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The Role of Andesitic–Dacitic–Rhyolitic Melts in the Crystallization of Phenocrysts in Andesite of Bezymyannyi Volcano, Kamchatka

M. L. Tolstykh *, V. B. Naumov *, G. E. Bogoyavlenskaya **, and N. N. Kononkova *

** Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, ul. Kosygina 19, Moscow, 117975 Russia*

*** Institute of Volcanology, Far East Division, Russian Academy of Sciences, bul'v. Piipa 9, Petropavlosk-Kamchatskii, 683006 Russia*

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Abstract—Melt inclusions were examined in plagioclase phenocrysts from the Novyi andesitic dome of Bezymyannyi volcano, Kamchatka. The examined rocks came from eruptions in 1956, 1974, 1979, 1985, 1987, and 1990. The inclusions were homogenized, and the glasses of more than sixty inclusions were analyzed on an electron microprobe. It was determined that the silicity of the melts varies over a wide range, from 56 to 81 wt % SiO_2, and an increase in the content of SiO_2 is associated with a decrease in the contents of Al_2O_3, MgO, FeO, and CaO and an increase in the concentration of Na_2O. The K_2O contents also vary within a broad range (from 1.8 to 6.6 wt %) regardless of the bulk melt composition. The composition of the Bezymyannyi melts was compared with that of Shiveluch volcano. It was demonstrated that the current concept of the origin of the Bezymyannyi volcano rocks as the products of only andesitic melt is erroneous. The processes that resulted in the rocks were extremely complex and call for further study.

INTRODUCTION

Bezymyannyi volcano, Kamchatka, is the only volcano of the Klyuchevskaya group whose edifice is fully composed of andesitic rocks [1]. The relatively small cone of the volcano witnessed extremely powerful eruptions in 1956 and 1985, a fact that attracted the interest of volcanologists. Along with the dynamics of the process [2–5], the composition of the volcanic products, which are noted for their minimal variability (pyroxene, pyroxene–amphibole, and amphibole andesite) was examined. Kadik *et al*. [6] attempted to model the genesis of these compositionally similar rocks. It is generally agreed that the rocks were produced by the crystallization of andesitic melt, about whose genesis, however, a variety of versions was proposed.

This paper presents the results of our study of melt inclusions in plagioclase phenocrysts of andesites from the 1956, 1974, 1979, 1985, 1987, and 1990 eruptions of Bezymyannyi volcano. These data provide evidence of the more complex evolution of the andesites of this volcano.

BRIEF MORPHOLOGICAL OUTLINE OF BEZYMYANNYI VOLCANO AND THE HISTORY OF ITS ERUPTIONS

Bezymyannyi volcano is situated in the central part of the Klyuchevskaya volcanic group, southwest of Klyuchevskii volcano, on the slope of Kamen' volcano. Bezymyanniy is currently a slightly east–west-elongated massif with a collapsed summit that is occupied by a vast crater 1.3 by 2.8 km. The Novyi dome is located in the crater. Sixteen volcanic domes are scattered on the southern and southeastern slopes and near the southern foot of the volcano [1].

The history of the volcano began in Late Pleistocene time, when dacite domes developed at the site of the modern volcano Bezymyannyi. Somewhat later, andesite and basaltic andesite protrusions and domes were formed. About 10–11 thousand years ago, Pra-Bezymyannyi volcano started to grow on a spur of Kamen' volcano. The bulk of this volcano was destroyed during the catastrophic 1956 eruption. The only intact fragment remained in the eastern portion of the edifice is compositionally dominated by andesite and basaltic-andesite pyroclastic material. The stratovolcano Bezymyannyi proper originated approximately 5000 years ago. The first 2000 years of its explosive and extrusive activity resulted in basaltic andesite flows and andesite domes and ended with a period of dormancy, after which volcanic activity developed in a series of intermittant pulses. The three major cycles of activity lasted 400–700 years each.

The first period (2400–1700 years ago) was noted for its high explosive activity and the voluminous outpouring of intermediate and mafic lava. The second period (1350–1000 years ago) was marked by catastrophic eruptions and the origin of pyroclastic flows.

Table 1. Composition (wt %) of andesites from Bezymyannyi volcano

Component	1956*	1974	1979	1985	1987	1990
SiO_2	59.54	57.54	56.42	56.54	56.58	58.36
TiO_2	0.88	0.71	0.83	0.81	0.82	0.79
Al_2O_3	17.57	16.11	17.80	18.10	18.46	18.70
Fe_2O_3	3.17	3.55	3.87	4.51	2.32	2.36
FeO	3.22	4.48	4.31	3.02	4.42	4.57
MnO	0.14	0.17	0.16	0.10	0.17	0.14
MgO	2.81	3.48	3.83	3.98	3.96	3.72
CaO	6.97	8.16	7.46	7.67	7.36	6.70
Na_2O	3.80	3.60	3.56	3.22	3.38	3.40
K_2O	1.32	1.35	1.27	1.24	1.34	1.33
H_2O^-	–	0.12	0.26	0.21	0.21	0.20
H_2O^+	–	0.18	–	0.25	0.37	–
P_2O_5	–	0.18	0.17	0.28	0.20	0.18
Total	99.82	99.61	100.06	99.93	99.59	100.45

* Sample numbers correspond to the year of eruption.

Table 2. Representative analyses (wt %) of plagioclase phenocrysts

Component	1	2	3	4	5	6	7	8	9	10
SiO_2	48.85	47.42	49.88	52.12	50.41	51.46	52.40	57.05	55.86	59.20
Al_2O_3	31.38	32.18	30.54	28.99	31.02	30.61	29.68	26.96	26.61	24.05
CaO	16.76	16.60	15.39	14.31	13.61	13.45	12.35	9.25	10.58	8.16
Na_2O	2.26	2.28	2.91	3.44	3.70	3.82	4.50	6.15	5.17	4.99
K_2O	0.08	0.05	0.10	0.15	0.16	0.12	0.16	0.27	0.28	0.72
FeO	0.37	0.26	0.34	0.37	0.54	0.38	0.56	0.39	0.33	0.91
Total	99.70	98.79	99.16	99.38	99.44	99.84	99.65	100.07	98.83	98.03
An	80.0	79.9	74.1	69.1	66.4	65.6	59.7	44.7	52.2	45.2
Ab	19.5	19.8	25.3	30.1	32.7	33.7	39.4	53.8	46.2	50.0
Or	0.5	0.3	0.6	0.8	0.9	0.7	0.9	1.5	1.6	4.8

The period was also responsible for the development of the youngest volcanic domes (all of which consist of intermediate volcanics). The most violent eruption occurred in 1955–1956, following a 1000-year-long dormant period, and marked the beginning of a new period of volcanic activity. Since this time, explosive and extrusive eruptions have occurred annually, the strongest of which was in 1985.

The current activity of the volcano is periodic and alternatingly involves the squeezing of extrusive blocks and the eruption of flows of pyroclastic material and viscous lava.

PETROGRAPHY AND MINERALOGY

Our samples are andesites from eruptions in 1956, 1974, 1979, 1985, 1987, and 1990 at the Novyi volcanic dome; their chemical analyses are listed in Table 1. The rocks can be subdivided into three groups based on their petrography, although all of them are quite similar mineralogically.

Group I consists only of the 1956 andesite. This is a massive light gray rock with approximately 40 vol. % phenocrysts of amphibole (~50% of phenocrysts), plagioclase (~40%), pyroxene (~5%), and opaque minerals. The groundmass consists of devitrified glass with

plagioclase laths and microlites of amphibole and opaque minerals.

Group II comprises the andesites of the 1974, 1979, and 1985 eruptions. These are dark gray porphyritic rocks of medium porosity with 25–30 vol. % phenocrysts, 65% of which is plagioclase, 20% orthopyroxene, 5% clinopyroxene, and ~10% opaque minerals. The rocks are noted for an abundance of large resorbed plagioclase phenocrysts, which are relatively rare in the andesite of group I.

Group III is the andesites of the 1987 and 1990 eruptions. The rocks are dark gray and much more porous than those of group II. The phenocrysts are also dominated by plagioclase (~70–75%), which sometimes occurs as megacrysts analogous to those described above. Pyroxene phenocrysts are relatively rare (~10–15%), and opaque minerals account for ~15% of the phenocrysts. The groundmass contains glass and microlites of plagioclase and, more rarely, of pyroxenes and opaque minerals.

Plagioclase crystals can be classified in two generations. One comprises large (up to 4–5 mm), nearly equant crystals or their cores, which are resorbed and bear abundant crystalline, melt, and, more rarely, fluid inclusions. The crystals display normal zoning and consist of *An* 80–60. The second generation is of smaller (up to 1 mm), seriate, elongated phenocrysts or marginal portions of large phenocrysts. This plagioclase is notably lower in inclusions, its zoning is also normal, and the composition is *An* 60–40. Table 2 demonstrates representative analyses of the plagioclases, and Fig. 1 illustrates the occurrence frequency of plagioclase of different composition as calculated on the basis of 92 analyses.

Amphibole is present in the rocks in the form of relatively small (no larger than 0.4 mm), elongated crystals with rounded angles and practically without zoning. The pyroxene is often hypersthene or, more rarely, augite (they usually occur in the proportion of 3 : 1). The crystals are slightly elongated or equant, almost devoid of zoning, and have a nearly constant composition. The composition of the pyroxenes and amphibole is illustrated by analyses in Table 3. The opaque minerals (titanomagnetite and magnetite) are extremely variable in composition (Table 4). Their largest phenocrysts bear exsolution lamellae. Apatite as encountered only as crystalline inclusions in plagioclase and

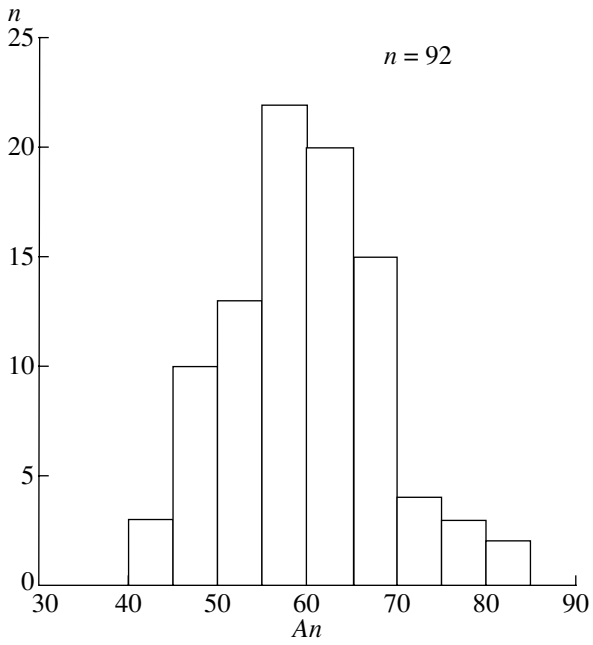

Fig. 1. Histogram of the composition of plagioclase in andesites of Bezymyannyi volcano.

Table 3. Composition (wt %) of pyroxenes and amphibole

Component	1	2	3	4	5	6	7	8	9
SiO_2	51.82	50.03	51.12	53.91	53.02	52.74	45.03	42.85	44.32
TiO_2	0.29	0.48	0.39	0.13	0.24	0.18	1.89	1.80	1.73
Al_2O_3	1.44	3.38	2.44	0.98	0.76	1.35	10.02	12.13	10.29
FeO	9.25	10.56	10.16	17.60	20.53	19.92	13.52	13.43	13.83
MnO	0.30	0.45	0.42	0.42	0.79	0.71	0.29	0.26	0.35
MgO	15.01	12.98	13.76	25.12	21.64	23.36	13.59	12.93	13.30
CaO	19.72	20.45	20.16	1.38	1.77	1.21	11.02	11.02	10.84
Na_2O	0.13	0.36	0.26	–	–	–	1.72	1.95	1.72
K_2O	0.00	0.00	0.00	–	–	–	0.45	0.46	0.42
Total	97.96	98.69	98.71	99.54	98.75	99.47	97.53	96.86	96.80

Note: (1–3) Clinopyroxene [(3) average of 10 analyses]; (4–6) orthopyroxene [(6) average of 32 analyses]; (7–9) amphibole [(9) average of 11 analyses].

Table 4. Composition (wt %) of opaque minerals

Component	1	2	3	4	5	6	7	8	9	10	11	12
FeO	63.50	66.22	66.88	66.53	82.12	83.42	83.43	86.65	85.83	87.53	88.61	90.74
TiO_2	31.86	29.93	29.16	28.24	14.08	10.48	9.61	8.47	7.21	5.19	5.06	0.96
MgO	1.63	1.65	1.31	1.65	1.65	1.88	1.84	1.69	2.03	1.77	1.51	3.91
MnO	0.38	0.30	0.28	0.25	0.52	0.57	0.54	0.68	0.50	0.54	0.46	0.89
CaO	0.02	0.04	0.06	0.23	0.17	0.19	0.29	0.07	0.03	0.04	0.01	0.00
Al_2O_3	0.47	0.49	0.53	0.65	1.22	2.09	2.14	2.10	2.58	2.90	2.89	4.06
SiO_2	0.00	0.01	0.01	0.04	0.12	0.09	0.11	0.07	0.07	0.05	0.07	0.00
Total	97.86	98.64	98.23	97.59	99.88	98.72	97.96	99.73	98.25	98.02	98.61	100.56

Note: All Fe is given as FeO.

pyroxene. Its composition is as follows (wt %): 52.1 CaO, 41.1 P_2O_5, 0.49 FeO, 0.09 MnO, 0.00 SrO, 3.77 F, and 1.97 Cl.

MELT INCLUSIONS IN MINERALS

Phenocrysts in the Bezymyannyi andesite contain crystalline, fluid, and melt inclusions. The crystalline inclusions are identical in all phenocrysts: these are clinopyroxene, apatite, and opaque minerals. Fluid inclusions were detected only in the first-generation plagioclase from the 1956 andesite. The inclusions are slightly elongated opaque bubbles 5–6 μm across. The low density of the inclusions precludes their analysis by cryometric techniques.

Melt inclusions were found in all minerals of the andesite. The inclusions are of regular oval shape in the mafic minerals and consist of clear glass without any gas bubble. Their size varies from 7 to 80 μm. The morphology of melt inclusions in the plagioclase is much more diverse. It can be regular equant or drop-shaped and twisted. The former inclusions always consist of colorless transparent glass, whereas some of the latter are brown. The size of the inclusions ranges from 3 to 85 μm, and their gas phase accounts for 10–15% by volume. The equant inclusions are single or form trails along relatively narrow growth zones. Twisted and drop-shaped inclusions usually occur as thick swarms (resorption zones) and are also spatially restricted to certain zones of phenocrysts (either their cores or broad belts closer to the margins). Inclusions of regular shape sometimes contain a daughter opaque mineral.

The thermometric study of melt inclusions in plagioclase was conducted in a micromuffle with a platinum heater, with an accuracy of temperature measurements of ±10°C, using the quenching technique [7]. This method enables us to observe the phase transitions even in the smallest inclusions 3–5 μm in size.

The composition of the glass was analyzed on a Camebax Microbeam microprobe at an accelerating potential of 15 kV, 30 nA current, and a raster over an area of 12 by 12 or 5 by 5 μm for glasses and 2 by 2 μm for crystalline phases. Elements were analyzed accurate to ±2% at contents of >10 wt %, to ±5% at contents of 5–10 wt %, and to ±10% at contents of 1–5 wt %. It should be mentioned that significant Na losses were noted when the glasses were analyzed by scanning over an area of 5 by 5 μm. This led us to analyze some large (30–50 μm in diameter) inclusions by scanning over various areas in order to calculate corrections to the Na contents measured in small melt inclusions.

On heating plagioclase phenocrysts to temperatures 1100–1200°C and subsequent quick cooling, the glasses of the melt inclusions were analyzed on a microprobe. The analyses are listed in Table 5 for rocks of the 1956 and 1974 eruptions, in Table 6 for those of the 1979, 1985, 1987, and 1990 eruptions, and in Table 7. The latter table presents analyses of melt inclusions detected in the same plagioclase phenocrysts.

The tables demonstrate that the inclusions are very diverse in composition. The most basic inclusions correspond to andesitic melts with 55.9–64.1 wt % SiO_2 and relatively high contents of MgO (up to 5.2 wt %), CaO (up to 7.1 wt %), FeO (up to 5.9 wt %), and Al_2O_3 (up to 19.4 wt %). Some of the andesitic melts are high-K (up to 6.1 wt %), whereas others are low-K (1.8 wt %), and there are all transitional varieties.

Most of the inclusions (ca. 80% of them) consist of dacitic and rhyolitic glasses, which compose a continuous series with SiO_2 concentrations ranging from 64 to 81 wt %. The contents of many components systematically decrease with increasing SiO_2 contents: Al_2O_3 to 10.9 wt %, FeO to 1.1 wt %, MgO to 0.1 wt %, and CaO to 0.7 wt % (Figs. 2a–2e). At the same time, the concentrations of K_2O vary (from 1.8 to 6.6 wt %) fully independently of the bulk composition of the melt.

The water content of the melts, which was assessed by the difference between 100% and the totals of all components analyzed on a microprobe, is normally small, less than 1–2 wt % for most analyses and attains

Table 5. Composition (wt %) of melt inclusions in plagioclase from andesite of the 1956 and 1974 eruptions

Compo-nent	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	56.30	63.84	64.66	64.80	66.39	67.30	69.98	64.06	69.25	72.48	73.04	74.09	77.84	79.36
TiO_2	0.58	0.41	0.33	0.28	0.34	0.36	0.27	0.37	0.20	0.28	0.33	0.37	0.38	0.48
Al_2O_3	17.76	16.22	19.23	16.85	19.21	17.42	17.60	17.23	17.09	12.98	13.96	13.29	13.34	10.63
FeO	4.97	3.60	1.40	2.51	1.05	1.64	1.39	3.57	2.27	1.86	3.28	1.78	1.52	1.78
MnO	0.08	0.18	0.02	0.06	0.05	0.05	0.09	0.06	0.11	0.06	0.05	0.07	0.07	0.01
MgO	1.73	2.23	0.29	1.74	1.38	0.52	0.36	0.60	0.42	0.30	0.26	0.32	0.36	0.28
CaO	6.45	4.68	5.25	4.01	3.23	4.66	3.67	4.44	3.50	2.70	2.63	2.14	2.03	1.43
Na_2O	4.56	4.44	5.86	3.37	4.13	4.98	3.22	4.15	3.89	4.53	3.67	2.98	2.27	1.42
K_2O	4.90	4.22	2.77	5.77	4.02	2.25	3.78	2.48	2.07	2.67	2.48	3.76	2.95	2.94
P_2O_5	0.28	0.25	0.08	0.08	0.10	0.11	0.09	0.07	0.05	0.13	0.07	0.04	0.09	0.03
Cl	0.06	0.03	0.11	0.00	0.04	0.14	0.11	0.18	0.12	0.19	0.13	0.11	0.13	0.14
S	0.01	0.02	0.04	0.02	0.04	0.02	0.03	0.04	0.05	0.02	0.05	0.05	0.04	0.04
Total	97.78	100.12	100.04	99.49	99.98	99.45	100.59	97.25	99.02	98.20	99.95	99.00	101.02	98.54
T, °C	1180	1180	1200	1180	1200	1180	1200	1180	1180	1200	1180	1180	1180	1180
An	70.3	58.3	46.6	65.2	46.6	58.3	46.6	64.2	71.5	71.0	71.5	71.5	64.2	64.2

Note: (1–7) 1956 eruption; (8–14) 1974 eruption.

Table 6. Composition (wt %) of melt inclusions in plagioclase from andesite of the 1979, 1985, 1987, and 1990 eruptions

Component	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	69.20	71.78	75.11	77.25	79.28	70.54	66.07	72.34	74.22	66.73	66.91	66.96	68.42	75.50
TiO_2	0.42	0.36	0.56	0.27	0.51	0.24	0.26	0.38	0.33	0.67	0.85	0.60	0.35	0.30
Al_2O_3	14.11	13.48	11.02	11.02	10.22	14.64	17.49	13.91	14.15	14.20	13.94	16.20	17.34	11.34
FeO	2.46	1.09	1.52	1.62	1.86	2.08	2.59	2.65	1.56	4.30	4.40	2.92	1.83	2.69
MnO	0.06	0.04	0.04	0.03	0.05	0.10	0.01	0.07	0.09	0.14	0.11	0.12	0.03	0.10
MgO	0.40	0.17	0.19	0.23	0.05	0.32	0.36	0.71	0.35	1.20	1.06	0.85	0.39	0.66
CaO	3.24	1.42	0.85	1.20	0.69	2.70	4.72	3.18	2.41	3.30	4.16	4.00	3.75	1.40
Na_2O	5.15	3.29	2.94	3.30	3.08	5.18	5.23	4.05	4.12	3.62	3.72	5.59	5.48	3.75
K_2O	2.70	6.65	4.39	3.86	4.35	2.92	5.24	2.80	2.68	3.58	2.82	2.67	2.13	3.26
P_2O_5	–	0.03	0.10	0.01	0.00	0.06	0.10	0.02	0.12	0.12	–	0.16	0.08	–
Cl	0.24	0.00	0.00	0.03	0.22	0.16	0.00	0.15	0.18	0.00	0.21	0.17	0.13	0.17
S	–	0.04	0.03	0.04	0.04	0.02	0.03	0.03	0.03	0.06	–	–	0.03	–
Total	97.98	98.35	96.75	98.86	100.35	98.96	102.11	100.29	100.24	97.92	98.18	100.24	99.96	99.17
T, °C	1120	1200	1200	1200	20	1200	1200	1200	1200	1170	1100	1170	1200	1100
An		49.3	52.6	45.2	58.3	74.0	60.0	56.0	80.0	77.5	52.2	64.6	52.0	52.2

Note: (1–5) 1979 eruption; (6) 1985 eruption; (7–9) 1987 eruption; (10–14) 1990 eruption.

Table 7. Composition (wt %) of melt inclusions in the same plagioclase phenocrysts

Component	1956		1974								
	1	2	3	4	5	6	7	8	9	10	11
SiO_2	65.67	73.90	56.62	59.48	62.10	63.59	65.55	72.52	75.08	77.34	78.26
TiO_2	0.23	0.44	0.22	1.14	0.79	0.46	0.29	0.65	0.58	0.51	0.53
Al_2O_3	15.78	11.54	17.04	15.31	16.92	12.99	16.49	9.90	11.56	10.91	11.40
FeO	1.48	2.08	5.43	6.37	7.18	5.93	4.55	1.80	1.52	1.44	1.51
MnO	0.05	0.03	0.17	0.29	0.14	0.16	0.15	0.06	0.00	0.00	0.02
MgO	0.24	0.52	4.85	3.53	1.53	4.47	1.99	0.36	0.11	0.10	0.25
CaO	3.98	1.69	7.71	8.10	5.72	6.13	6.03	1.39	1.15	0.96	0.87
Na_2O	3.96	2.89	5.03	4.29	3.93	4.27	3.76	2.81	3.47	3.16	2.97
K_2O	5.43	2.99	2.68	1.80	1.82	2.36	1.75	4.24	4.07	3.99	4.06
P_2O_5	0.12	0.06	0.08	0.17	0.19	0.17	0.09	0.12	0.04	0.04	0.03
Cl	0.13	0.10	0.03	0.00	0.18	0.04	0.09	0.07	0.03	0.07	0.04
S	0.02	0.02	0.03	0.05	0.03	0.04	0.05	0.03	0.03	0.04	0.04
Total	97.09	96.26	99.89	100.53	100.53	100.61	100.79	93.95	97.64	98.56	99.98

Component	1979		1985		1987			
	12	13	14	15	16	17	18	19
SiO_2	68.96	76.36	55.87	80.89	56.35	57.15	63.78	72.45
TiO_2	0.18	0.13	0.16	0.31	0.36	0.35	0.40	0.39
Al_2O_3	15.55	9.87	19.44	10.05	16.33	16.68	16.38	12.91
FeO	2.04	2.78	3.02	1.99	5.42	4.92	3.57	2.98
MnO	0.09	0.00	0.14	0.02	0.16	0.17	0.05	0.12
MgO	0.30	0.26	5.17	0.24	4.06	4.16	2.24	1.86
CaO	3.56	0.97	7.13	1.60	6.96	7.12	3.66	2.43
Na_2O	3.60	3.53	3.23	2.40	4.34	4.12	3.70	3.82
K_2O	3.64	3.15	5.73	2.44	2.69	2.70	4.02	4.03
P_2O_5	–	–	–	–	0.10	0.15	0.37	0.41
Cl	0.16	0.06	0.01	0.09	0.01	0.03	0.00	0.00
S	–	–	–	–	0.01	0.01	0.02	0.02
Total	98.08	97.11	99.90	100.03	96.79	97.56	98.19	101.42

3–4 wt % in the sample from the 1956 eruption (Table 7). The Cl and S contents average 0.09 and 0.03 wt %, respectively.

It is pertinent to note that inclusions broadly varying in composition, including fairly contrasting ones, often occur together in one phenocryst (Table 7), commonly among inclusions of regular shape. This fact definitely points to the very complicated crystallization history of these phenocrysts, and, hence, of the melts that produced the Bezymyannyi andesite.

DISCUSSION

Our research led us to establish that the Bezymyannyi andesite crystallized from magmatic melts not only of intermediate, but also of acid composition. Similar compositional relationships between rocks and melt inclusions were determined in the rocks of the 1980–1982 eruption of Mount St. Helens volcano, United States: the SiO_2 contents varied from 60.5 to 64.3 wt % (averaging 63.0 wt %) in the rocks (20 samples) and from 67.9 to 76.6 wt % in the melt inclusions (more than 300 inclusions) [8]. The acid composition of the melts is also confirmed by analyses of the groundmass glass, which is even higher in SiO_2: from 70.8 to 79.6 wt %. The differences between the contents of other major components in the rocks and melt inclusions are also quite large. Direct analyses of the water content in the melt inclusions on an ion microprobe also yielded high contents, from 3 to 7 wt %. Similar results on melt inclusions in samples from the same eruption of Mount St. Helens were obtained later by other researchers [9].

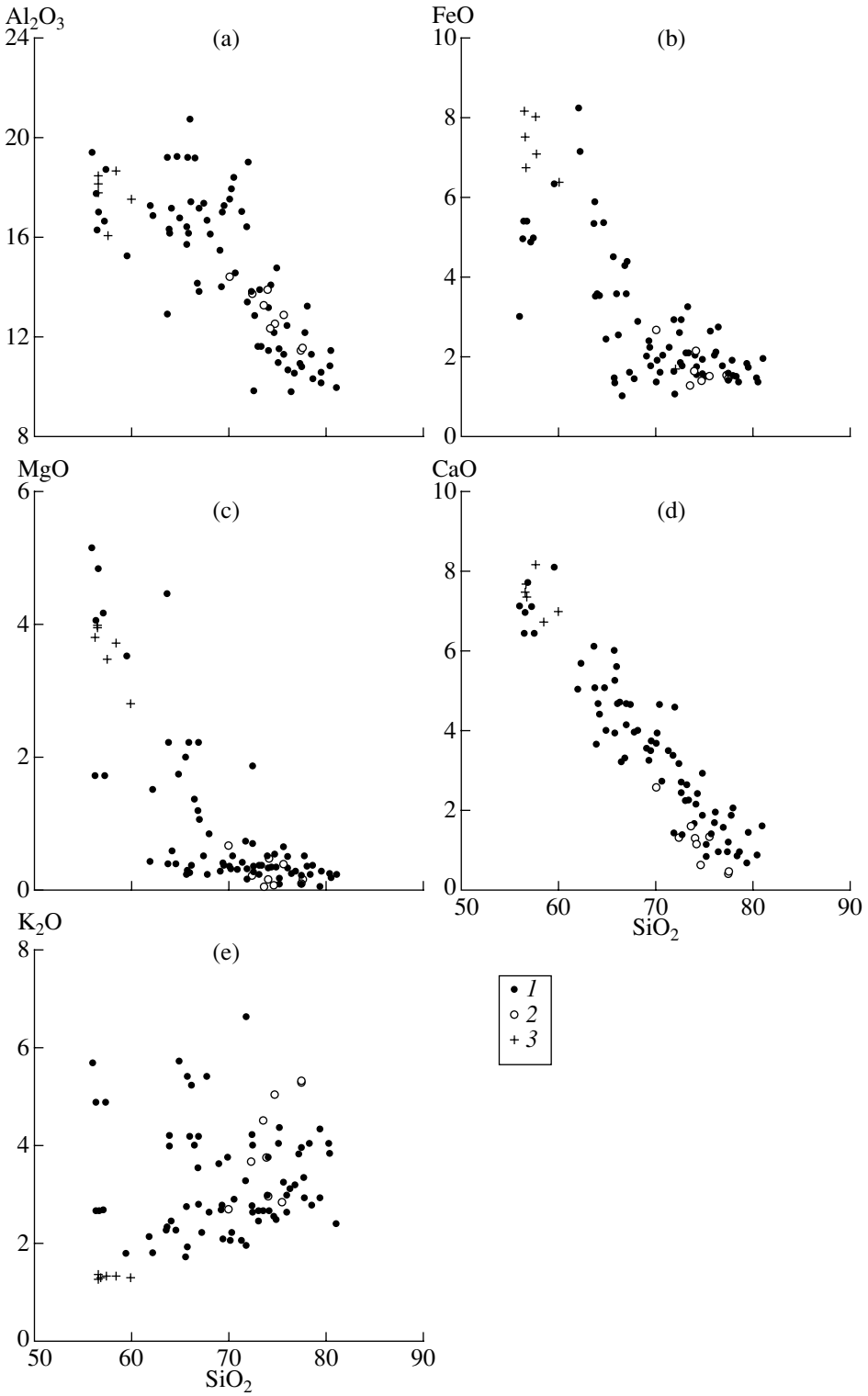

Fig. 2. Correlations between the contents of SiO_2 and (a) Al_2O_3, (b) FeO, (c) MgO, (d) CaO, and (e) K_2O in (*1*) melt inclusions, (*2*) groundmass glass, and (*3*) whole rocks (andesites).

Analogous relations between rocks and melts are quite common in andesitic volcanics [8–11]. As was demonstrated in the review [10] of all preexisting materials (85 analyses of andesites and 317 analyses of melt inclusions in minerals of these rocks), the overwhelming majority of andesites were formed by the crystallization of dacitic and rhyolitic magmatic melts. However, the rocks of Bezymyanny volcano are noted for some uncommon major-element features. First, the melts of intermediate composition occur here relatively

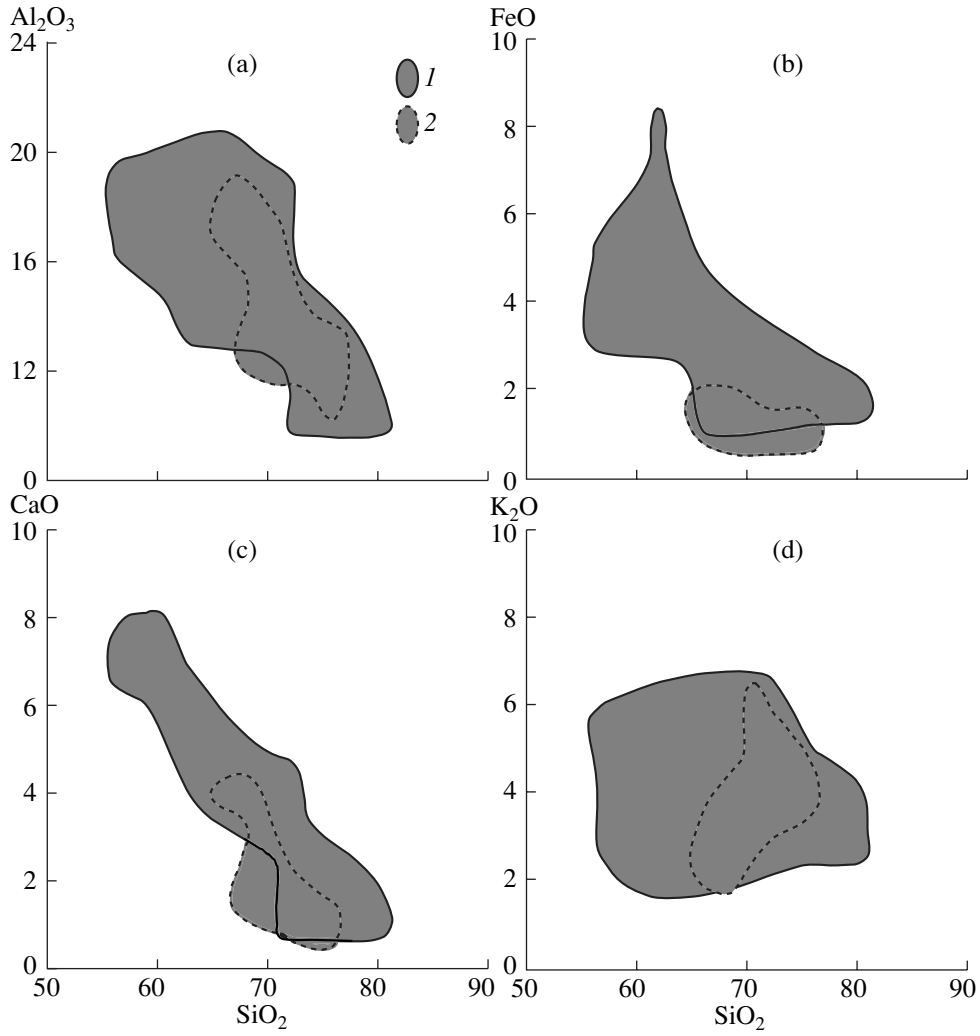

Fig. 3. Composition of melt inclusions in plagioclase from andesites of (*1*) Bezymyannyi and (*2*) Shiveluch volcanoes.

widely, along with all transitional varieties between andesite and rhyolite, the Al_2O_3, FeO, MgO, and CaO contents systematically decrease, and the Na_2O contents also systematically increase with the decreasing silicity of the melts. Second, the contents of K_2O significantly vary (from 1.8 to 6.6 wt %) regardless of the contents of other components. Both high- and low-K varieties occur among the acid and intermediate melts. Third, the Bezymyannyi melts are relatively low in water.

In other centers of andesitic volcanism, such as Shiveluch volcano in Kamchatka and the Stiavnica caldera in central Slovakia, the compositional spread of the inclusions is much more narrow and restricted to the acid region (Fig. 3). At the same time, these glasses are typically high in water: up to 5–6 wt % in the melts of Shiveluch [12] and 7–13 wt % in the melts of Stiavnica [13].

It follows that Bezymyannyi volcano is probably characterized by a somewhat different type of andesitic magmatism. It is premature to make final conclusions concerning the processes responsible for the origin of the rocks, but it can be definitely established that these rocks did not result from the equilibrium crystallization of andesitic melts alone, as was previously hypothesized in [6]. As alternative mechanisms, we propose the processes of crystallization differentiation, magma mingling, and interaction between the melt and crustal rocks or an alkaline aqueous fluid [14]. Let us assess the probability of the participation of each of these processes in the genesis of the Bezymyannyi rocks.

The melt compositions cluster around clear-cut differentiation trends in covariance diagrams (Fig. 2). However, no correlations were detected between the composition of melt inclusions and the basicity of their host minerals. Inclusions of different compositions, including low- and high-K ones, often occur closely spaced in a single phenocryst. This rules out the possibility of the sequential origin of the melts solely as a result of andesitic melt differentiation.

The participation of mixing in rock-forming processes is usually reliably identified by characteristic petrographic features [15, 16]. However, our rocks display neither structural heterogeneity, nor contrasting mineral assemblages and xenocrysts, although some morphological features of the plagioclase (resorption zones as evidence of discontinuous disequilibrium crystallization) provide indirect arguments for melt mixing. In any event, it seems to be unlikely that mixing was the only process responsible for the andesite origin.

Contamination in one or another form perhaps also contributed to the process. At least, it could explain the appearance of high-K melts (K is sometimes believed to be an indicator of crustal contamination [14]), although very high contents of this element were occasionally detected in primary primitive melts such as the picrite basalt from the Tumrok Range, eastern Kamchatka [17]. The absence of precise estimates of the water content precludes ascribing the origin of the high-K varieties to the interaction of the melt with aqueous alkaline fluid. Data available so far do not point to any correlation between the water and potassium contents.

Most probably, all of these processes variably participated in the development of Bezymyannyi volcano. However, genetic conclusions require a more thorough investigation into the volcano.

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