4	0.1	0.03
Mendeleev Volcano																	
22	G-94/8	0.3	0.5	43	1	298	0.39	1.3	1	0.29	0.2	0.77	0.14	0.2	2.3	0.2	0.03
23	G-94/9	1	0.4	44	1	222	0.9	0.5	1.2	0.4	0.46	0.23	0.33	0.05	6	0.2	0.33
24	G-94/10	0.5	0.9	34	1	290	0.54	1.6	1.7	0.52	0.24	0.11	0.1	0.06	4.8	0.3	0.03
Zavaritskii Volcano																	
25	C-320/1	0.4	0.9	16	8	253	0.34	1.1	0.9	0.3	0.22	0.11	0.25	0.04	2.9	0.3	0.03
26	C-320/2g	0.1	0.6	15	1	191	1.2	1	0.8	0.29	0.52	0.23	0.38	0.57	4.2	0.1	0.03

The proportions of minerals crystallized on the inclusion walls were determined graphically from the compositions of glasses in the coexisting minerals and host mineral compositions. The average values are 4.5 and 18.7 wt % for olivine and plagioclase, respectively.

Based on the compositions of melt inclusions and crystallizing phases, we assayed the temperature of coeval olivine and plagioclase crystallization at 1050–1100°C. Compositions of plagioclase in equilibrium with the melt and the plagioclase crystallization temperature were calculated using the formula of Ariskin and Barmina [18]. The anorthite proportions in the calculated plagioclase compositions are 7–10% lower than natural compositions. The elevated *An* proportions in plagioclases of allivalites can be accounted for by an elevated H_2O content in the parent magma, according to the well known positive correlation between the water content in the melt and the Ca proportion in the

Table 3. (Contd.)

Zr	Hf	Sn	Mo	Nb	Zn	Cu	Co	Ni	Sc	V	Cr	As	Ga	Ge	S	Cl	$^{87}Sr/^{86}Sr$
Volcanic rocks																	
Ksudach Volcano																	
73	1.9	1.9	0.6	1.7	96	67	19	2	31	158	3	6.5	21	1.6	20	25	0.7035
29	0.69	0.5	0.6	1.7	69	99	29	9	38	305	31	2.5	17	1.5	170	160	0.7034
73	1.7	1.3	0.8	1.5	101	72	19	1	30	188	2	5.3	20	1.8	130	520	0.7034
Golovin Volcano																	
58	1.47	0.8	0.5	1.1	85	60	24	10	35	210	24	2.4	17	2	190	410	0.7035
60	1.69	1.8	1	1.3	86	59	23	8	36	272	13	4.5	18	2	75	510	0.7035
Mutnovskii Volcano																	
41	0.95	–	0.3	1.6	98	80	27	11	40	361	4	2.3	22	–	1090	80	–
93	2.56	–	0.2	2.7	97	84	20	6	33	231	3	4.5	23	–	60	75	–
98	2.38	–	0.6	2.4	81	95	29	27	30	226	68	5.1	18	–	170	210	–
43	1.34	–	0.7	1.5	77	45	26	17	37	297	43	2.8	20	–	1030	180	–
44	1.38	–	0.4	1.8	82	127	29	19	39	306	50	2.2	21	–	120	190	–
105	2.76	–	1.1	2.5	82	95	27	21	33	260	53	9.4	19	–	1790	75	–
55	1.69	–	0.4	2	86	121	26	25	34	283	52	2.6	21	–	25	160	–
44	1.27	–	0.4	1.9	86	95	27	19	37	314	46	3.2	20	–	550	190	–
Mendeleev Volcano																	
46	0.84	0.8	0.5	1.2	81	35	25	9	29	224	7	11	14	1.8	1090	450	0.7034
60	1.69	1.8	1	1.3	86	59	23	8	36	272	13	4.5	18	2	75	510	0.7035
Zavaritskii Volcano																	
57	1.44	1.2	1.8	1.8	112	86	18	2	35	259	2	2.2	20	1.9	120	200	0.7033
55	1.13	0.8	1.1	2.2	84	96	18	2	33	241	5	3.7	20	1.5	5	210	0.7033
55	1.28	0.9	0.2	1.9	88	97	20	1	35	245	2	1.9	19	1.9	100	230	0.7033
Inclusions																	
Ksudach Volcano																	
1.1	0.5	0.6	0.5	1	20	12	29	52	42	94	4.19	0.5	13	1.5	120	65	0.7034
1	0.2	0.5	0.2	0.6	14	9	21	35	55	34	7	0.5	14	1.3	15	5	0.7034
2.6	0.7	0.5	0.2	0.9	35	18	52	68	54	123	4.34	0.5	13	1.7	110	70	0.7034
Mendeleev Volcano																	
2.3	0.2	0.5	0.2	1	37	18	36	41	4.7	41	35	0.5	16	1.6	60	160	0.7035
1.2	0.8	1.2	0.5	1	32	13	44	28	49	444	129	1.9	18	1.4	110	240	0.7034
3.7	0.3	1	0.2	0.5	38	35	34	40	11	84	32	2	16	1.4	165	200	0.7034
Zavaritskii Volcano																	
3.6	0.3	0.5	0.5	1.2	31	19	40	23	11	77	10	14	22	1.3	110	190	0.7033
0.8	0.8	0.5	0.4	0.8	36	5	44	60	54	294	316	0.5	14	1.5	20	10	0.7036

Note: The analyses were conducted in 1985 at the Laboratory of Copenhagen University under supervision of Dr. J. Beyly. REE, Cs, U, Th, Hf, Co, and Sc concentrations were determined by INAA, others were analyzed by XPF on a RW1400 analyzer.

crystallizing plagioclase. The olivine compositions and crystallization temperatures were calculated by Ford's model [19]. The water content in the parent melt was estimated by the inconsistency between the olivine and plagioclase crystallization temperatures [20] and by Ca partitioning between plagioclase and the melt [21]. These methods gave similar estimates (1.5% and 1.65%, respectively).

EXPERIMENTAL TEMPERATURE DETERMINATION

The calculation results were verified by several heating experiments. Olivine and plagioclase (100 grains each) with primary glassy inclusions containing a gas phase and bearing no evidence of recrystallization or secondary mineralization were selected for the experiments.

Table 4. Compositions of melt inclusions in olivine and plagioclase and compositions of parent melts for allivalites (wt %)

Number	SiO_2	TiO_2	Al_2O_3	FeO_{tot}	MnO	MgO	CaO	Na_2O	K_2O	Cl	Total
1	53.95	1.51	17.92	8.77	0.19	2.68	10.89	3.48	0.6	0.11	100
2	54.05	1.27	18.6	8.23	0.09	2.36	11.74	3.14	0.53	0.25	100
3	52.83	1.18	18.26	9	0.21	3.51	10.8	3.7	0.52	<0.1	99.99
4	56.33	1.07	17.86	7.81	<0.1	2.58	9.49	4.05	0.83	<0.1	100
5	53.38	1.19	18.65	8.28	<0.1	3.16	10.6	4.17	0.57	0.11	100
6	53.49	1.26	17.88	8.99	<0.1	3.41	10.51	3.9	0.55	0.12	100
7	57.54	1.14	14.24	9.79	<0.1	5.64	7.9	2.99	0.77	<0.1	100
8	60.22	0.79	13.06	9.46	<0.1	5.4	7.3	2.83	0.94	<0.1	100
9	57.25	0.98	14.56	9.97	<0.1	5.76	8.42	2.35	0.71	<0.1	100
10	50.15	0.9	19.23	9.11	0.28	5.57	13.01	1.6	0.15	<0.1	100
11	49.34	0.82	19.47	9.18	0.35	5.53	13.16	1.84	0.19	0.12	100
12	48.8	0.79	19.69	9.1	0.21	5.33	13.7	2.23	0.15	<0.1	100
13	50.13	0.82	18.94	9.11	0.16	5.57	13.01	2.13	0.13	<0.1	100
14	51.67	0.97	17.79	9.15	0.44	5.8	12.31	1.62	0.14	0.11	100
15	48.29	0.57	22.61	9.13	0.29	5.58	12.02	1.23	0.28	<0.1	100
16	53.03	0.9	17.12	9.14	0.06	5.67	11.75	2.1	0.11	0.12	100
17	51.57	0.88	18.05	9.12	0.11	5.6	12.33	2.04	0.2	0.10	100
18	50.5	1.02	18.88	9.13	0.19	5.46	12.61	2.05	0.16	<0.1	100
19	46.9	0.91	21.1	9.14	0.22	5.24	14.11	2.16	0.22	<0.1	100
20	49.79	1.02	19.6	9.44	0.27	6.33	10.44	2.58	0.54	–	100
21	50.46	1.15	18.97	9.65	0.19	6.79	9.94	2.28	0.56	–	100
22	50.28	0.74	19.42	9.59	0.16	6.86	10.53	2.15	0.3	–	100
23	49.89	0.84	20.04	9.18	0.19	6.85	11.12	1.6	0.19	–	100
24	50.10	0.94	19.51	9.47	0.20	6.71	10.51	2.15	0.40	–	100
25	54.19	1.21	17.06	9.15	0.13	4.56	9.88	3.18	0.64	–	100

Note: (1–6) glassy inclusions in olivine; (7–9) glassy inclusions in plagioclase; (10–19) representative compositions of melt inclusions in olivine after the thermometric experiments Zavaritskii Volcano; (20–24) compositions of the most magnesian melts obtained during the thermometric experiments: (20) Ksudach Volcano, (21) Mutnovskii Volcano, (22) Golovin Volcano, (23) Zavaritskii Volcano, and (24) average composition; (25) calculated composition of parent melt for allivalites from Mutnovskii Volcano. The analyses were conducted at the Laboratory of Microanalytical Techniques, Department of Petrology, Moscow State University. Analysts E.V. Guseva and N.N. Korotaeva. CamScan-4DV electron microscope, equipped with a Link-10 000 analytical system.

The average size of the inclusions was 15–20 μm. The experiment was performed in a furnace with the assistance of A.D. Babanskii at the Institute of the Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry (Moscow).

The inclusions were homogenized in a platinum container filled with graphite powder. A stepwise (by 20°C) heating method above 1000°C was used in the experiment. The temperatures were measured accurate to ±10°C. On heating to a certain temperature, the sample was held for 2–3 min at a constant temperature, then removed from the heating stage and quenched at room temperature. The homogenization event was visually identified by the disappearance of the gas phase. Most of the melt inclusions were homogenized at 1050–1100°C. The rare inclusions that could not be homogenized even at 1200°C were rejected. They may have been depressurized or formed by heterogeneous entrapment of the melt and a gas–liquid phase.

DISCUSSION

The compositions of the melts from which the allivalite minerals crystallized were estimated by microanalysis of the experimentally quenched melt inclusions and by calculation. Table 4 demonstrates the average composition of the melt calculated from the compositions of primary glassy inclusions in allivalite plagioclases from Mutnovskii Volcano with the addition of 18.7% of the host mineral, from the compositions of the olivine inclusions (coexisting with the above plagioclase), and 4.53% the host mineral, and from the compositions calculated using the method of reciprocal fractionation [18].

The experimental results are highly consistent (Fig. 2), which testifies to their validity. Similar melt compositions for different volcanoes suggest the existence of a common low-K tholeiitic parent magma. The calculated melt compositions are less mafic than those obtained in the experiments. This is probably related to the initial samples selected for analysis. For example, the calculations were performed for the $Fo_{78–79}$ + $An_{90–91}$ assemblage, because the more magnesian olivines and more calcic plagioclases are dominated by partly recrystallized inclusions. In contrast, the samples selected for the thermometric experiments comprised the partly recrystallized inclusions in the $Fo_{81–82}$ + $An_{93–96}$ assemblage. The lower iron proportion in the calculated compositions probably resulted from diffusional redistribution of iron in the host olivine during chamber crystallization [22].

The parent magma compositions obtained in the thermometric experiments are plotted between the compositional fields of allivalites and lavas in the major-element diagrams at the beginning of the evolutionary trends of the low-K tholeiitic series (Fig. 2). Volcanic rocks with $SiO_2 < 50\%$ are rare in this series. Their origin is probably related to the local accumulation of early phenocrysts. The trends of the above series indicate that olivine and plagioclase fractionation were the principal mechanisms of magma differentiation. Thus, the data presented here prove the cumulative origin of allivalites [1, 8, 14].

The evolutionary trends calculated using the COMAGMAT program [4] from the average magma compositions obtained in the thermometric experiments are close to the trends of natural compositions of igneous rocks with $SiO_2 < 58\%$ (Fig. 2). The rock compositions for Mendeleev Volcano are plotted near the trend calculated by the fractional crystallization model with a water content of 2% in the initial magma and an oxygen fugacity of 0.4–0.6 logarithmic units above the NNO buffer. It is suggested that the magma in Ksudach and Zavaritskii volcanoes evolved at a higher oxygen fugacity (1.0–1.4 logarithmic units above the NNO buffer) and lower H_2O contents in the parent melt (1.0–1.2%). The rocks of Mutnovskii Volcano and silicic rocks deviate from the calculated trends, probably because crystal fractionation was not the only process operating at the later stages of magmatic evolution. The contribution of crustal material to the magma composition is indicated by regular differences in the total alkali contents between the rocks of Kamchatka and the Kuril Islands (Fig. 2c).

The balance of major elements (parent magma = allivalite + basalt) shows that the fractionation of 7–8% olivine–plagioclase cumulate from the parent magma is necessary for the formation of basalt of the Kuril–Kamchatka island arc.

The inclusions are particularly abundant in the mature volcanoes passing the caldera stage of evolution. According to the great variability in the compositions of volcanic rocks and inclusions, the feeding magma systems beneath such volcanoes are vertically zoned by temperature and composition and are represented either by a large layered chamber or several smaller multilevel chambers filled with magmas of various differentiation degrees. The compositional differences between the inclusions and host rocks are related to the evolution of the magmatic system, i.e., the magma differentiation accompanied by crystal accumulation and formation of silicic derivatives. The replenishment of magma chambers caused the convection and ascent of solid or highly viscous mafic material from the deepest parts of the system to the upper horizons and its transportation to the surface as inclusions. The latter could represent cumulates or fragments of intrusive bodies solidified at various depths from earlier magma fractions.

CONCLUSIONS

(1) The glassy melt inclusions in allivalite minerals provide information on the early stages of melt evolution in magma chambers. The compositions of early magmas for different volcanoes are fairly similar and correspond to the parent melt for the low-K tholeiite series of the Kuril–Kamchatka island arc volcanoes (Zavaritskii, Golovin, Ksudach, Mutnovskii, Mendeleev, etc.).

(2) The data on melt inclusions proved the previous suggestion of the cumulative origin of allivalites. However, the occurrence of inclusions of other rock types is also possible.

(3) The temperature of coeval olivine and plagioclase crystallization in allivalites is estimated at 1050–1100°C at an H_2O content of 1.5–2.0 wt % in the parent melt.

(4) The general compositional similarity of melts equilibrated with the allivalite minerals at different volcanoes of the Kuril–Kamchatka island arc indicates that these melts are close to the parent low-K tholeiitic magma typical of the studied region.

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REFERENCES

1. Frolova, T.I., Beili, D.K., Burikova, I.A., and Dril', S.I., On the Genetic Similarity of Low Silicic Inclusions and Host Rocks of the Kurile Island Arc, *Tikhookean. Geol.*, 1988, no. 3, pp. 27–35.
2. Irvine, T.N. and Barager, W.R.A., A Guide to the Chemical Classification of the Common Volcanic Rocks, *Can. J. Earth Sci.*, 1971, vol. 8, pp. 523–548.
3. Myashiro, A., Volcanic Rock Series in Island Arcs and Active Continental Margins, *Am. J. Sci.*, 1974, vol. 274, pp. 321–355.

4. Ariskin, A.A., Frenkel, M.Ya., Barmina, G.S., and Nielsen, R.L., COMAGMAT: A Fortran Program to Model Magma Differentiation Processes, *Comput. Geosci.*, 1993, vol. 19, pp. 1155–1170.
5. Pearce, J.A., Trace Element Characteristics of Lavas from Destructive Plate Boundaries, *Andesites,* Thorpe, R.S., Ed., London, 1982, pp. 526–547.
6. Taylor, S.R. and McLennan, S.M., *The Continental Crust: Its Composition and Evolution,* Oxford: Blackwell, 1985. Translated under the title *Kontinental'naya kora: ee sostav i evolyutsiya*, Moscow: Mir, 1988.
7. Bailey, J.C., Larsen, O., and Frolova, T.I., Strontium Isotope Variations in Lower Tertiary–Quaternary Volcanic Rocks from the Kurile Island Arc, *Contrib. Mineral. Petrol.*, 1988, no. 95, pp. 155–165.
8. Volynets, O.N., Shcheka, S.A., and Dubik, Yu.M., Olivine–Anorthite Inclusions in Volcanoes of Kamchatka and Kurile, in *Vklyucheniya v vulkanicheskikh porodakh Kurilo–Kamchatskoi dugi* (Inclusions in Volcanic Rocks of the Kurile–Kamchatka Arc), Moscow: Nauka, 1978, pp. 124–167.
9. Ermakov, V.A., Volynets, O.N., and Koloskov, A.V., Inclusions in Volcanic Rocks of the Kurile–Kamchatka Arc and Their Importance for Understanding the Petrogenesis, in *Petrologiya i geokhimiya ostrovnykh dug i okrainnykh morei* (Petrology and Geochemistry of Island Arcs and Marginal Seas), Moscow: Nauka, 1987, pp. 293–312.
10. Frolova, T.I., Burikova, I.A., Dril', S.I., *et al.*, The Nature of Low Silicic Olivine–Anorthite Inclusions and the Environment of Their Formation, *Tikhookean. Geol.*, 1989, no. 6, pp. 85–95.
11. Shcheka, S.I., *Bazit-giperbazitovye intruzii i vklyucheniya v effuzivakh Dal'nego Vostoka* (Basic–Ultrabasic Intrusions and Inclusions in Extrusive Rocks of the Far East), Moscow: Nauka, 1983.
12. Arculus, R.D.J. and Wills, K.J.A., The Petrology of Plutonic Blocks and Inclusions from the Desser Antiles Island Arcs, *J. Petrol.*, 1980, vol. 21, part 4, pp. 743–799.
13. Conrad, W.C., Ray, S.M., and Ray, R.W., Magma Mixing in the Aleutian Arc: Evidence from Cognate Inclusions and Composite Xenoliths, *Volc. Geotherm. Res.*, 1983, vol. 18, nos. 1–4, pp. 279–296.
14. Frolova, T.I. and Dril', S.A., Andesitic Volcanism of Island Arcs and Its Geologic Importance, *Tikhookean. Geol.*, 1993, no. 3, pp. 3–14.
15. Roedder, E., *Fluid Inclusions*, *Reviews in Mineralogy*, vol. 12, Michigan: Mineral. Soc. Am., 1984.
16. Sobolev, A.V., Melt Inclusions in Minerals as a Source of Principle Petrological Information, *Petrology*, 1996, no. 4(3), pp. 228–239.
17. Lu, F., Anderson, A.T., and Davis, A.M., Diffusional Gradients at the Crystals/Melt Interface and Their Effect on the Composition of Melt Inclusions, *J. Geol.*, 1995, vol. 103, pp. 591–597.
18. Frenkel', M.Ya., Yaroshevskii, A.A., Ariskin, A.A., *et al.*, *Dinamika vnutrikamernoi differentsiatsii bazitovykh magm* (Dynamics of In-Chamber Differentiation of Basic Magmas), Moscow: Nauka, 1988.
19. Ford, C.E. *et al.*, Olivine–Liquid Equilibria: Temperature, Pressure and Composition Dependence of the Crystal/Liquid Cation Partition Coefficients for Mg, Fe^{2+}, Ca, and Mn, *J. Petrol.*, 1983, vol. 24, pp. 256–265.
20. Danyushevsky, L.V., The Effect of Small Amount of H_2O on Fractionation of Mid-Ocean Ridge Magmas, *EOS*, 1998, vol. 79, no. 17, suppl.: *Abstracts of Papers, AGU Spring Meeting*, p. 375.
21. Pletchov, P.Yu. and Gerya, T.V., Effect of H_2O on Plagioclase–Melt Equilibrium, *Exp. Geosci.*, 1998, no. 7(2), pp. 7–9.
22. Danyushevsky, L.V. and Della-Pasqua, F.N., Reequilibration of Melt Inclusions Trapped by Magnesian Olivine Phenocrysts from Subduction-Related Magmas: Petrological Applications, *Contrib. Mineral. Petrol.* (in press).