JOURNAL OF PETROLOGY | VOLUME 45 | NUMBER 11 | PAGES 2325–2345 | 2004 | doi:10.1093/petrology/egh059

The 1996 Eruption of Karymsky Volcano, Kamchatka: Historical Record of Basaltic Replenishment of an Andesite Reservoir

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RECEIVED DECEMBER 5, 2002; ACCEPTED JULY 8, 2004
ADVANCE ACCESS PUBLICATION AUGUST 27, 2004

The simultaneous eruption in 1996 of andesite from Karymsky volcano and of basalt from the Academy Nauk vent 6 km away appears to provide a case of mafic recharge of an andesite reservoir for which the time of recharge is exactly known and direct samples of the recharging magma are available. The explosive phreato-magmatic eruption of basalt was terminated in less than 24 h, whereas andesite erupted continuously during the following 4 years. Detailed petrological study of volcanic ash, bombs and lavas of Karymsky andesite erupted during the period 1996–1999 provides evidence for basaltic replenishment at the beginning of the eruptive cycle, as well as a record of compositional variations within the Karymsky magma reservoir induced by basaltic recharge. Shortly after the beginning of the eruption the composition of the matrix glass of the Karymsky tephra became more mafic and then, within 2 months, gradually returned to its original state and remained almost constant for the following 3 years. Further evidence for basaltic replenishment is provided by the presence of xenocrysts of basaltic origin in the andesite of Karymsky. A conspicuous portion of the plagioclase phenocrysts in the Karymsky andesite has calcic cores, with compositions and textures resembling those of plagioclases in the Academy Nauk basalt. Similarly, the earlier portion of the andesite of the eruption sequence contains rare olivines, which occur as resorbed cores in pyroxenes. The composition of the olivine matches that of olivines in the Academy Nauk basalt. The sequence of events appears to be: (1) injection of basaltic magma into the Karymsky chamber with immediate, compensating expulsion of pre-existing chamber magma from the Karymsky central vent; (2) direct mixing of basaltic and andesitic magmas with dispersal of phenocrysts associated with the basalt throughout the andesite so that newly mixed magma appeared at the vent within 2 months; (3) re-establishment of thermal and chemical equilibrium within the reservoir involving crystallization in the new hybrid liquid, which returned the melt composition to 'normal', formed rims on inherited calcic plagioclase, and caused the resorption of dispersed olivine xenocrysts. Taken together, these findings indicate that the Karymsky magma reservoir was recharged by basalt at the onset of the 1996 eruptive cycle. The rapidity and thoroughness of mixing of the basalt with the pre-existing andesite probably reflects the modest contrast in temperature, viscosity, and density between the two magmas.

KEY WORDS: *Karymsky; Kamchatka; magma mixing; andesite; volcanic glass; plagioclase*

INTRODUCTION

Basaltic replenishments transport heat and mass to long-lived crustal magma storage reservoirs and may trigger volcanic eruptions. Petrological evidence for this process includes the presence of mafic enclaves and phenocryst zoning patterns in many arc magmas (e.g. Eichelberger, 1975; Singer *et al.*, 1995; Pallister *et al.*, 1996; Davidson *et al.*, 2001). Although the fingerprints of magma mixing—the major result of replenishment—are commonly found in volcanic rocks, the magmas produced by mixing may strongly vary in terms of the degree of homogenization, both in space and time. In some cases, e.g. Soufrière Hills, Montserrat (Murphy *et al.*, 2000), the presence of abundant mafic enclaves and non-equilibrium

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phenocryst assemblages in the erupted magmatic rocks demonstrates that mixing of mafic and silicic end-members had not advanced to complete homogenization prior to eruption. In others, e.g. Arenal, Costa Rica (Streck *et al.*, 2002), the erupted products are apparently homogeneous and the record of basaltic replenishment is preserved only in the phenocrysts.

Several approaches have been used to explain this difference. Both physical and numerical models have been used to investigate the process of magma mixing (e.g. Sparks & Marshall, 1986; Snyder & Tait, 1996; Bergantz & Breidenthal, 2001). The best way to validate such models is to compare their predictions with records of actual basaltic replenishment events, where the rates of mixing can be constrained. Unfortunately, such records are limited to a few well-documented historical eruptions (Nakamura, 1995; Pallister *et al.*, 1996; Streck *et al.*, 2002).

The eruption of Karymsky volcano, Kamchatka, which started in 1996 with the simultaneous eruption of andesite and basalt from neighboring vents and is still continuing, provides an important natural laboratory to investigate the dynamics of mixing of andesite and basalt magmas. This paper presents the results of a detailed petrological study of lava, volcanic bombs, and tephra erupted from Karymsky volcano between 1996 and 1999. These results strengthen and extend the previous work of Eichelberger & Izbekov (2000) and Izbekov *et al.* (2002). We argue, on the basis of compositional variations of groundmass glass and the presence of xenocrysts, that the 1996 eruption of Karymsky was triggered by basaltic recharge. This model is supported by the eruption chronology and geological observations. The homogeneity of the Karymsky andesite magma erupted 2 months after the beginning of the eruption suggests that mixing was fast and efficient, perhaps as a result of a modest contrast in temperatures and physical properties between the basalt and andesite.

GEOLOGICAL SETTING

Karymsky volcano and the adjacent Academy Nauk caldera are located in the central part of the Eastern Volcanic Front of Kamchatka (Fig. 1), above where the subducting Pacific plate reaches a depth of *c.* 120 km (Gorbatov *et al.*, 1997). Centered 9 km apart, both Karymsky and Academy Nauk belong to the greater Karymsky volcanic center, a group of volcanoes, calderas and maars constructed since the Pliocene (Masurenkov, 1980). Within this center, Karymsky and Academy Nauk form part of a chain of eruptive vents, whose location is thought to be controlled by a north–south-trending fault (Fig. 1). Magmas erupted during the Holocene along this fault have varied in composition from basalt to rhyolite, with andesites and dacites being the most voluminous. Numerous hot springs and geysers are currently active along the fault in the vicinity of Karymsky and Academy Nauk.

Karymsky volcano

Karymsky is a stratovolcano that occupies most of a 5 km diameter caldera. The caldera formed *c.* 7900 yr BP as a result of a catastrophic eruption that produced 5–7 km^3 of dacite (Braitseva & Melekestsev, 1991). The cone of Karymsky was built by lavas, pyroclastic flows, and ash-fall deposits throughout the last 5300 years, interrupted by a period of extended repose between *c.* 2800 and 500 yr BP. In the 20th century, Karymsky has been in a state of nearly continuous explosive and effusive activity during 1908–1915, 1921–1925, 1929–1935, 1943–1947, 1952–1967 and 1970–1982 (Ivanov, 1970; Tokarev, 1989). The most recent eruptive cycle of Karymsky started in January 1996 and continues at present.

The eruptive behavior of Karymsky is typically confined to a Strombolian type of activity with frequent, yet remarkably regular explosions that send ash and gas to an altitude of up to 2–3 km above the vent. Continuous effusion of blocky lava flows often occurs at the same time and from the same vent as the explosions. Eruptive activity is usually more vigorous and regular at the beginning of an eruptive cycle, whereas closer to the end of the cycle eruptions become sporadic. The total volume of andesite erupted during a single cycle usually does not exceed 0·1 km^3 (Tokarev, 1989; Ivanov *et al.*, 1991).

During the last 500 years Karymsky has produced andesites of remarkably uniform composition (59–62 wt % SiO_2). The andesites are homogeneous and almost never contain xenoliths. Phenocryst phases include plagioclase and lesser amounts of clinopyroxene, orthopyroxene, and magnetite. In addition, rare olivine xenocrysts (Fo_{70-75}) have been reported in banded lavas and volcanic bombs erupted at the beginning of the 1970–1982 eruptive cycle (Ivanov, 1996).

Seismic data collected by a temporary local network during March–December 1985 indicated that hypocenters of volcano-tectonic earthquakes were clustered around a cylindrical zone that starts at 4 km below Karymsky and reaches a diameter of *c.* 5 km at 6·5 km depth. The absence of earthquakes inside this zone suggests the presence of magma and thus the hypocenters may define the location of the roof of a Karymsky magma reservoir (Shirokov *et al.*, 1988).

Academy Nauk caldera

The Academy Nauk caldera is located *c.* 9 km south of Karymsky (Fig. 1). It was formed by a voluminous eruption of dacites and collapse of the Academy Nauk volcano *c.* 28–48 kyr ago (Masurenkov, 1980). The age of the caldera is based on a fission-track study of obsidian xenoliths within the basal plinian fall layer. At present the

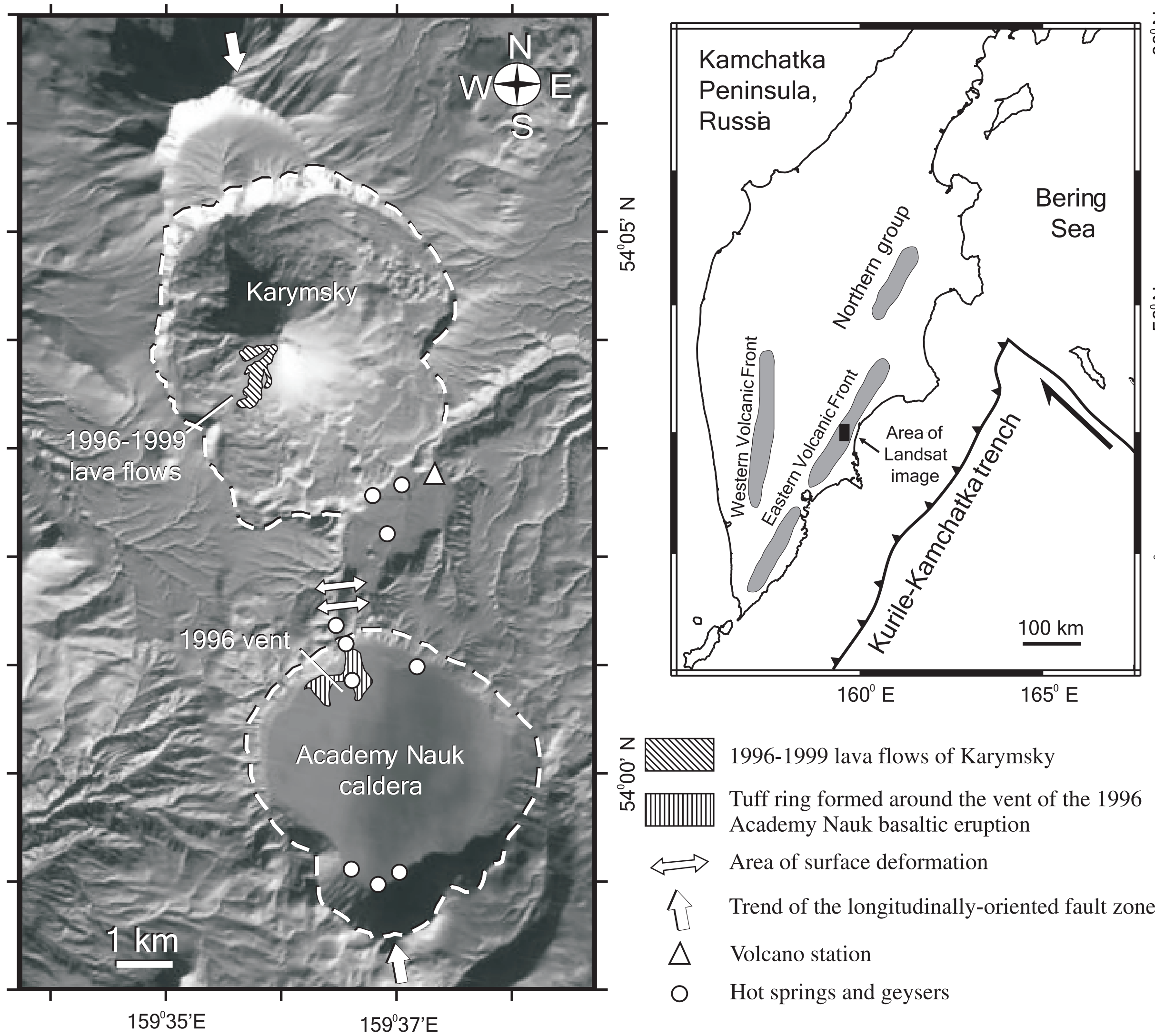

Fig. 1. Landsat-4 image of Karymsky volcano and Academy Nauk caldera. Karymsky volcano occupies a caldera formed at 7900 yr BP. Academy Nauk caldera (40 ka BP) is centered 9 km south of it, on the same longitudinally oriented fault zone, the trend of which is indicated by arrows. Dashed lines indicate the rims of Karymsky (north) and Academy Nauk (south) calderas.

caldera is occupied by Karymsky Lake, which reaches *c.* 60 m depth (Ushakov & Fazlullin, 1998).

Since the caldera-forming event, activity within the caldera has been confined to phreato-magmatic eruptions that have produced small volumes of basalt at least twice since 5000 yr BP (Braitseva, 1998; Belousov & Belousova, 2001). These eruptions formed distinctive maars in the northern and southern parts of the caldera.

THE 1996 ERUPTION OF KARYMSKY AND ACADEMY NAUK

The first signs of unrest at Karymsky were observed in March 1995, after a 13 year period of dormancy, when the number of volcano-tectonic earthquakes at Karymsky and Academy Nauk began to increase. On 1 January 1996, the number of seismic events rose abruptly and in 4 h culminated in a magnitude 6·6 earthquake. The epicenter of the main shock was located 17 km south of Karymsky at *c.* 10 km depth, on the lateral extension of the fault that connects Karymsky and Academy Nauk (Gordeev *et al.*, 1998; Zobin & Levina, 1998).

Several hours after the main shock, on 2 January, the eruption of Karymsky began with a steady gas-and-ash emission from the summit vent, forming a 3000 m high eruptive cloud trailing to the east from the volcano. Approximately 12 h later, a separate eruption started from a new vent formed in the northern part of the Academy Nauk caldera (Belousov & Belousova, 2001).

During the following 18 h the two vents erupted simultaneously: the summit vent of Karymsky produced a continuous ash plume, whereas the newly formed vent in the northern part of Academy Nauk caldera generated intermittent phreato-magmatic blasts, sending volcanic bombs, ash, and vapor to an altitude of 8000 m. Eighteen hours after its onset the eruption of Academy Nauk ceased, whereas the eruption of Karymsky continued.

During the first 6 weeks after the onset of the eruption, the eruptive style of Karymsky fluctuated significantly. Several pyroclastic flows occurred associated with large explosions; the rate of explosions varied from 2–3 per day to 4–6 per hour. After February 1996, however, the eruption became more regular, characterized by 4–6 explosions per hour, sending ash plumes to an altitude of 400–900 m above the vent (Johnson *et al.*, 1998; Muravyev *et al.*, 1998). In addition to explosions, a lava flow was almost continually active on the western flank of the volcano. The activity remained constant until early 1999, when the eruption became sporadic, slowly declined, and ceased by mid-2000. In November 2001, however, it resumed and currently continues with the same remarkable regularity of explosions.

Details of the eruption have been given by Muravyev *et al.* (1998) and Belousov & Belousova (2001), and here we emphasize only the main points relevant to this study. First, the eruption was preceded by a strong 6·6 M earthquake on the fault that hosts the vents, which was probably not coincidental. Whether the earthquake triggered the eruption or, alternatively, the magma ascent facilitated the release of accumulated strain is still disputed (Gordeev *et al.*, 1998; Zobin & Levina, 1998). Second, significant ground deformation occurred between the eruptive vents. Cracks as long as 700 m were formed parallel to the north–south fault (Leonov, 1998). The area of major ground cracks coincides with maximum east–west extension, reaching an amplitude of 2·33 m (Maguskin *et al.*, 1998). Extension between the eruptive vents probably occurred gradually rather than catastrophically, as no damage was done to a wood-frame building located nearby, thus suggesting that a basaltic dike may have propagated along the active fault. Given that a measurable extension also occurred north of the Karymsky vent, such a dike would probably have intercepted the crustal magma system beneath Karymsky. Third, the magmas simultaneously erupted from neighboring vents had different bulk compositions. The Academy Nauk vent erupted basalt (51·8 ± 0·2 wt % SiO_2), whereas the Karymsky summit vent erupted andesite (62·4 ± 0·4 wt % SiO_2). The latter was almost identical to andesites erupted during previous periods of activity (Ivanov, 1996). The 1996 magmas were compositionally distinct from each other and lacked evidence of mechanical mixing, i.e. no mafic enclaves were found in the andesites, nor were bands or xenoliths of andesite found in the basalt, and no intermediate magma compositions were erupted.

Considered together, the characteristics of the 1996 eruption of Karymsky and Academy Nauk are consistent with the hypothesis that a basalt dike was injected along the pre-existing fault, intersected the crustal magma reservoir beneath Karymsky, and triggered the eruption. The eruption of basalt was fortunate, because it provides actual samples of the mixing end-member and thereby allows us to test this hypothesis by direct comparison of phenocrysts in the basalt with those in the erupted andesite. This assumes, of course, that the basalt composition was initially homogeneous along the dike.

SAMPLES AND ANALYTICAL METHODS

Volcanic ash, bombs, and lava flows from the 1996–1999 period of activity of Karymsky, as well as pyroclastic material from the Academy Nauk center, were sampled during 1997, 1998, and 1999. Tephra samples from the January–July 1996 period of eruption were provided by Dr V. A. Budnikov (Institute of Volcanology, Petropavlovsk-Kamchatsky). Most volcanic ash samples were collected at Karymsky Volcano Station, ~3·6 km from the active summit vent, and represent cumulative ash falls produced by discrete explosions during a 0·5–4 h period. Dr Y. D. Muravyev (Institute of Volcanology, Petropavlovsk-Kamchatsky) provided tephra samples of the 1996–1997 winter period, which were extracted from snow cores. The availability of samples of Karymsky pyroclasts vs time of eruption is shown in Fig. 2.

Whole-rock compositions of volcanic bombs and lavas (Table 1) were obtained at Washington State University using X-ray fluorescence spectrometry (XRF) for major element oxides, Ni, Cr, V, Zr, Ga, Cu and Zn, and inductively coupled plasma mass spectrometry (ICP-MS) for rare earth elements (REE), Ba, Th, Nb, Y, Hf, Ta, U, Pb, Rb, Cs, Sr and Sc. Analytical procedures and uncertainties have been discussed by Nye *et al.* (1994). Modes of phenocrysts in Table 1 were determined by point counting (1000 points) using a petrographic microscope and automated stage.

Ash particles were mounted into epoxy, polished, and carbon-coated to a thickness of 25 nm. Matrix glasses were analyzed for major elements by electron probe microanalysis (EPMA) at the University of Alaska Fairbanks using a Cameca SX-50 system, which is equipped with four wavelength-dispersive and one energy-dispersive spectrometers. The analytical conditions for analyses of glass were 15 kV accelerating voltage, 10 nA beam current, and 10 μm diameter electron beam. Na and Al were analyzed first to reduce the effect of volatilization. All analyses of tephra glass were completed in a single

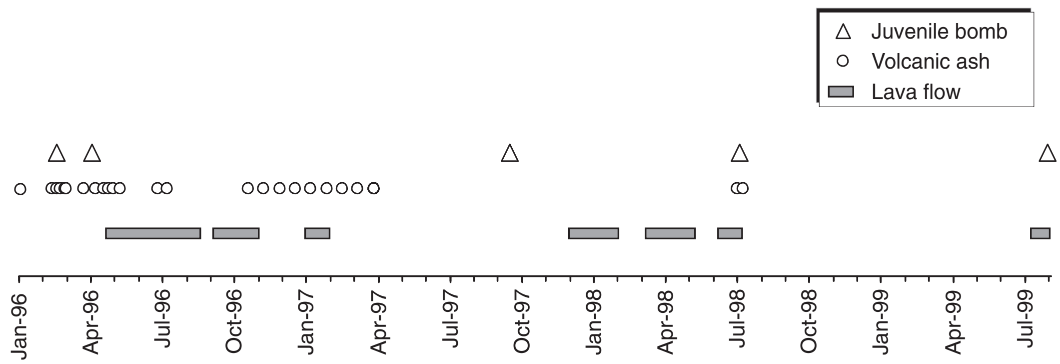

Fig. 2. Samples of pyroclastic eruptive products of Karymsky volcano vs time of their eruption. Length of horizontal bars corresponds to an approximate time of the effusion of the lava flows.

uninterrupted 72 h session; the quality of data was monitored by repeated analyses of an internal standard (Old Crow rhyolite). To avoid interference with microlites, areas of microlite-free groundmass glass were selected for EPMA based on back-scattered electron (BSE) imagery. After acquisition all analyses were carefully checked for elevated concentrations of Ca, Mg, Al, and Fe to ensure that the glass analyses were not compromised by the presence of plagioclase and pyroxene microlites. At least five BSE images of different ash particles within each tephra sample were acquired in raster mode at 15 kV and 50–150 nA beam current. The microlite content in the tephra was determined from these BSE images using MicroImage software (Advanced Microbeam Co.).

Samples of volcanic bombs and lavas were prepared as polished thin sections, examined using a petrographic microscope, and carbon-coated. The analytical conditions for mineral analyses were similar to those for the glass analyses (15 kV, 10 nA), but a 1–3 μm focused electron beam was used. BSE images of plagioclase phenocrysts were acquired at 15 kV and 50–150 nA beam current. The typical analytical errors for mineral and glass EPMA data can be found in the Electronic Appendix, which may be downloaded from *Journal of Petrology Online* at http://www.petrology.oupjournals.org.

Representative plagioclase phenocrysts from the Academy Nauk basalt (samples 97IPE3 and 98IPE22a in Table 1) and Karymsky andesite (samples BV170296, 98IPE25, 98IPE26, and 99IPE8) were chosen for electron microprobe traverses from which more than 1600 major element analyses were obtained along core-to-rim traverses in 25 crystals. Sr and Ba contents in multiple spots along the microprobe traverses of the representative plagioclase phenocrysts were analyzed by laser-ablation inductively coupled plasma mass spectrometer (LA-ICP-MS) using a Micromass Plasma instrument equipped with a Cetac LSX 200 laser-ablation system at Michigan State University. The 266 nm Nd:YAG laser was focused to a 25 μm spot size. The beam propagated into the sample at a rate of 3 μm/s. Concentrations of Sr and Ba were calculated by using peak intensities of ^{88}Sr, ^{138}Ba, and ^{44}Ca calibrated against an NIST 612 glass standard and EPMA determinations of Ca in analyzed spots as outlined by Norman *et al.* (1996). The typical analytical error was 1 ppm for Ba and 14 ppm for Sr.

PETROGRAPHY AND MINERALOGY OF ACADEMY NAUK BASALT

In less than 18 h the eruption of Academy Nauk vent produced *c.* 0·04 km^3 of volcanic bombs and ash, forming a tuff ring in the northern part of the Academy Nauk caldera (Muravyev *et al.*, 1998). The predominant product of the eruption was a porphyric basalt, the whole-rock composition of which is close to the composition of basalts erupted during a similar event at 4800 yr BP (Table 1). The basalt contains conspicuous, but volumetrically minor, silicic xenoliths of granophyre, granite, rhyolitic pumice, and altered silicic tuff (Grib, 1998; Izbekov *et al.*, 2004). The xenoliths commonly show signs of disintegration and assimilation by the host basalt, such as melting and mechanical blending.

Basaltic bombs are highly vesicular (20–40 vol. % porosity) and phenocryst-rich, containing 40–45 vol. % phenocrysts of plagioclase, clinopyroxene, and olivine (Fig. 3a). Euhedral magnetite microphenocrysts occur as a minor phase. Orthopyroxene microphenocrysts occur in trace amounts as inclusions in olivine. Although we attempted to collect samples of basalt with no visual signs of contamination by silicic material, rare 1–3 mm silicic enclaves, as well as xenocrysts of quartz, were occasionally observed petrographically. The whole-rock composition of the basalt shows little variation from one bomb to another in major and trace elements (Table 1, Fig. 4).

Groundmass and melt inclusions

The groundmass of the Academy Nauk basalt is pilotaxitic and consists of 60 vol. % dark brown glass and 32 vol. % elongated plagioclase microlites. The amounts

Table 1: Whole-rock composition of lavas and volcanic bombs

Sample:[1]	J-4491	97IPE3	98IPE22A	98IPE22B	98IPE22C	98IPE22D	BV170296	BV040496	98IPE27	98IPE28
Location:	Karymsky	Acad. Nauk	Acad. Nauk	Acad. Nauk	Acad. Nauk	Acad. Nauk	Karymsky	Karymsky	Karymsky	Karymsky
Eruption date:	1976	2 Jan. 1996	2 Jan. 1996	2 Jan. 1996	2 Jan. 1996	2 Jan. 1996	17 Feb. 1996	4 Apr. 1996	6 Apr.— 13 Aug. 1996	Sep. — Oct. 1996
Major elements										
SiO_2	62·89	51·98	51·87	51·58	51·62	51·72	61·46	62·88	61·87	61·97
Al_2O_3	16·33	18·73	19·02	19·18	19·17	19·31	16·41	16·35	16·29	16·33
TiO_2	0·88	0·74	0·73	0·74	0·74	0·74	0·91	0·88	0·91	0·90
FeO*	5·47	7·65	7·47	7·67	7·55	7·48	5·73	5·26	5·76	5·91
MnO	0·14	0·15	0·15	0·15	0·15	0·15	0·15	0·14	0·15	0·15
CaO	5·06	10·32	10·51	10·54	10·68	10·66	5·43	4·94	5·31	5·33
MgO	1·74	5·35	5·71	5·28	5·42	5·5	1·88	1·64	1·91	1·85
K_2O	1·67	0·59	0·58	0·59	0·57	0·56	1·56	1·69	1·6	1·59
Na_2O	4·78	2·84	2·86	2·9	2·84	2·88	4·63	4·84	4·68	4·73
P_2O_5	0·26	0·14	0·14	0·14	0·14	0·14	0·26	0·26	0·26	0·26
Total	99·22	98·49	99·03	98·76	98·88	99·13	98·41	98·88	98·74	99·02
Trace elements										
Ni	3	26	33	25	29	30	1	3	4	3
Cr	3	81	88	81	87	87	6	6	10	12
V	110	221	210	200	216	199	121	115	135	131
Zr	146	74	71	73	72	71	138	148	143	141
Ga	20	15	15	18	16	20	17	18	19	16
Cu	22	57	58	71	65	68	29	18	30	28
Zn	75	62	62	55	59	60	73	74	71	73
La	12·17	5·17	5·46	5·36	5·46	5·34	11·55	11·84	11·95	11·12
Ce	28·01	11·50	12·20	12·37	12·39	12·24	26·57	27·39	26·68	25·95
Pr	3·75	1·66	1·74	1·74	1·74	1·73	3·73	3·72	3·62	3·57
Nd	17·65	8·26	8·12	8·33	8·21	8·34	17·40	17·33	17·17	16·95
Sm	4·95	2·42	2·52	2·49	2·56	2·50	4·91	4·93	5·02	4·70
Eu	1·51	0·91	0·95	0·92	0·94	0·93	1·49	1·47	1·54	1·46
Gd	5·24	2·69	2·79	2·70	2·70	2·72	5·17	5·07	5·23	5·04
Tb	0·88	0·45	0·46	0·46	0·46	0·46	0·86	0·87	0·87	0·85
Dy	5·57	2·89	2·92	2·91	2·93	2·84	5·54	5·51	5·58	5·45
Ho	1·17	0·60	0·60	0·59	0·61	0·59	1·16	1·18	1·12	1·14
Er	3·21	1·66	1·59	1·65	1·61	1·61	3·22	3·30	3·08	3·17
Tm	0·48	0·24	0·24	0·24	0·24	0·24	0·47	0·49	0·48	0·48
Yb	3·10	1·45	1·47	1·49	1·51	1·50	3·08	3·12	2·95	3·03
Lu	0·49	0·23	0·23	0·24	0·24	0·23	0·49	0·50	0·47	0·49
Ba	426	165	173	171	170	168	399	418	410	398
Th	1·79	0·52	0·61	0·59	0·60	0·57	1·76	1·80	1·62	1·77
Nb	3·45	1·30	1·40	1·37	1·44	1·33	3·30	3·44	3·23	3·28
Y	32·02	15·61	16·09	15·82	15·17	15·46	31·17	32·48	30·46	31·50
Hf	4·09	1·62	1·68	1·71	1·68	1·64	4·05	4·09	3·95	3·97
Ta	0·26	0·11	0·11	0·10	0·11	0·10	0·26	0·26	0·26	0·25
U	0·93	0·31	0·31	0·31	0·30	0·30	0·90	0·91	0·85	0·88
Pb	6·29	2·64	2·65	2·43	2·59	2·61	5·99	6·21	5·94	6·15
Rb	22·87	7·66	7·50	7·38	7·04	6·67	21·30	22·91	21·22	21·75
Cs	0·94	0·30	0·29	0·30	0·28	0·27	0·86	0·93	0·85	0·85
Sr	354	466	466	457	443	455	353	353	345	369
Sc	22·17	31·94	34·24	32·26	31·49	31·00	23·40	22·84	22·35	24·51

Sample:[1]	J-4491	97IPE3	98IPE22A	98IPE22B	98IPE22C	98IPE22D	BV170296	BV040496	98IPE27	98IPE28
Location:	Karymsky	Acad. Nauk	Acad. Nauk	Acad. Nauk	Acad. Nauk	Acad. Nauk	Karymsky	Karymsky	Karymsky	Karymsky
Eruption date:	1976	2 Jan. 1996	2 Jan. 1996	2 Jan. 1996	2 Jan. 1996	2 Jan. 1996	17 Feb. 1996	4 Apr. 1996	6 Apr.— 13 Aug. 1996	Sep.— Oct. 1996
Modal analysis										
Gm	72·9	61·2	58·8	54·5	56·7	69·8	74·7	71·6	73·1	73·6
Pl	21·4	28·1	30·6	29·9	35·1	23·0	21·5	24·8	22·6	21·0
Cpx	3·3	7·8	7·2	9·2	2·8	4·1	1·8	1·6	2·1	2·6
Opx	0·8	0·8	0·6	n.d.	n.d.	0·3	0·4	1·3	0·9	1·5
Ol	n.d.	2·0	2·6	5·9	5·0	2·1	traces	n.d.	traces	n.d.
Mt	1·5	0·2	0·1	0·6	0·3	0·7	1·7	0·6	1·3	1·3

Sample:	98IPE29	97IPE5	98IPE25	98IPE24	98IPE26	98IPE33	99IPE 9	99IPE 8	99IPE 2a	99IPE 2b
Location:	Karymsky	Karymsky	Karymsky	Karymsky	Karymsky	Karymsky	Karymsky	Karymsky	Acad. Nauk	Acad. Nauk
Eruption date:	Jan.— Feb. 1997	8 Sep. 1997	Dec. 1997— Feb. 1998	Mar.— May 1998	June— July 1998	21 July 1998	9 Aug.— 23 Aug. 1999	24 Aug. 1999	4800 yr BP	4800 yr BP
Major elements										
SiO_2	62·03	61·72	61·75	61·47	61·77	61·99	61·8	61·8	56·22	52·91
Al_2O_3	16·43	16·09	16·34	16·27	16·3	16·41	16·81	16·51	16·39	16·45
TiO_2	0·92	0·90	0·90	0·91	0·91	0·91	0·90	0·91	0·80	0·86
FeO^*	5·61	5·92	5·90	5·92	5·77	5·77	5·63	5·93	7·75	8·55
MnO	0·15	0·15	0·14	0·15	0·15	0·15	0·15	0·15	0·16	0·18
CaO	5·37	5·31	5·34	5·37	5·34	5·41	5·7	5·51	8·9	10·3
MgO	1·94	1·92	1·91	1·92	1·9	1·9	2·03	2·02	5·16	6·41
K_2O	1·59	1·57	1·59	1·58	1·6	1·58	1·52	1·55	1	0·72
Na_2O	4·69	4·52	4·7	4·65	4·67	4·7	4·61	4·57	3·27	2·76
P_2O_5	0·26	0·26	0·26	0·26	0·26	0·26	0·25	0·25	0·15	0·14
Total	98·98	98·35	98·83	98·50	98·66	99·09	99·40	99·20	99·80	99·28
Trace elements										
Ni	4	0	2	0	3	5	4	3	17	33
Cr	7	7	12	9	15	12	11	11	116	214
V	143	130	128	123	141	130	139	132	234	281
Zr	140	139	143	142	142	140	136	139	86	62
Ga	19	19	19	20	19	17	16	16	15	17
Cu	29	37	38	38	30	35	39	36	76	86
Zn	69	76	76	78	75	74	73	73	69	73
La	11·28	11·26	11·54	11·58	11·61	11·32	10·71	11·03	6·69	5·37
Ce	26·21	25·28	25·66	26·77	26·55	26·08	24·49	25·40	15·36	12·31
Pr	3·64	3·52	3·59	3·61	3·61	3·57	3·38	3·49	2·12	1·76
Nd	16·95	16·41	17·17	16·75	16·78	16·70	15·97	16·39	10·22	8·64
Sm	4·88	4·84	4·94	4·77	4·99	4·78	4·56	4·70	3·09	2·69
Eu	1·48	1·47	1·54	1·48	1·55	1·47	1·43	1·43	1·02	0·92
Gd	5·10	5·03	5·38	5·06	5·07	4·89	4·74	4·85	3·26	2·93
Tb	0·87	0·85	0·87	0·85	0·86	0·84	0·82	0·83	0·57	0·51
Dy	5·48	5·37	5·52	5·45	5·48	5·33	5·03	5·18	3·62	3·17
Ho	1·17	1·15	1·12	1·14	1·14	1·10	1·05	1·08	0·76	0·66
Er	3·23	3·11	3·13	3·21	3·11	3·10	3·01	2·97	2·11	1·85
Tm	0·47	0·47	0·48	0·46	0·46	0·45	0·44	0·44	0·31	0·26
Yb	3·06	2·84	2·96	3·05	2·97	2·98	2·75	2·89	1·99	1·67

Table 1: continued

Sample:	98IPE29	97IPE5	98IPE25	98IPE24	98IPE26	98IPE33	99IPE 9	99IPE 8	99IPE 2a	99IPE 2b
Location:	Karymsky	Karymsky	Karymsky	Karymsky	Karymsky	Karymsky	Karymsky	Karymsky	Acad. Nauk	Acad. Nauk
Eruption date:	Jan.—Feb. 1997	8 Sep. 1997	Dec. 1997—Feb. 1998	Mar.—May 1998	June—July 1998	21 July 1998	9 Aug.—23 Aug. 1999	24 Aug. 1999	4800 yr BP	4800 yr BP
Lu	0·49	0·46	0·48	0·48	0·47	0·46	0·45	0·45	0·32	0·27
Ba	398	387	407	398	394	392	385	391	244	186
Th	1·80	1·31	1·62	1·63	1·63	1·64	1·54	1·61	1·00	0·75
Nb	3·26	3·15	3·24	3·14	3·22	3·21	3·15	3·18	1·96	1·47
Y	30·81	30·31	30·40	30·00	30·29	29·62	30·23	31·50	22·14	18·84
Hf	3·98	3·80	4·07	3·83	3·90	3·83	3·76	3·76	2·34	1·69
Ta	0·24	0·25	0·25	0·24	0·25	0·24	0·23	0·24	0·14	0·10
U	0·91	0·83	0·87	0·87	0·87	0·85	0·79	0·84	0·52	0·41
Pb	5·93	5·79	5·97	5·76	5·84	5·74	5·52	5·65	3·69	3·51
Rb	21·20	21·43	20·78	20·69	20·96	21·50	20·33	21·23	14·06	9·18
Cs	0·81	0·86	0·86	0·84	0·82	0·83	0·84	0·86	0·52	0·44
Sr	365	368	350	354	354	366	376	374	381	414
Sc	23·96	22·65	22·67	21·52	21·49	24·19	23·08	22·92	40·44	45·52
Modal analysis										
GM	69·4	70·2	69·3	67·8	75·8	69·5	66·42	68·2	n.a.	n.a.
Pl	23·2	22·0	22·7	27·3	18·2	23·5	26·10	24·4	n.a.	n.a.
Cpx	4·9	6·2	4·3	3·9	1·4	5·4	5·68	5·5	n.a.	n.a.
Opx	0·9	0·8	1·3	0·4	2·4	0·8	0·94	0·9	n.a.	n.a.
Ol	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.a.	n.a.
Mt	1·6	1·9	2·4	0·5	2·2	1·8	1·60	1·8	n.a.	n.a.

[1]Descriptions of samples can be found in the Electronic Appendix, which may be downloaded from the *Journal of Petrology* web site at http://www.petrology.oupjournals.org.
Major oxides in wt % with all Fe reported as FeO, concentrations of Ni—Zn (ppm) determined by XRF, and concentrations of La—Sc (ppm) determined by ICP-MS. Gm, groundmass (glass and microlites); Pl, plagioclase; Cpx, clinopyroxene; Opx, orthopyroxene, Ol, olivine; Mt, magnetite; n.d., not detected; n.a., not analyzed; traces, $<0{\cdot}05$ vol. %.

of clinopyroxene and magnetite microlites usually do not exceed 7 and 1 vol. %, respectively. The groundmass glass is andesitic and shows significant compositional variation within samples (Table 2, Fig. 5). Rare silicic enclaves in the basalt are often fused and rimmed by a light brown glass with a higher SiO_2 content than the groundmass glass. Therefore, the compositional variability of groundmass glass in the Academy Nauk basalt can probably be attributed to contamination by silicic material.

Several 35–70 μm glass inclusions in clinopyroxene phenocrysts were analyzed by electron microprobe to provide estimates of pre-eruptive volatile content in the Academy Nauk basalts, following the 'difference method' of Devine *et al.* (1995). The glass inclusions were microlite-free and did not exhibit obvious signs of leaking. When compared on an anhydrous basis, their compositions are very close to that of the matrix glass (Table 2). The deficit in totals of glass inclusion analyses averages $2{\cdot}3 \pm 0{\cdot}5$ wt %.

Plagioclase

Plagioclase phenocrysts make up 30–35 vol. % of the Academy Nauk basalt and show little variation in composition or texture. As noted previously (Izbekov *et al.*, 2002), the majority of plagioclase is euhedral and has a coarse-sieved interior (Fig. 3c). This texture is due to the presence of abundant melt inclusions, which vary from circular to elongate and irregular. The high concentration of inclusions suggests that they form a system of interconnected channels permeating the crystals' interiors. Similar textures have been reproduced in decompression (Nelson & Montana, 1992) and heating (Johannes *et al.*, 1994) experiments, where they resulted from dissolution rather than skeletal growth. Both melt inclusions and matrix glass are commonly vesicle- and microlite-rich, attributes that could be due to coupled syneruptive vesiculation and crystallization (Blundy & Cashman, 2001). The compositional and textural similarity of the melt inclusions in the plagioclase to the matrix glass, and evidence of their syneruptive

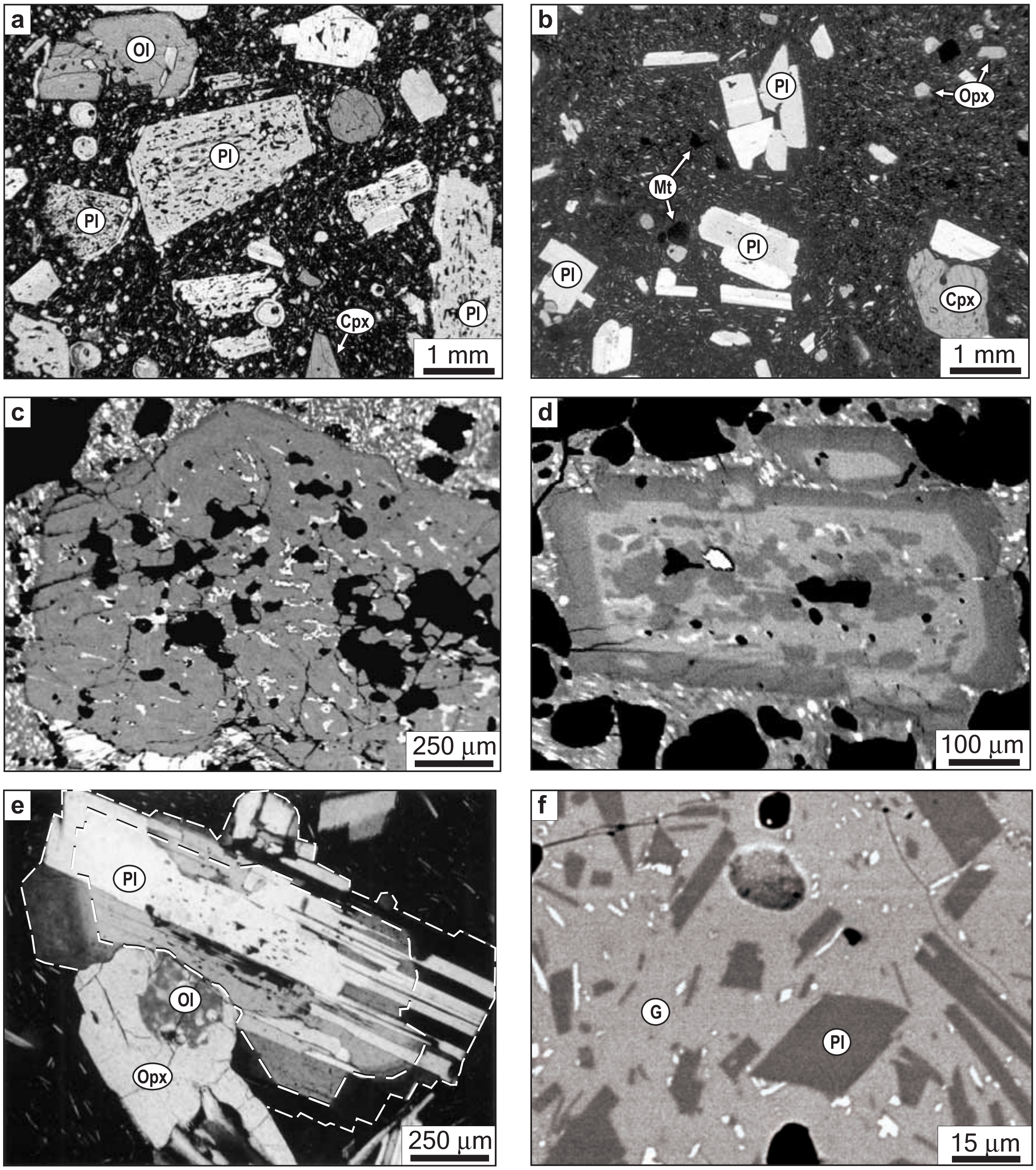

Fig. 3. Photomicrographs of (a) Academy Nauk basalt and (b) Karymsky andesite showing phenocrysts of plagioclase (Pl), clinopyroxene (Cpx), orthopyroxene (Opx), olivine (Ol) and magnetite (Mt) in plane-polarized light. Back-scattered electron images (BSE) of (c) plagioclase phenocryst in Academy Nauk basalt and (d) rimmed plagioclase phenocryst in Karymsky andesite. Black areas are voids. (e) Photomicrograph of olivine xenocryst in a plagioclase–orthopyroxene aggregate (crossed polars). Dashed lines indicate the inner calcic core and the outer sodic rim of plagioclase phenocryst. It should be noted that the olivine is attached to the calcic core of the plagioclase phenocryst. (f) BSE image of volcanic ash from Karymsky erupted on 28 February 1996 showing abundant plagioclase (dark) and pyroxene (bright) microlites in the matrix glass (G).

vesiculation, indicates that the system of interconnected melt channels within the plagioclase phenocrysts was open with respect to the surroundings during magma ascent.

The compositions of plagioclase cores, rims, microphenocrysts, and microlites within the Academy Nauk basalt are nearly constant at 80–90 mol. % anorthite (An) (Fig. 6a). EPMA profiles across the phenocrysts show either oscillatory or, rarely, normal zoning. Sr/Ca and Ba/Ca ratios are low and form a distinctive isolated cluster in compositional space (Fig. 6b).

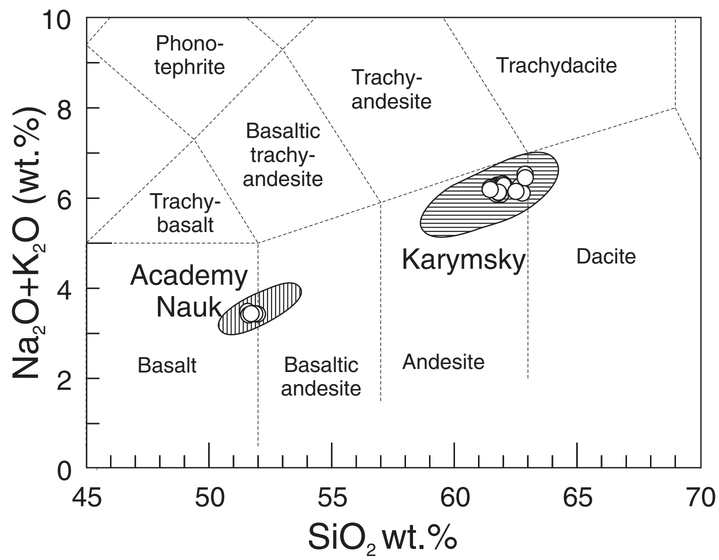

Fig. 4. Total alkalis vs silica for the Karymsky andesites and Academy Nauk basalts. Shaded areas correspond to andesitic (horizontal hatching) and mafic (vertical hatching) magmas erupted at Karymsky and Academy Nauk since 5300 yr BP [including data from Braitseva & Melekestsev (1989) and Ivanov (1996)]. Symbols represent compositions reported in this paper.

Pyroxenes

Clinopyroxenes are ubiquitous in the Academy Nauk basalt and occur as phenocrysts, microphenocrysts, and microlites, whereas orthopyroxenes occur only in trace amounts as inclusions in olivine phenocrysts (Table 1). Clinopyroxene phenocrysts are euhedral or slightly rounded, and contain abundant inclusions of glass and titanomagnetite. Petrographic examination, BSE imagery, and EPMA transects show no apparent discontinuities or significant compositional variations within clinopyroxenes. The composition of clinopyroxenes is uniform ($En_{46}Fs_{9}Wo_{44}$) and does not vary among samples (Table 3).

Olivine

Olivine phenocrysts make up 2–5 vol. % of the Academy Nauk basalt and occur as separate euhedral 0·5–5 mm grains, as well as in olivine–plagioclase–clinopyroxene aggregates. A small, but conspicuous, number of phenocrysts are resorbed. Olivines commonly contain inclusions of An_{80-90} plagioclase, magnetite, and, less frequently, melt inclusions. Olivine phenocrysts are usually unzoned ($Fo_{77 \pm 3}$), and show little compositional variation among grains and between samples (Table 3).

Magnetite

Magnetite occurs as euhedral equant microphenocrysts and microlites, normally not exceeding 0·5 mm in size. It also occurs as inclusions in clinopyroxene and olivine phenocrysts, and as an interstitial phase in crystal aggregates. The composition of magnetites does not vary significantly (Table 3).

PETROGRAPHY AND MINERALOGY OF KARYMSKY ANDESITE

Similar to previous eruptive events, the juvenile material erupted from Karymsky between 1996 and 1999 consists of porphyritic andesite (modal phenocryst content 25–32 vol. %) containing plagioclase, clinopyroxene, orthopyroxene, and magnetite (Table 1, Fig. 3b). Lavas are normally vesicle-poor, whereas the porosity of volcanic bombs sometimes exceeds 50–60 vol. %. No enclaves have been reported in the andesites. Only a few small (1–3 mm) glomerocrysts of plagioclase, pyroxene, and magnetite were found. The whole-rock composition of Karymsky andesites erupted during the period April 1996–August 1999 is nearly constant at 61·9 ± 0·4 wt % SiO_2 and is almost identical to that of the previous cycle of eruptive activity (Table 1). The composition of lavas and volcanic bombs erupted during the first 3 months of 1996 is more variable, with silica contents as low as 60·7 wt % in early February 1996 (Muravyev *et al.*, 1998).

Groundmass and melt inclusions

The groundmass of the Karymsky andesites is pilotaxitic and consists of light brown dacitic to rhyolitic glass (50–70 vol. %), elongated plagioclase microlites (20–45 vol. %), and subordinate amounts of pyroxene and magnetite. The groundmass of the volcanic bombs and volcanic ash fragments typically contains 30–50 vol. %

Table 2: Composition of matrix glass in volcanic ash and melt inclusions

Time of eruption	*n*	SiO_2	Al_2O_3	TiO_2	FeO^*	CaO	MgO	K_2O	Na_2O	Cl	Total	Microlites
Academy Nauk												
2 January 1996	31	57·10 (3·08)	20·24 (5·86)	0·79 (0·51)	6·04 (3·25)	8·68 (2·54)	2·01 (1·59)	0·83 (0·49)	4·23 (0·54)	0·08 (0·05)	98·52	45·05 (7·88)
Glass inclusions in Cpx	22	60·28 (2·46)	16·34 (3·04)	1·20 (0·41)	7·34 (3·13)	7·01 (1·49)	2·06 (1·66)	1·28 (0·44)	4·35 (0·67)	0·13 (0·03)	97·71	n.a.
Karymsky												
2 January 1996	17	74·75 (1·23)	12·41 (0·90)	0·82 (0·12)	3·14 (0·56)	1·29 (0·52)	0·29 (0·10)	3·42 (0·63)	3·76 (0·71)	0·13 (0·04)	99·16	43·32 (2·45)
11 February 1996	6	68·90 (1·37)	14·34 (0·36)	0·93 (0·17)	4·23 (1·02)	2·83 (0·36)	0·90 (0·37)	2·34 (0·23)	5·40 (0·16)	0·12 (0·05)	99·09	42·15 (5·54)
18 February 1996	12	70·58 (1·18)	14·49 (0·76)	0·88 (0·07)	3·96 (0·30)	2·08 (1·04)	0·89 (0·25)	2·72 (0·83)	4·36 (0·96)	0·05 (0·06)	97·27	42·70 (3·45)
22 February 1996	12	69·53 (1·66)	14·85 (1·87)	0·79 (0·21)	3·67 (1·06)	2·86 (0·92)	0·71 (0·43)	2·78 (0·62)	4·76 (0·77)	0·05 (0·04)	98·99	38·02 (5·28)
28 February 1996	9	71·34 (1·37)	14·39 (1·02)	0·94 (0·12)	4·07 (0·45)	2·00 (0·54)	0·85 (0·23)	2·75 (0·44)	3·61 (1·45)	0·06 (0·05)	98·82	35·30 (5·35)
1 March 1996	18	73·82 (1·20)	12·82 (0·96)	0·78 (0·14)	3·27 (0·43)	1·62 (0·46)	0·38 (0·11)	3·06 (0·53)	4·16 (0·45)	0·10 (0·04)	99·22	43·23 (5·30)
24 March 1996	12	73·77 (0·87)	12·51 (0·63)	0·93 (0·16)	3·50 (0·37)	1·47 (0·30)	0·33 (0·08)	3·14 (0·43)	4·22 (0·70)	0·14 (0·03)	98·08	41·12 (8·18)
8 April 1996	9	71·89 (1·15)	13·38 (0·92)	1·01 (0·15)	4·19 (0·36)	2·24 (0·38)	0·55 (0·09)	2·73 (0·16)	3·91 (0·45)	0·10 (0·03)	99·33	n.a.
18 April 1996	11	71·57 (0·76)	12·95 (0·61)	0·99 (0·18)	4·51 (0·39)	2·16 (0·36)	0·78 (0·47)	2·77 (0·20)	4·15 (0·33)	0·12 (0·04)	99·04	36·08 (3·63)
25 April 1996	14	72·18 (0·55)	12·67 (0·25)	1·14 (0·12)	4·48 (0·45)	2·00 (0·15)	0·64 (0·19)	2·86 (0·17)	3·91 (0·42)	0·12 (0·03)	99·77	37·25 (8·73)
1 May 1996	11	72·18 (0·88)	13·10 (0·73)	0·95 (0·13)	4·15 (0·31)	2·24 (0·47)	0·64 (0·18)	2·80 (0·22)	3·81 (0·40)	0·13 (0·03)	99·66	37·41 (6·60)
10 May 1996	13	72·09 (0·61)	12·87 (0·49)	1·11 (0·17)	4·48 (0·24)	2·06 (0·24)	0·61 (0·18)	2·74 (0·14)	3·91 (0·32)	0·12 (0·04)	99·39	
27 June 1996	11	72·71 (0·94)	13·06 (0·95)	0·94 (0·19)	3·85 (0·63)	1·85 (0·45)	0·40 (0·13)	2·94 (0·41)	4·15 (0·66)	0·10 (0·03)	100·05	35·83 (6·78)
10 July 1996	19	73·55 (1·94)	12·89 (1·10)	0·91 (0·25)	3·21 (1·03)	1·69 (0·67)	0·29 (0·17)	2·54 (0·93)	4·83 (0·91)	0·10 (0·06)	99·11	38·60 (3·76)
23 October 1996	9	71·50 (0·58)	13·23 (0·83)	0·99 (0·17)	4·26 (0·67)	2·11 (0·41)	0·52 (0·27)	2·99 (0·33)	4·27 (0·39)	0·13 (0·04)	99·81	42·70 (2·59)
12 November 1996	12	71·94 (1·01)	13·09 (0·50)	0·95 (0·16)	4·15 (0·48)	2·16 (0·50)	0·37 (0·15)	2·83 (0·39)	4·36 (0·56)	0·13 (0·07)	99·68	n.a.
3 December 1996	21	72·56 (0·54)	12·64 (0·34)	0·99 (0·12)	4·37 (0·29)	1·78 (0·27)	0·41 (0·11)	3·08 (0·31)	4·03 (0·46)	0·14 (0·03)	99·40	n.a.
23 December 1996	11	72·41 (0·99)	12·85 (0·67)	0·93 (0·23)	4·22 (0·28)	1·99 (0·49)	0·45 (0·11)	2·82 (0·68)	4·21 (0·82)	0·12 (0·04)	99·47	n.a.
11 January 1997	13	72·23 (0·46)	12·72 (0·34)	1·06 (0·15)	4·31 (0·19)	1·78 (0·18)	0·43 (0·10)	2·96 (0·29)	4·39 (0·27)	0·11 (0·02)	99·76	43·00 (0·89)
2 February 1997	14	72·69 (0·72)	12·78 (0·47)	1·01 (0·15)	4·04 (0·39)	1·64 (0·27)	0·35 (0·13)	2·92 (0·26)	4·44 (0·38)	0·13 (0·04)	99·58	n.a.
22 February 1997	11	73·12 (0·88)	12·37 (0·23)	0·95 (0·20)	4·17 (0·30)	1·67 (0·37)	0·37 (0·08)	2·84 (0·67)	4·40 (0·67)	0·12 (0·03)	100·02	n.a.
13 March 1997	16	73·19 (0·68)	12·48 (0·54)	0·91 (0·12)	3·87 (0·38)	1·67 (0·27)	0·35 (0·07)	2·72 (0·43)	4·70 (0·52)	0·11 (0·03)	99·69	42·74 (4·70)
4 April 1997	11	72·78 (0·56)	12·70 (0·43)	0·96 (0·10)	3·95 (0·44)	1·72 (0·23)	0·45 (0·19)	2·84 (0·26)	4·50 (0·29)	0·11 (0·05)	99·40	n.a.
3 April 1997	13	72·95 (0·49)	12·63 (0·35)	1·00 (0·11)	4·14 (0·33)	1·58 (0·24)	0·36 (0·12)	3·05 (0·44)	4·15 (0·64)	0·15 (0·04)	99·05	n.a.
18 July 1998	12	73·24 (0·50)	12·48 (0·23)	0·90 (0·10)	4·00 (0·29)	1·39 (0·20)	0·37 (0·07)	3·20 (0·15)	4·31 (0·19)	0·11 (0·03)	99·02	n.a.
25 July 1998	10	72·79 (0·40)	12·63 (0·25)	0·98 (0·16)	4·26 (0·26)	1·85 (0·21)	0·49 (0·06)	2·70 (0·67)	4·18 (0·72)	0·13 (0·04)	98·85	39·07 (2·71)
Glass inclusions in Cpx	7	68·53 (3·25)	14·14 (1·09)	0·90 (0·20)	4·68 (0·48)	2·86 (0·82)	1·04 (0·46)	2·81 (0·12)	4·88 (0·53)	0·17 (0·05)	98·63	n.a.

The average of *n* analyses (in wt %) is given together with the standard deviation (number in parentheses) with all Fe reported as FeO; n.a., not analyzed. Analyses are normalized to 100 wt % total, although the non-normalized totals are reported. The original EPMA data can be found in the Electronic Appendix, which may be downloaded from the *Journal of Petrology* web site at http://www.petrology.oupjournals.org. The microlite content (undifferentiated crystalline phases, in vol. %) was determined from BSE images of several ash particles.

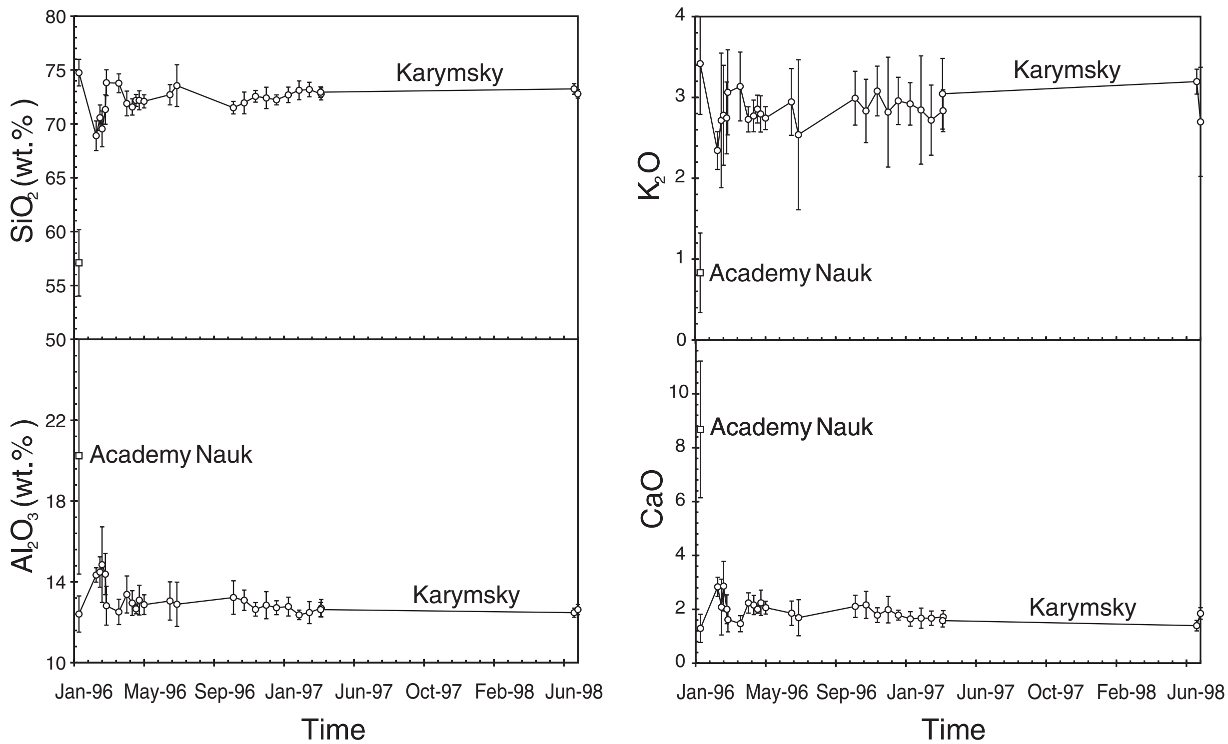

Fig. 5. Composition of volcanic ash glasses plotted against the date of eruption. The glass in the Karymsky andesite, which erupted in February 1996, is the most mafic. Error bars correspond to the standard deviation of the electron microprobe analyses of the matrix glass in samples of volcanic ash.

of microlites (Fig. 3f), whereas the microlite content in the groundmass of lavas often exceeds 50–60 vol. %, which may be attributed to the slower cooling of the latter.

Microprobe analyses of groundmass glass in the Karymsky volcanic ash erupted from 1996 to 1999 show significant variations in major elements. The glasses of the earliest andesite, erupted on 2 January 1996, contain 74·8 wt % SiO_2 (Table 2). The glasses of the ash erupted 1 month later have the lowest SiO_2 (68·9 wt %) and K_2O (2·3 wt %) contents and the highest concentrations of Al_2O_3 (14·6 wt %) and CaO (2·8 wt %). Figure 5 shows that *c.* 2 months after the onset of the eruptive activity, the silica content of the glasses gradually increased and eventually stabilized at 72·6 wt % SiO_2. At the same time, the concentration of K_2O rose to 3·0 wt %, whereas the concentrations of Al_2O_3 and CaO gradually decreased to 12·2 wt % and 1·6 wt % respectively, and then remained nearly constant until the end of 1998.

Five to eight BSE images of each sample of volcanic ash were acquired to determine the microlite content of the groundmass. Textural analysis showed that the microlite content of all samples is approximately the same, including those with the lowest SiO_2 contents in the glass (Table 2), and does not vary significantly with time (Fig. 7a).

Several glass inclusions within phenocrysts, predominantly clinopyroxenes, were analyzed by electron microprobe to provide estimates of pre-eruptive volatile content in Karymsky andesites, following the 'difference method' of Devine *et al.* (1995). The glass inclusions were microlite-free and did not exhibit obvious signs of leaking. The deficit in totals of glass inclusion analyses averages at 1·4 ± 0·5 wt %.

Plagioclase

Plagioclase phenocrysts form 20–25 vol. % of the Karymsky andesite. Unlike plagioclase in the Academy Nauk basalt, there are significant variations in composition and texture (Izbekov *et al.*, 2002). Most the phenocrysts form two distinctive populations: (1) oscillatory-zoned sodic plagioclases ($An_{48–62}$); (2) rimmed plagioclases (Fig. 3d), characterized by the presence of calcic cores ($An_{76–90}$) and sodic rims ($An_{48–62}$). Oscillatory-zoned plagioclases form 70–80 vol. % of all phenocrysts and the majority of microphenocrysts. Their compositional profiles usually show fine oscillation superimposed on a weak normal zoning; small jumps in An content occur at major dissolution surfaces (Izbekov *et al.*, 2002). The Ba/Ca and Sr/Ca ratios of oscillatory-zoned plagioclases in the andesite are significantly higher than those in

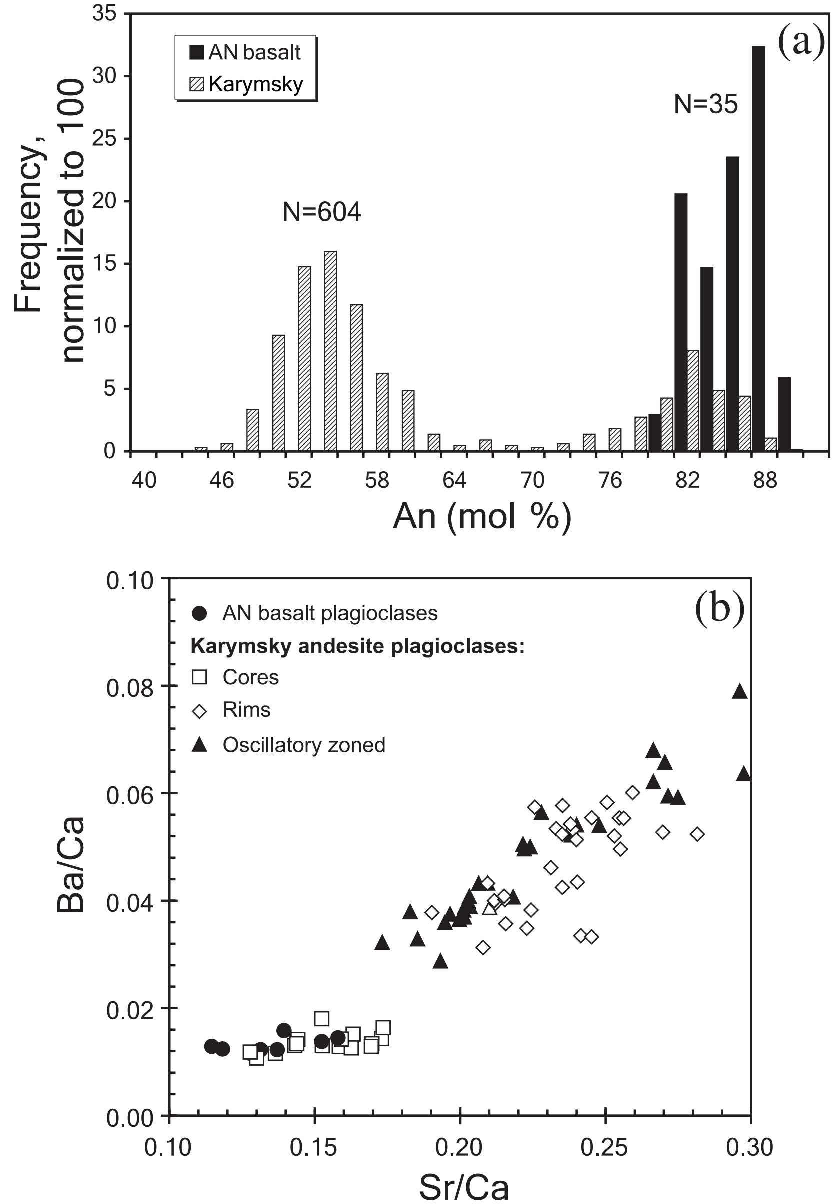

Fig. 6. (a) Electron microprobe and (b) LA-ICP-MS data for plagioclase phenocrysts in Karymsky andesites and Academy Nauk basalts. The composition of the Karymsky plagioclases is bimodal as a result of the presence of calcic cores, which match Academy Nauk plagioclases in terms of major and trace element composition.

the basalt, forming a distinct trend without overlap in composition (Fig. 6b).

Rimmed plagioclases consist of euhedral calcic cores, often with coarse-sieved interiors, and oscillatory-zoned rims. The texture of the calcic cores mimics that of plagioclase in the basalt. However, unlike the latter, voids are filled with sodic plagioclase and melt, rather than with melt only, forming a texture frequently referred to as 'patchy' zoning (Vance, 1965). Rimmed plagioclases are also present in the andesites of the previous eruptive cycle.

Both EPMA and LA-ICP-MS data show that the calcic cores of the andesitic plagioclase are compositionally similar to plagioclases in the Academy Nauk basalt, whereas the rims outside and 'patches' inside the calcic cores are close to the composition of the oscillatory-zoned plagioclases (Fig. 6a and b). Rimmed plagioclases typically have an abrupt boundary between core and rim, wherein the composition changes from An_{80} to An_{52} within a 30 μm distance. The rims commonly lack major dissolution surfaces and associated jumps in An content, which are characteristic of the large

Table 3: Composition of minerals in lavas and volcanic bombs

Sample	*n*	SiO_2	Al_2O_3	TiO_2	FeO^*	CaO	MnO	MgO	K_2O	Na_2O	Total
Plagioclase											
AN	35	47·76 (1·49)	33·49 (1·13)	n.a.	0·73 (0·19)	16·95 (1·07)	n.a.	n.a.	0·04 (0·02)	1·72 (0·53)	100·67
KO	225	55·68 (0·99)	28·28 (0·65)	n.a.	0·63 (0·08)	10·80 (0·63)	n.a.	n.a.	0·17 (0·04)	5·26 (0·40)	100·82
KR	148	55·18 (1·69)	28·44 (1·07)	n.a.	0·67 (0·08)	11·18 (1·17)	n.a.	n.a.	0·16 (0·04)	5·08 (0·66)	100·72
KC	186	48·24 (1·14)	33·05 (0·71)	n.a.	0·74 (0·10)	16·30 (0·79)	n.a.	n.a.	0·05 (0·03)	2·14 (0·45)	100·53
KP	45	54·58 (0·88)	28·88 (0·58)	n.a.	0·75 (0·13)	11·63 (0·65)	n.a.	n.a.	0·17 (0·10)	4·82 (0·33)	100·83
Pyroxene											
AN, Cpx	83	51·55 (0·49)	2·74 (0·18)	0·49 (0·07)	7·68 (0·52)	20·98 (0·40)	0·21 (0·07)	15·78 (0·30)	n.a.	0·27 (0·05)	99·67
KAR, Cpx	102	51·84 (0·60)	2·21 (0·67)	0·57 (0·11)	9·75 (0·87)	20·28 (0·55)	0·39 (0·11)	14·78 (0·43)	n.a.	0·32 (0·05)	100·30
AN, Opx	4	54·16 (0·43)	1·54 (0·11)	0·23 (0·03)	15·5 (0·44)	1·75 (0·12)	0·37 (0·07)	26·02 (0·22)	n.a.	n.d.	99·64
KAR, Opx	39	53·63 (0·88)	0·84 (0·13)	0·29 (0·09)	19·53 (1·28)	1·70 (0·30)	0·79 (0·18)	23·29 (1·38)	n.a.	n.d.	100·16
Olivine											
AN	67	38·34 (0·45)	n.d.	n.d.	22·34 (1·88)	0·17 (0·03)	0·37 (0·10)	38·79 (1·47)	n.a.	n.d.	100·08
KAR	96	37·44 (0·52)	n.d.	n.d.	24·65 (2·36)	0·14 (0·02)	n.d.	36·42 (1·95)	n.a.	n.d.	99·22

	n	FeO	Fe_2O_3	TiO_2	Al_2O_3	MgO	MnO	Cr_2O_3	Total
Magnetite									
AN	9	34·24 (0·68)	47·02 (0·93)	8·99 (0·45)	4·25 (0·20)	3·41 (0·29)	0·36 (0·05)	0·78 (0·50)	99·18
KAR	48	38·40 (1·09)	43·88 (1·91)	12·02 (0·91)	2·63 (0·24)	2·39 (0·42)	0·59 (0·12)	0·05 (0·03)	100·04

The average of *n* analyses (in wt %) is given together with the standard deviation (number in parentheses); n.a., not analyzed; n.d., not detected. The original EPMA data can be found in the Electronic Appendix, which may be downloaded from the Journal of Petrology web site at http://www.petrology.oupjournals.org. AN, Academy Nauk; KO, Karymsky oscillatory; KR, Karymsky rim; KC, Karymsky core; KP, Karymsky patches; KAR, Karymsky; Cpx, clinopyroxene; Opx, orthopyroxene.

oscillatory-zoned plagioclases coexisting with them. Although we did not quantify variations in rim width with time of eruption, rims of plagioclases in andesites erupted 2–4 months after the beginning of eruption do appear to be smaller compared with those erupted 2–3 years after that (Izbekov *et al.*, 2002).

Pyroxenes

Clinopyroxene and orthopyroxene form 2–7 vol. % of the Karymsky andesite and are present throughout the course of the eruption in all eruptive products as phenocrysts, microphenocrysts, and microlites. Phenocrysts of both pyroxene types are euhedral, and typically contain fewer glass inclusions than do pyroxenes in the Academy Nauk basalt.

In addition to the available polished thin sections (one for each sample of lava or volcanic bomb), more than 30 phenocrysts of clinopyroxene were separated from the bulk sample 98IPE27 (andesite lava erupted from 6 April to 13 August 1996) and prepared as polished grain mounts. These phenocrysts were thoroughly investigated using BSE imagery and EPMA. We found no apparent compositional discontinuities or significant compositional variations within the phenocrysts. The composition of the clinopyroxene is nearly constant at $En_{42}Fs_{15}Wo_{43}$ and overlaps considerably with that of clinopyroxenes in the Academy Nauk basalt (Table 3). Orthopyroxene phenocrysts ($En_{66}Fs_{30}Wo_4$) are generally unzoned or infrequently show slight normal zoning.

Olivine

Olivine is extremely scarce in the andesites of Karymsky. A few grains of olivine were found in lavas erupted at the beginning of the eruptive cycle in 1996. Olivine occurs as isolated anhedral grains in the cores of orthopyroxene phenocrysts, or in orthopyroxene–plagioclase aggregates. Figure 3e shows an example of a 0·2 mm olivine grain attached to the calcic core of a plagioclase phenocryst at one side and rimmed by orthopyroxene at the other. Both olivine and orthopyroxene are overgrown by the sodic

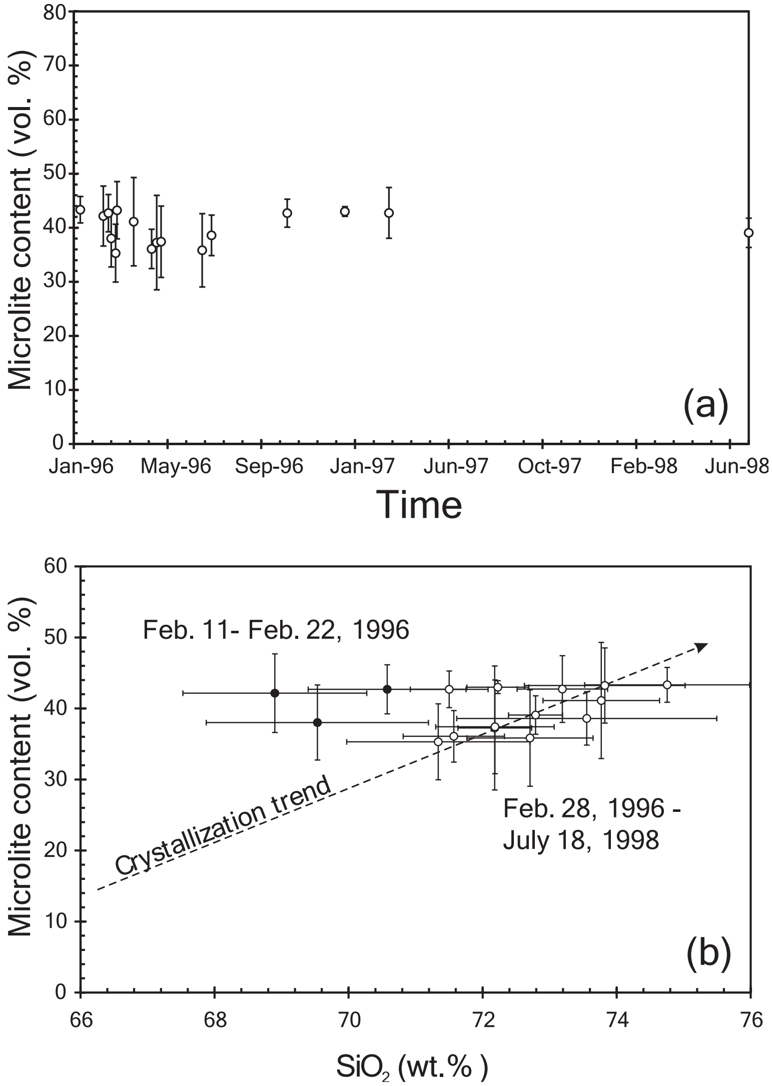

Fig. 7. (a) Variations of microlite content in the Karymsky volcanic ash. (b) Microlite content vs SiO_2 in the Karymsky volcanic ash. The difference in the SiO_2 content in the ash erupted during 11–22 February 1996 from the predicted crystallization trend requires an addition of a mafic component to the andesite at the beginning of the eruption (see discussion in the text).

rim of the plagioclase phenocryst. This example demonstrates clearly that (1) olivine is not an equilibrium phase in the andesite and was transformed (by reaction with the melt) to orthopyroxene, and (2) olivine and calcic plagioclase crystallized simultaneously in a magma other than their host andesite. Olivines are compositionally homogeneous ($Fo_{73 \pm 5}$) and overlap with those in the Academy Nauk basalt (Table 3).

Magnetite

Magnetite occurs in the andesite of Karymsky as sub- to euhedral phenocrysts, microphenocrysts and microlites, as well as inclusions in pyroxenes. Vermicular magnetite inclusions are found within orthopyroxene phenocrysts at the boundary with xenocrystic olivine cores. Magnetites are compositionally uniform and have significantly lower Cr_2O_3 and Al_2O_3 contents and higher TiO_2 compared with those in the Academy Nauk basalt (Table 3). No significant variations of Karymsky magnetite composition were observed throughout the 1996–1999 period of eruption.

DISCUSSION

Origin of variations in Karymsky melt compositions

Three general explanations can be suggested to account for the variations in the groundmass glass composition at the beginning of the eruption: (1) pre-eruptive compositional heterogeneity of the Karymsky magma reservoir; (2) higher magma flux at the beginning of eruption; (3) basaltic recharge.

If the Karymsky reservoir was compositionally heterogeneous, then why did the composition of volcanic glass stabilize and remain constant after the first 2 months of eruption? Indeed, previous periods of activity, with the exceptions noted above, have shown that Karymsky is characterized by a uniform composition of its eruptive products. Therefore, heterogeneity of the Karymsky reservoir developed prior to the eruption seems unlikely to account for variations of groundmass glass composition at the beginning of the current eruptive cycle.

The second possibility is that these variations could be related to higher magma flux at the beginning of the eruption, which produced magma that had undergone less syneruptive, decompression-induced crystallization as a result of faster ascent and therefore erupted with less evolved glass. If so, this would be reflected by a variation in the microlite content in the glass, whereas the overall magma composition would be constant (Blundy & Cashman, 2001).

Experimental data on equilibrium crystallization in magma systems have led to the development of numerical models that can be used for simulating phase equilibria in crystallizing melts. One of them, COMAGMAT (Ariskin, 1999), was used here to model compositional variations within the melt during the crystallization of the Karymsky andesite. According to the model, an increase of SiO_2 in the crystallizing melt of 2 wt %, when the major precipitating phase is An_{50} plagioclase, should correspond to an increase in the volume fraction of microlites of 9 vol. % (crystallization trend, Fig. 7b). If variations of melt composition are related to different degrees of crystallization, then the microlite content in the volcanic ash should follow the calculated crystallization trend. The microlite content in the volcanic ash erupted in February 1996, however, does not conform with the trend. It is nearly the same as the microlite content in the ash erupted during the following 17 months. The silica content in the February glasses is, however, significantly lower compared with the latter. This could not be explained solely by different degrees of syneruptive crystallization of andesitic magma batches, thus reducing the likelihood of this scenario.

With the elimination of these alternatives and support from the eruption chronology, it appears that the third possible explanation is the most probable: the significant variations of the composition of groundmass glass early in the eruption were caused by the input of heat and/or mafic melt as the result of basaltic replenishment. The addition of basalt could have led to two possible scenarios. First, if the temperature of the basalt was significantly higher than that of the andesite, the andesite would be heated, resulting in a decrease in its crystallinity and correspondingly make the composition of the matrix glass more mafic. In this scenario thermal equilibration would cause crystallization of the basalt, which would hinder its mixing with the host andesite (Eichelberger, 1978). Alternatively, if the temperatures and physical properties of basalt and andesite were not greatly dissimilar, the magmas could mix effectively and produce a hybrid with a melt composition that is more mafic than the host andesite.

We argue below that variations in the groundmass glass composition in the andesite were caused by basaltic recharge, which induced fast and efficient formation of a homogeneous hybrid andesite magma that erupted within 2 months of the beginning of the eruption. The most convincing evidence is the presence of xenocrysts of basaltic origin in the Karymsky andesite.

Origin of calcic plagioclase and olivine in the Karymsky andesites

Calcic cores in rimmed plagioclase phenocrysts in the Karymsky andesite texturally and compositionally mimic plagioclases in the Academy Nauk basalt, which erupted at the beginning of the eruptive cycle in 1996. Detailed discussion of this observation has been given by Izbekov *et al.* (2002), and here we only summarize the major points.

Two important questions regarding the origin of the calcic cores are (1) whether they originate from the basalt contemporaneously erupted in the Academy Nauk caldera, and (2) whether they were introduced into the Karymsky andesite system by basaltic replenishment at the beginning of the 1996 eruption. The compositional similarity, in terms of both major and trace elements, suggests that the calcic cores could have originated from the same magma that produced the Academy Nauk basaltic plagioclases (Fig. 6a and b). The textural similarity (Izbekov *et al.*, 2002) also suggests that the basaltic plagioclases and calcic cores of rimmed plagioclases in the Karymsky andesite experienced similar dissolution events, perhaps during the ascent of the basalt and associated decompression (Nelson & Montana, 1992). Thermodynamic modeling using COMAGMAT (Ariskin, 1999) indicates that plagioclase as calcic as An_{76-90} cannot crystallize in magma of Karymsky andesite composition at any plausible pressure, temperature, or water content, and thus must have been introduced into the andesite from a more mafic source.

Similarity to the Academy Nauk plagioclase does not necessarily imply, however, that the calcic plagioclase was introduced into the Karymsky andesite at the beginning of the 1996 eruptive cycle. The zoning and width of the sodic rims on rimmed plagioclases can be used to distinguish calcic cores introduced in 1996 from those that may have been introduced during previous basaltic recharges. The rimmed plagioclases, whose sodic rims lack major dissolution boundaries and associated increases in An content, probably experienced no disturbances and grew in equilibrium since the introduction of their calcic cores. Their calcic cores then must have been introduced by the most recent basaltic replenishment. Additionally, the widths of the sodic rims, which we infer to have grown around these cores since 1996 at the maximum growth rate of *c.* $2{\cdot}5 \times 10^{-9}$ mm/s, are consistent with experimentally determined plagioclase growth rates (e.g. Hammer & Rutherford, 2002).

The presence of Fo_{73} olivine in the earlier 1996 andesites is additional evidence for basaltic recharge. Ivanov (1996) provided petrochemical evidence that forsteritic olivine is not an equilibrium phase in the Karymsky andesite. Our petrographic observations show that olivine occurs in the Karymsky andesite predominantly as xenocrystic cores in orthopyroxene. Compositional similarity of olivine in the Karymsky andesites to that in the Academy Nauk basalt, where it is a major equilibrium phase, implies that the latter is the most plausible source of the olivine xenocrysts in the andesites. The overgrowth of both the olivine xenocryst and the calcic plagioclase core by the sodic plagioclase rim, which has no apparent dissolution boundaries (Fig. 3e), suggests that both olivine and calcic plagioclase were introduced into the Karymsky andesite by the most recent basaltic replenishment, specifically at the beginning of the 1996 eruption.

Mechanism of mixing in the Karymsky magma system

The presence of xenocrysts and variations in the Karymsky groundmass glass composition, eruption chronology, and the evidence of basaltic dike emplacement indicate that at the beginning of the 1996 eruption, the Karymsky magma system was replenished by the same basalt that erupted simultaneously in the northern part of Academy Nauk caldera. An interesting finding is that within only 2 months of the onset of the eruption, Karymsky produced homogeneous andesite containing newly introduced basaltic components. Why was the mixing so fast and efficient at Karymsky, whereas it never approached such a complete homogenization in many other cases, e.g. Unzen, Japan (Nakamura, 1995), Dutton, Alaska (Miller *et al.*, 1999) and Soufrière Hills, Montserrat (Murphy *et al.*, 2000)?

Sparks & Marshall (1986) suggested that the ability for magmas to mix depends on their physical properties after thermal equilibration, because thermal diffusion rates are orders of magnitude faster than chemical diffusion rates. The physical properties, particularly the viscosity and density of a magma, strongly depend on: (1) the composition of melt including the concentration of water; (2) the volume fractions of solid phases and bubbles suspended in the melt; (3) temperature; (4) total pressure. It is difficult, however, to estimate with adequate precision these four parameters.

According to the experimental study of Kadik *et al.* (1989), the simultaneous crystallization of olivine, clinopyroxene, and plagioclase in high-aluminum basalts of Kamchatka occurs at pressures lower than 700–750 MPa. The COMAGMAT model predicts that this assemblage is stable in the Academy Nauk basalt at pressures lower than 570–630 MPa, assuming a water content in the magma of $2{\cdot}3 \pm 0{\cdot}5$ wt %, as suggested by EPMA data for melt inclusions. The high volume fraction of phenocrysts in the Academy Nauk basalt also supports the view that it was probably stored in a crustal-level reservoir prior to the eruption. Therefore, based on the mineral assemblage of the Academy Nauk basalt, we assume a pressure of *c.* 600 MPa and a corresponding depth of 18 km as maximum limits for the crustal storage of the Academy Nauk basalt.

All plagioclase phenocrysts in the Academy Nauk basalt and the calcic cores of rimmed plagioclases in the Karymsky andesites typically have coarse-sieved interiors. The similarity of their textures to those reproduced in the experiments of Nelson & Montana (1992) suggests that they were probably formed by decompression during the ascent of the Academy Nauk basalt magma from its crustal source. According to their experiments, a minimum of 200 MPa decompression for 60 h is required to cause 10% resorption of plagioclase, whereas decompression of the order of 400 MPa for the same duration results in 30% resorption. Although the experimental results should be applied with caution to the Academy Nauk basalt because of the more silicic starting material (56·08 wt % SiO_2) and very oxidizing conditions (hematite–magnetite buffer) in the experiments, 300 MPa might be a reasonable estimate for the decompression required to form a coarse-sieved texture such as that of plagioclases in the Academy Nauk basalt. If this is correct, then the Academy Nauk basalt experienced a pressure decrease from 600 to 300 MPa prior to entering the magma system of Karymsky, which corresponds to magma ascent from about 18 km to 9 km depth.

Only a very approximate estimate can be made for the depth at which magma mixing occurred. The minimum depth is constrained by the roof of the crustal reservoir of Karymsky, which is thought to be located *c.* 4 km below the edifice of Karymsky volcano (Shirokov *et al.*, 1988). The maximum depth is constrained by the depth at which the Academy Nauk basalt breached the bottom or the side of the Karymsky magma chamber (*c.* 9 km, based on the dissolution texture of plagioclase phenocrysts as discussed above). Therefore, the pressure in the magma reservoir where the mixing occurred is considered to lie in the interval from *c.* 100 to 300 MPa.

The physical properties of the intruding basalt and the host andesite were estimated using COMAGMAT for modeling variations in the volume fractions of solid phases in the melts (Ariskin, 1999), and CONFLOW for calculating corresponding changes of viscosities and densities of the magmas (Mastin & Ghiorso, 2000). We modeled isobaric crystallization of the Academy Nauk basalt and Karymsky andesite at 200 MPa pressure, assuming concentrations of water of 2·3 wt % in the basalt and 1·4 wt % in the andesite inferred from EPMA data for melt inclusions in pyroxenes, and an oxygen fugacity at the nickel–nickel oxide (NNO) buffer, as suggested by the whole-rock compositions of the magmas (Grib, 1998).

Under the specified conditions, the compositions of clinopyroxene, orthopyroxene, and plagioclase in the Karymsky andesite are best reproduced by COMAGMAT at temperatures from 1023 to 1057°C. The deviations of the modeled compositions from the natural ones do not exceed 5 mol % for any mineral phase. According to CONFLOW, the viscosity of the Karymsky andesite at this temperature range is $10^{3·3}$–$10^{3·6}$ Pa s, and its bulk density is 2470 kg/m^3 (Fig. 8).

Assuming that the mineral assemblage of the Academy Nauk basalt was last equilibrated at *c.* 600 MPa, we used olivine–melt and clinopyroxene–melt equilibria to estimate the basalt temperature before it ascended and entered the Karymsky magma system. According to COMAGMAT, the compositions of olivine and clinopyroxene are best reproduced at temperatures from 1090 to 1120°C. This overlaps with the temperature interval predicted by COMAGMAT where simultaneous crystallization of the olivine–clinopyroxene–plagioclase assemblage is possible (1080–1115°C) at the given pressure and water content in the Academy Nauk basalt. At these conditions the viscosity of the basalt calculated by CONFLOW ranges from $10^{1·6}$ to $10^{2·0}$ Pa s, and its density is *c.* 2550 kg/m^3.

The ascent of the Academy Nauk basalt from deep crustal storage to the level where it encountered the Karymsky andesite magma reservoir was probably close to isothermal, and therefore the temperature of the basalt upon entering the andesitic magma system can be considered to be *c.* 1100°C. Assuming that the volume of the basaltic influx is subordinate to the volume of the host andesite and does not significantly affect the average temperature of the latter, thermal equilibration would have cooled the basalt to *c.* 1040°C, corresponding to an increase of its crystallinity to 35 vol. % and viscosity to $10^{3·3}$ Pa s (Fig. 8). The combined effect of pressure decrease during magma ascent and fall in temperature as a result of the thermal equilibration would cause a decrease in the basalt density from 2550 to 2466 kg/m^3, virtually equal to the density of the host andesite. As a result, both the Academy Nauk basalt and the Karymsky andesite would have nearly the same physical properties after thermal equilibration, and thus have an ability to mix effectively.

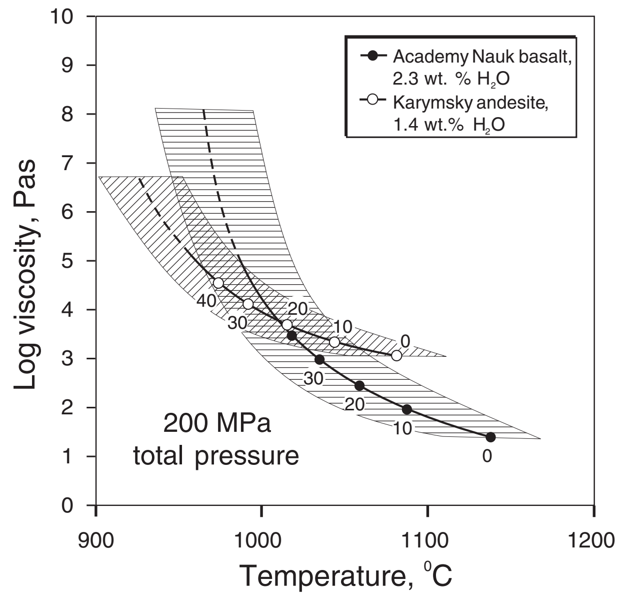

Fig. 8. Variations of viscosity vs temperature in the Academy Nauk basalt and Karymsky andesite, which crystallize isobarically at 200 MPa. Viscosity is calculated using the CONFLOW algorithm (Mastin & Ghiorso, 2000) based on melt compositions and crystallinities (numbers along the curves) predicted by COMAGMAT (Ariskin, 1999). The input parameters for COMAGMAT were (1) whole-rock compositions for the Academy Nauk basalt and Karymsky andesite reported in Table 1, (2) water contents of 2·3 wt % for the Academy Nauk basalt and 1·4 wt % for the Karymsky andesite as suggested by EPMA data for melt inclusions, and (3) oxygen fugacity at NNO buffer. The shaded areas show possible errors caused by the uncertainty in the estimated pre-eruptive water contents of ±0·5 wt %.

Perhaps the factor that distinguishes the mixing scenario at Karymsky from that of dacitic–andesitic volcanoes, where mixing is less thorough, is the flux of mafic magma that maintains a heat and mass balance of the crustal magma reservoir under a particular volcano. For the case in which basaltic replenishments are rare (once in hundreds of years), the temperature and viscosity contrasts between the new mafic input and the pre-existing, crystal-rich, magma of the crustal reservoir are likely to be high. Mafic magma will pond at the bottom of the reservoir and crystallize largely as a separate volume (Fig. 9b). Heating of adjacent parts of host magma initiates convection, and cooling of the mafic magma leads to second boiling (Eichelberger, 1980), which leads to entrainment of the quenched mafic debris and produces a hybrid. When the hybrid magma erupts, its composition shows distinctive signs of disequilibrium, such as the presence of mafic enclaves, 'dusty-zoned' plagioclases, and abundant xenocrysts (e.g. Koyaguchi & Kaneko, 2000).

In magma systems such as that of Karymsky, where replenishments occur more frequently (once in a decade),

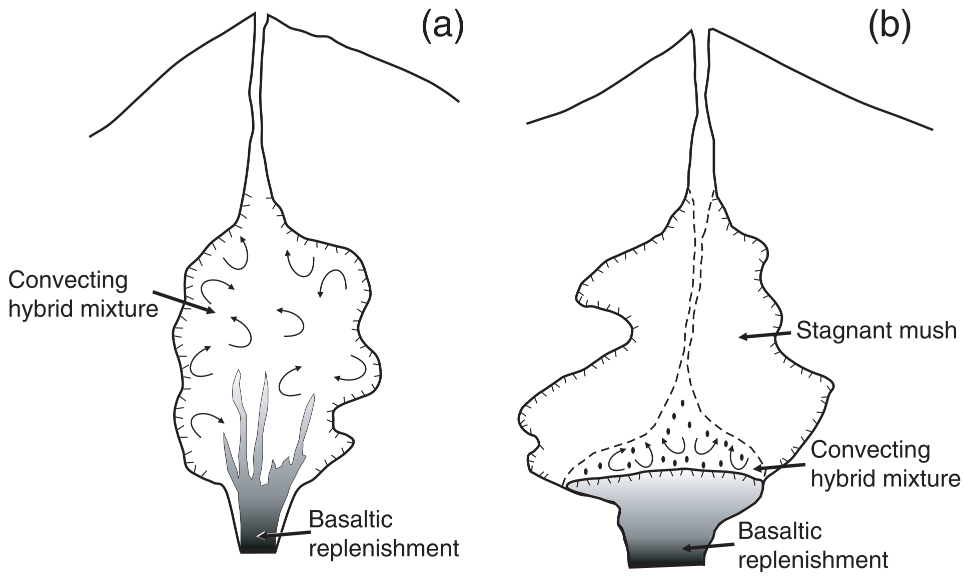

Fig. 9. Schematic illustration of mixing scenarios for crustal reservoirs with (a) short and (b) long intervals between basaltic replenishments. In case (a), the low temperature and viscosity contrast between the host magma and a new basaltic input allows a fast and efficient magma mixing; the erupted hybrid magma is nearly homogeneous. In case (b), the high temperature and viscosity contrast makes the magma mixing less efficient than in the previous case and the eruptive products contain abundant signs of disequilibrium (i.e. xenoliths).

cooling and crystallization of the reservoir magma during repose periods may not advance to a point at which the convection stops. The contrasts in temperature and viscosity between the injected and the stored magma are likely to be smaller, and thus allow a different mechanism of mixing, one in which the mafic magma does not solidify as a result of thermal equilibration and becomes involved with the magma chamber convection system immediately upon injection into the reservoir (Fig. 9a). The temperature of the hybrid magma in the chamber may rise temporarily, but to a lesser extent than in the previous case, because magma mixing and dispersal of the basaltic component is thorough from the outset—locally high concentrations of hotter basaltic components never reach shallower levels. The erupted hybrid magma is texturally and compositionally homogeneous. The only petrological signs of mixing are the presence of xenocrysts and subtle temporal variations in magma composition, which can be observed only in continuous sequences of erupted volcanic rocks.

CONCLUSION

Petrological and geochemical data provide evidence for basaltic replenishment of the Karymsky magma system at the beginning of the current cycle of eruptive activity. The composition of glass in the volcanic ash became more mafic almost immediately after the beginning of eruption and then, within 2 months, gradually returned to its original composition and remained almost constant for the following 3 years. These variations cannot be explained by heterogeneity within the Karymsky magma storage reservoir or by variations in magma flux at the beginning of eruption, and require an input of basaltic magma.

Further evidence for basaltic replenishment includes the presence of xenocrysts of basaltic origin in the andesite of Karymsky. A conspicuous portion of the plagioclase phenocrysts in the Karymsky andesite contains calcic cores (An_{76-90}), which compositionally and texturally mimic plagioclases in the Academy Nauk basalt. In addition to plagioclase, the earlier volumes of the andesite contain rare xenocrysts of olivine, which occur as resorbed cores in pyroxene phenocrysts. The composition of olivine xenocrysts matches that of olivines in the Academy Nauk basalt.

It appears that a basalt dike intruded along a pre-existing fault, intercepted a shallow andesite magma reservoir beneath the Karymsky caldera, and triggered an eruption of the Karymsky volcano. Because of the modest contrasts in temperature and viscosity between the basalt and the andesite, direct mixing of melts was possible, and mafic enclaves were not formed by the intruding magma. The introduced volume of basalt was quickly blended into the host andesitic magma, portions of which reached the surface soon after. Within 2 months, however, the new ‘hybrid’ andesite produced by mixing with the basalt either was exhausted or was blended with the host andesite below the limits of detection, and then the regular andesite of the Karymsky reservoir erupted.

One implication of this work is that the earliest output from an eruptive sequence should receive special attention. Early products may contain evidence of eruptive triggering that are erased as thermal and chemical equilibrium within the source reservoir is re-established. The Karymsky case is fortunate in that the triggering intrusion also breached the surface directly. In other cases, for example at Pinatubo (Pallister *et al.*, 1996) and Redoubt (Wolf & Eichelberger, 1997), the earliest eruptive rocks alone contain the critical evidence of magmatic encounters.

ACKNOWLEDGEMENTS

Thomas A. Vogel and Lina C. Patino at Michigan State University helped tremendously with LA-ICP-MS study of plagioclases. Thorough and constructive reviews by Valentin Troll, Martin Streck, George Zellmer and an anonymous reviewer, and editorial comments by M. Wilson considerably improved the manuscript. This work was supported by the Volcano Hazards Program of the US Geological Survey through the Alaska Volcano Observatory. Additional funding was provided by the Russian Foundation for Basic Research, grant 99-05-65495 to B.V.I.

SUPPLEMENTARY DATA

Supplementary data for this paper are available at *Journal of Petrology* online.

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