

Eruptive history of Karymsky volcano, Kamchatka, USSR, based on tephra stratigraphy and ^{14}C dating

OA Braitseva and IV Melekestsev

Institute of Volcanology, Academy of Sciences USSR, 9 Piip Boulevard, Petropavlovsk-Kamchatsky, 683006, USSR

Received March 21, 1990/Accepted August 20, 1990

Abstract. Eruptions of the active Karymsky stratovolcano began about 5300 (6100 ^{14}C) B.P. from within a pre-existing caldera which formed 7700 ^{14}C B.P. AS indicated by 32 ^{14}C determinations on buried soils and charcoal, the volcano has gone through two major cycles of activity, separated by a 2300 year period of repose. The first cycle can be divided into two stages (6100-5100 and 4300-2800 B.P.). The earlier stage began with especially intense eruptions of basaltic andesite to dacite. The later stage was characterized by moderate-strength eruptions of andesite. The second cycle, which is characterized by weak to moderate intermittent eruptions of andesite, started 500 B.P. and continues to the present. Eruptive patterns suggest that this cycle may continue for at least another 200 years with an eruptive character similar to that of the recent past.

flows have been mapped, their age determined by radiocarbon methods, eruptive volumes calculated, and compositions determined for all major eruptions. These results permit use of the eruptive history for a long-term forecast of future activity.

Study methods and main results

Tephra studies

The general pyroclastic sequence (Fig. 3) is based on the study of 40 tephra sections from the flanks of the volcano. Two major pyroclastic assemblages are present: deposits of the caldera-forming eruption (KRM), and those of the later activity from Karymsky volcano (KM).

Pyroclastic deposits of the caldera-forming eruption are dacitic to rhyodacitic. The main horizons are (1) lower pumice-fall and pyroclastic flow deposits, (2) volcanic ash containing dispersed charcoal, and (3) upper lapilli-fall deposits (Braitseva et al. 1979; Masurenkov 1980). These tephra blanket all drainages both near the caldera and east to the ocean. The sections are similar everywhere, except for the decreasing thickness and coarseness of the tephra away from the center of eruption (Fig. 2). The pumiceous pyroclastic flow deposits have displayed thicknesses up to 70 m in river valleys. On valley sides, the lowest deposits are horizon 2 (volcanic ash containing charcoal), deposited from the ash clouds associated with the pyroclastic flows.

The tephra of Karymsky volcano can be divided into two groups, IKM and IIKM, which reflect two major cycles of activity. Intercalated buried soils are thin and rare within each tephra group, but they are separated by thick (25 cm) buried soils which contain only three tephra layers from Karymsky volcano and reflect a sustained period of reduced activity.

The pyroclastic deposits from Karymsky volcano vary in composition. Dominant andesitic tephra include (1) gray lithic volcanic sand and gravel and (2) intercalated white to yellow pumiceous tephra close to

Introduction

Karymsky volcano, constructed within the older Karymsky caldera (Figs. 1, 2), is among the most active in the eastern Kamchatka volcanic zone. Its symmetrical cone, virtually undissected by erosion, had an elevation of 1586 m in 1981. The summit crater changes size and shape from eruption to eruption (Magus'kin et al. 1982). The enclosing Karymsky caldera (5 x 6.5 km at the rim and 4 x 5 km at the floor) is part of the Zhupanovsky volcano-tectonic depression in east-central Kamchatka, which contains several discrete nested calderas (Newhall and Dzurisin 1988).

The general geology of Karymsky volcano has been described by Vlodayets (1947), Ivanov (1970), and a research team (Masurenkov 1980). Its eruptive history has been interpreted by Braitseva, Yegorova, and Sulerzhitsky (1979; Masurenkov 1980), who used tephra stratigraphy and radiocarbon dating of tephra to determine the main stages of activity. More recently, the lava

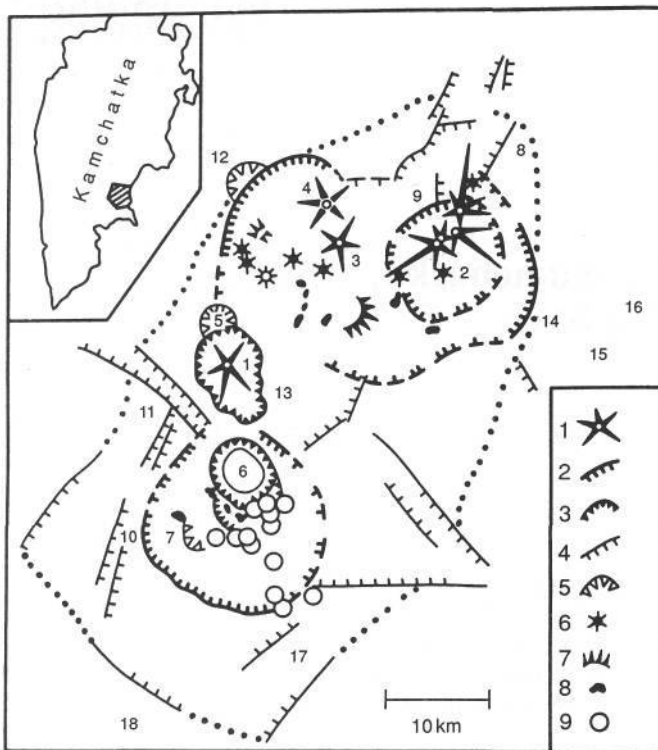


Fig. 1. Volcanoes of the Karymsky complex (from Newhall and Dzurisin 1988). Key to inset legend, with numbered symbols: 1, modern volcanoes; 2, caldera escarpments; 3, position of the ring fractures of ancient and young caldera groups; 4, fractures expressed in topography of displaced blocks; 5, explosion craters; 6, cinder cones and lava domes; 7, maar; 8, extrusions; 9, epicenters of volcano-tectonic earthquakes in 1975 with focal depths of 0-10 km. Key to numbers on map proper: 1, Karymsky volcano; 2, Maly Semiachik volcano; 3, Sukhoy; 4, Stupenchaty Bastion; 5, Dvor Caldera; 6, Akademii Nauk and Odnoboky calderas; 7, Belyankina; 8, Drevny Karymsky; 9, Semiachik caldera; 10, Krainy; 11, Razlaty; 12, Soboliny caldera; 13, Berezovy; 14, Stena caldera; 15, Pribezchny Yuzhny; 16, Pribezchny Severny; 17, Ditmara; 18, Zhupanovsky volcano-tectonic depression. Dotted line indicates approximate location of outer caldera rim

the cone and coarse ash at greater distances. In total, 12 horizons of light-colored pumiceous tephra can be distinguished (symbols PM_1 - PM_{12} ; Fig. 3), intercalated with thin, coarse ash horizons. Tephra of basaltic andesite occur as (1) deposits low in the sequence from early eruptions, i.e., stratified gray and greenish-gray volcanic sands with gravel, lapilli, and scoria bombs mixed with xenoliths of older rocks (fragments of lava, agglomerate tuffs, altered rocks), and (2) layers of porous black and brown scoria high in the sequence (layer SC), which are as much as 1-1.5 m thick on flanks of the volcano.

Karymsky volcano is the primary source for tephra in the region, but some thin tephra layers increase in thickness and coarseness toward Maly Semiachik volcano (Fig. 1). These are black and grayish-black scoriaeous sand and gravel (basalt to basaltic andesite in composition). Two layers of black sand high in the tephra sequence overlie group VIII lavas (400 B.P.), and several horizons are present within the soils that divide

KM from KPM deposits (not shown on Fig. 3). Thin tephra erupted from distant volcanoes are also present; their thickness and grain size are nearly constant across the Karymsky-Semiachinsky region. These are thin pink to pink-white ash, and yellow to gray volcanic sand (numbers 1-12 in Fig. 3).

Dating the tephra: age of the volcano and caldera

Times of eruptive activity were dated by radiocarbon methods, mainly on buried soil horizons and some charcoal from the soil or overlying tephra (Braitseva et al. 1989). For soils containing abundant humus, alkaline leachates of the sample were also dated. The range of dates gives information on the duration of soil formation and thus provides more precise ages for overlying and underlying tephra and for duration of repose periods. Dates from the flanks of Maly Semiachik volcano also were used. The results permit interpretation of the history of volcanic activity (Table 1). For the history of Karymsky volcano, we use a calibrated time scale based on the tables of Arslanov (1978). For the earlier part of the Holocene, for which corrections are still lacking, we use the uncorrected radiocarbon ages.

Karymsky caldera formed about 7700 ^{14}C B.P., as shown by several accordant dates on buried soil and charcoal from the lower lapilli horizon (Fig. 3). Two dates on charcoal from the pyroclastic flows and ash-cloud deposits are considered to be older than their true age due to absorption by charcoal of CO from the hot gas-saturated deposits (Masurenkov 1980). The initial eruptions of Karymsky volcano, as determined by dating soil horizons underlying the lowest pyroclastic deposits, began about 6100 (5300 ^{14}C) B.P.

Ages of lava flows

Eleven age groups of lava flows (I-XI) were separated with reference to the interlayered, radiometrically dated tephra (Fig. 3).

Group I flows, exposed only on the southeastern flank of the volcano (Fig. 4), are overlain by tephra horizon PM_1 , and its thin soil layer; they were erupted about 5400 (4700 ^{14}C) B.P.

Group II flows, on the southern and southwestern flanks, are overlain by a buried soil and the PM_2 tephra. They concluded the eruption at about 5100-5200 (4400-4500 ^{14}C) B.P., which also erupted the PM_3 pumice.

Group III flows formed about 4300 (3800 ^{14}C) B.P. They were erupted following deposition of a thin white ash layer during the start of the eruption, followed by coarse ash.

Group IV flows were erupted at about 4000 (3700 ^{14}C) B.P., shortly after eruption of a gray ash and were covered by the PM_3 pumice at the end of the same eruption.

Group V flows are overlain by stratified ash and then by the PM_4 layer. Group VI flows overlie the PM_5

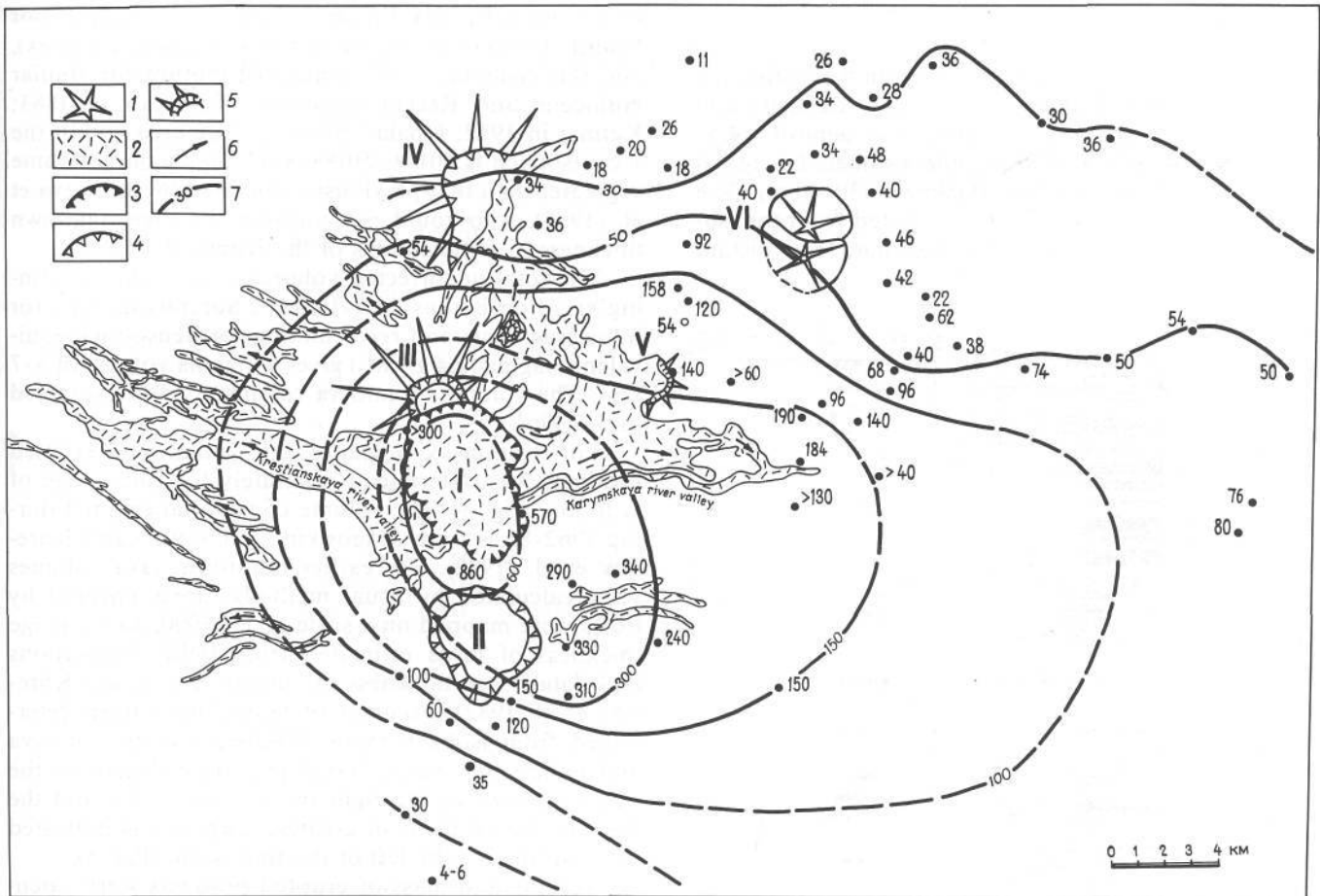


Fig. 2. Distribution of pyroclastic flows accompanying formation of Karymsky caldera and isopachs for tephra of the caldera-forming eruption. 1, pyroclastic flows; 2, stratovolcanoes; 3, scarp of Karymsky caldera; 4, scarps of Upper Pleistocene-Holocene calderas; 5, maars; 6, direction of flow of pyroclastic flows; 7, iso-

pachs of combined upper and lower lapilli horizons of the caldera-forming eruption, in cm; numerical values listed for tephra observations points. I, Karymsky caldera; II, Maly Semiachik volcano; III, Soboliny volcano; IV, Karymsky Lake caldera

layer, but most underlie the soil or stratified volcanic sands which are beneath the SC layer. These two groups of flows have not been dated precisely: they are within the time interval from 2800 (2600 ^{14}C) to 4100 (3600 ^{14}C) B.P. We suggest that the age is approximately 3300-3400 B.P. for group V flows, and 3000-3100 B.P. for group VI flows.

Group VII flows lie immediately beneath the scoria layer SC and formed about 2800 (2600 ^{14}C) B.P. This layer was deposited by distinctive pyroclastic flows containing dark andesitic bomblike scoria, some with dense cores.

Lava flows of groups VIII-IX were erupted during the last 500 years. The voluminous VIII lava flow and the group IX flows were erupted about 400 and 200-250 B.P., respectively. Lava flow X is morphologically similar to historic flows, and considering its position under gray andesitic ash of the uppermost part of the sequence, could have formed during the eruption of 1934-1935. Lava flow VIII, which was assigned to this eruption by Vlodayets (1947), is considerably older according to our data, in agreement with Ivanov (1970).

Group XI consists of flows from the 1962-1981 eruptions, described by Magus'kin et al. (1982) and Khrenov et al. (1982).

Compositions

Detailed petrology is beyond the scope of this study and will be reported separately. The general evolution of volcanic rocks and tephra is documented by analyses of tephra collected from each widespread layer and lavas from each age group (representative data in Table 2). Changes in SiO_2 content are plotted in Fig. 3; plotted compositions of all pyroclastic samples are recalculated to be volatile free.

Pyroclastic deposits of the caldera-forming eruption are dacite and rhyodacite. Lavas and pyroclastics of Karymsky volcano are mostly andesite (57-64% SiO_2); dacite (to 65% SiO_2) is present only among group-II lavas. The initial pyroclastics and the 2800 B.P. SC tephra are basaltic andesite (52-56% SiO_2).

Volumes

The volume of caldera-forming eruption was estimated by adding volumes of pyroclastic flow deposits and tephra. The volume of pyroclastic flow deposits (4.5-6 km³) was determined using the estimated original area (150 km²) and average thickness (30-40 m). The tephra volume (8-10 km³) was calculated from the isopach map of the study area, thickness data from distant

points in the Eastern Volcanic Zone and the Komandor Islands (500 km northeast of the Karymsky complex), and the systematics of tephra distribution for similar Holocene and Recent eruptions (Krakatau in 1883; Katmai in 1912; Opala 1500 B.P.). The area within the 1-cm isopach is 40000-50000 km². This tephra volume is greater than that previously estimated by Braitseva et al. (1985), who could not consider the then unknown thickness in remote areas of the Komandor Islands.

The total uncorrected volume of the caldera-forming eruption is thus 12.5-16 km³. Subtracting 10% for lithic fragments and recalculating for dense-rock-equivalent magma (2.4 g/cm³) gives a magma volume of 5-7 km³. The volume of caldera collapse is also estimated as 5-7 km³.

For Karymsky volcano, the volume of erupted products was determined separately for each stage of eruption (Fig. 5). The volume of material erupted during 1962-81 is from Magus'kin et al. (1982) and Khrenov et al. (1982). For earlier eruptions, lava volumes were calculated by usual methods: areas covered by flows were mapped on a scale of 1:10000, and average thickness of lavas estimated from field observations and data about thickness of similar lava flows (Khrenov et al. 1982). Volumes of tephra have been determined from isopach maps. Relative volumes of lava and tephra for specific eruptions are reflected in the size of arrows to the right of the time scale, and the mass of the products of greatest eruptions is indicated by bold lines to the left of the time scale (Fig. 5).

Volume and mass of erupted products were calculated for the two major volcanic cycles (IKM and IIKM) and also for separate stages and eruptive phases of the IKM cycle (Table 3, Fig. 3). Eruptive volumes for the IIKM cycle and stages of the IKM cycle were determined directly from the volumes of their pyroclastics

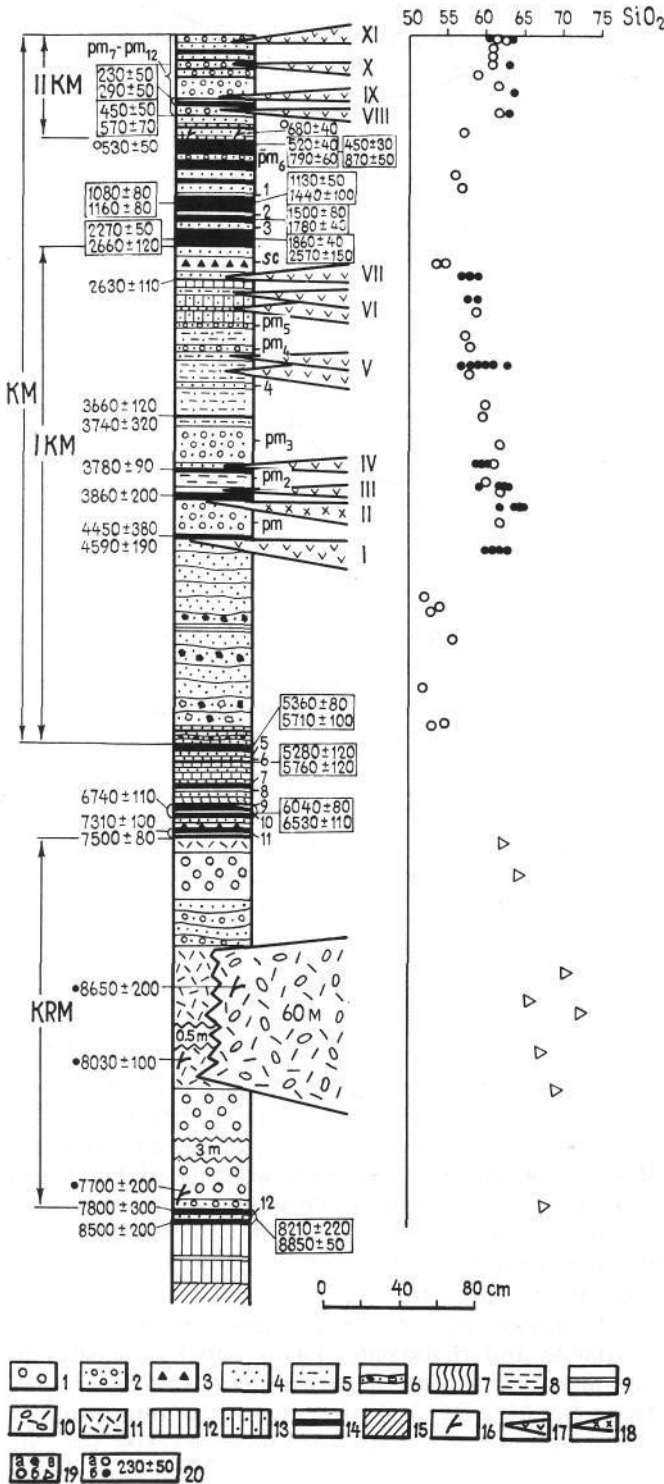


Fig. 3. Composite cross section of lavas and pyroclastic deposits on the flanks of Karymsky volcano. 7, bombs and pumice lapilli; 2, pumice lapilli with volcanic sand; 3, scoria lapilli with volcanic sand; 4, volcanic sand, nonstratified; 5, stratified volcanic sand; 6, stratified pyroclastics of initial volcanic eruptions of the volcano, volcanic sands; the same sands with lapilli, bombs and admixed xenolithic material; 7, volcanic sands, ochered; 8, volcanic sands and fine ashes, stratified; 9, intercalated fine sands; 10, pyroclastic flow deposits; 11, fine ash from ash-clouds of the caldera-forming eruption; 12, sandy soils; 13, sandy soils with admixed volcanic sands; 14, buried soils; 15, pre-karymsky deposits; 16, wood and charcoal; 17, andesitic lava flows; 18, andesitic and dacitic lava flows; 19, data points for chemical compositions: a, tephra of Karymsky volcano; b, lavas of the same volcano; c, pyroclastics of the caldera-forming eruption (compositions of a and b are recalculated volatile free); 20, radiocarbon dates; a, from wood; b, from charcoal; others from buried soils (in the framework of dates for alkaline leachates from the same soil sample). KPM, deposits associated with formation of Karymsky caldera; IKM, IIKM, main periods of activity of Karymsky volcano; I-XI, groups of lava flows; PM₁-PM₁₂, pumiceous tephra horizons; SC, intercalated scoria. 1-12, Tephra from distant sources (layer 2, from Opala volcano; 3, from Ksudach volcano; layers 4-5, from Avacha volcano; layer 10, from Khangar volcano; layer 11, from Kizimen volcano; for other layers, the source is not presently known)

Table 1. Eruptive history of Karymsky volcano

	Soil-pyroclastic cover deposits at the foot of volcano	Lava flows	Composition of products	Age borders, years ago	Style of volcanic activity	Up-surge periods
Karymsky volcano	Layers of pumice tephra (PM ₇ -PM ₁₂) and gray coarse ashes, separated by thin layers of buried soils	XI X IX VIII	andesite	500	Upsurge of volcanic activity frequent effusive-explosive eruptions, separated by short repose period	II KM
	Soil with coarse ash and pumice tephra interlayers the upper part PM ₆		andesite		Repose period with single slight explosive eruptions at the end of period	
	Bombs and cinder lapilli, coarse ash		basaltic andesite	2800	Strong explosive eruption	
	Stratified coarse gray ashes, interlayers of pumice tephra PM ₄ and PM ₅	VII VI V	andesite		Intense explosive-effusive activity, further growth of the volcano cone	
	Pumice bombs and lapilli, coarse ash (PM ₁ and PM ₃), thin and coarse ashes (PM ₂) separated by interlayers of soils	IV III II	andesite	4100	Two large explosive-effusive eruptions	I KM
				4200		
	Stratified coarse ashes separated layers with lapilli and bombs, admixture of resurgents material	I ?	andesite, Basaltic andesite	4300	800-year-long repose period Intense explosive-effusive eruption	
				5100		
				5400	Onset of formation of Karymsky volcano: the cone growth, intense explosive activity, lava flow outpouring	
	Bench of buried soils with tephra of Maly Semyachik volcano and with interlayers of transite ashes			6100	Repose period	
Bombs and lapilli of pumice, coarse and thin ash, pyroclastic deposits		dacite, Rhyodacite	7600	Caldera-forming eruptions: pumice ejections, pyroclastic flows, collapse caldera formation	KRM	
			7700 ¹⁴ C			

and lavas: lava volumes are the sums of volumes of lava flows formed during each stage or cycle, and the volume of pyroclastic material was calculated for each cycle using the corresponding isopach map. The volume of pyroclastics within the cone has been considered to compose about 40% of the total tephra volume (Braitseva et al. 1984). The volume of volcanic products of the IKM cycle (and its beginning stage IKM₁) were determined as the difference between the total volume of volcanic products and the sum of volumes erupted during these stages. The total volume of volcanic products (6.3 km³) is the combined volume of the volcanic cone (2.9 km³), tephra (1 km³), and caldera-filling deposits above the level of the lake inferred to have filled the caldera (2.4 km³). This caldera fill can be approximated as the volume of the segment of a sphere with area of 19 km² and height of 0.25 km. In evaluating the mass of erupted products (in accord with data from the literature), the specific gravity of andesitic lava flows was taken as 2-2.2 g/cm³, andesitic and andesite-dacitic tuffs as 1.1-1.3 g/cm³, dacitic pyroclastics of the caldera-forming eruption as 1 g/cm³, and compacted pyroclastics of the volcano as 1.5-1.7 g/cm³.

Volcanic history and eruptive dynamics

A strong caldera-forming eruption began at the Karymsky center about 7700 ¹⁴C B.P. It started with massive outbursts of pumiceous tephra ("lower lapilli"), which rest directly on the underlying soil. Blast deposits are absent in these lower tephra, even close to the caldera. The main axis of tephra fall is ESE. The tephra fall was succeeded by pyroclastic flows, which mainly followed valleys of the Krestyanskaya and Karymskaya rivers (Fig. 2). Ash clouds which accompanied the pyroclastic flows spread thin ash veneers over large areas. Immediately after eruption of the pyroclastic flows, explosive outbursts generated additional ash falls, the coarsest of which is the "upper lapilli" layer (Fig. 3). The depositional axis of this ash fall is ENE. The combined thickness of the lower and upper tephra near the Karymsky center is shown in Fig. 2; the thickness of tephra reaches 3 cm on Bering Island, the easternmost of the Komondor Islands (Kirianov and Yegorova, 1986). In size of caldera collapse and the volume of erupted material (12.5-16 km³), this caldera-forming

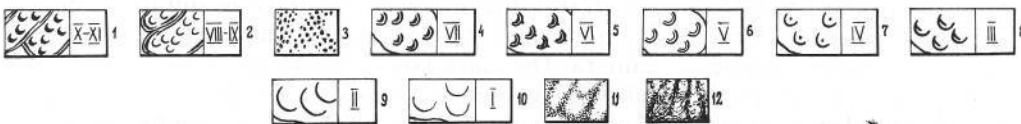
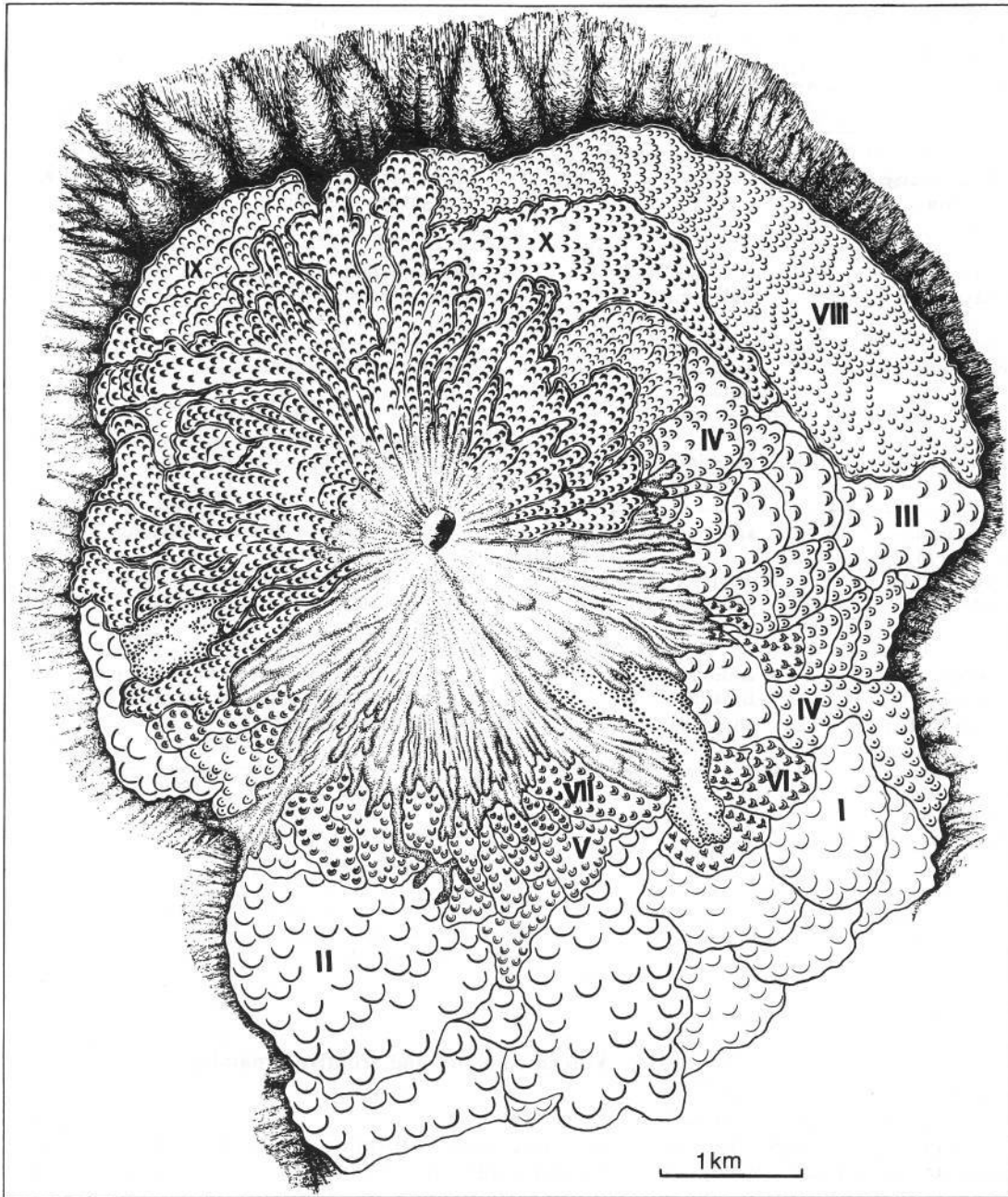


Fig. 4. Map of lava flow groups on Karymsky volcano. 1, andesitic flows of historic eruptions (XI, 1962-1980; X, 1931-1937?); 2, andesitic flows IX (200-250 B.P.) and VIII (400 B.P.); 3, pyroclastic scoria avalanche deposits (about 2800 B.P.); 4, andesitic flows VII (2800 B.P.); 5, andesitic flows VI (3000-3100 B.P.); 6, andesitic

flows V (3300-3400 B.P.); 7, andesitic flows IV (4200 B.P.); 8, andesitic flows III (4300 B.P.); 9, dacitic and andesitic flows II (5100-5200 B.P.); 10, andesitic flows I (about 5400 B.P.); 11, pyroclastic deposits of the volcanic cone and pyroclastic avalanches of historic eruptions; 12, caldera rim

eruption was comparable to the famous Krakatau eruption in 1883.

After formation of the caldera, volcanic activity ceased for at least 1600 years, as expressed by buried soils which contain only ash layers from Maly Semia-

chik volcano (Fig. 1) and other distant sources. Alluvial-fan and lacustrine deposits, which probably accumulated within the caldera during this period, are mostly now covered by lavas of Karymsky volcano. A remnant of the lake bottom is probably represented by

Table 2. The chemistry of lavas and tephra of Karymsky and its eruption associated with the Karymsky Caldera formation

Components	Caldera-forming eruption					Karymsky volcano					
	Lower lapilli	Pyroclastic flows and fine ash				Upper lapilli	Pyroclastics of the eruptive phase KM ₁ (6100–5400 B.P.)				
		278 ^a /5	330/1	300/1	4/17		5a/3	5a/4	286/8	319/14	285/1a
SiO ₂	65.38	65.44	63.16	68.98	63.48	69.88	52.62	52.26	53.58	51.52	53.94
TiO ₂	0.64	0.56	0.57	0.40	0.40	0.31	0.88	0.92	0.85	0.83	0.83
Al ₂ O ₃	14.40	14.93	16.09	14.27	16.11	13.66	16.40	15.85	16.31	16.99	16.32
Fe ₂ O	1.72	1.28	1.17	1.67	4.02	1.20	3.60	3.20	3.44	3.66	3.47
FeO	3.22	2.47	3.10	1.06	1.09	1.37	5.86	6.32	5.63	6.32	5.11
MnO	0.12	0.17	0.17	0.08	0.08	0.08	0.18	0.17	0.20	0.15	0.19
MgO	1.12	1.34	1.88	1.02	1.08	0.49	5.84	6.54	5.83	5.83	4.92
CaO	3.93	3.04	4.29	1.96	1.88	1.85	10.34	10.21	9.78	10.28	8.05
Na ₂ O	4.15	3.48	3.91	3.52	3.01	4.49	2.90	2.82	2.62	2.62	2.58
K ₂ O	2.38	2.25	2.10	2.74	2.31	2.82	0.86	0.91	1.48	0.82	1.02
H ₂ O ⁻	1.16	0.92	0.74	0.70	1.78	0.68	0.48	0.25	0.35	0.79	1.08
H ₂ O ⁺	1.20	0.38	0.33	3.08	4.48	3.22		0.13	0.20	0.36	1.66
P ₂ O ₅	0.15	0.06	0.07	0.12	0.15	0.12	0.16	0.13	0.16	0.20	0.16
Ignition loss		3.40	2.74	0.94							
Total	99.57	99.72	100.32	100.58	100.22	100.23	100.07	99.51	100.43	100.37	99.33

Period of increased activity I KM (6100–2800 yrs ago)

Components	Lagerny cone		Lava flows I			Eruption 5100–5200 B.P.				
	286/20	SL-12	391/1	345	353	Tephra PM ₁	Lava flows II			
						343/2	372	390	384	369
SiO ₂	46.12	55.86	59.90	61.38	63.16	61.68	64.08	64.68	62.08	65.14
TiO ₂	0.73	0.86	0.80	0.85	0.88	1.06	0.80	0.76	0.73	0.80
Al ₂ O ₃	19.20	16.76	17.71	16.57	16.32	16.02	16.00	16.00	18.18	16.32
Fe ₂ O ₃	4.39	2.14	3.27	2.00	2.07	1.33	0.97	1.41	2.37	2.08
FeO	4.56	6.10	2.79	4.31	3.74	4.65	3.79	3.51	2.28	2.39
MnO	0.15	0.16	0.10	0.20	0.16	0.15	0.15	0.15	0.10	0.18
MgO	4.30	4.56	2.09	2.49	2.33	2.52	1.67	1.34	1.39	1.65
CaO	6.32	8.04	7.35	5.80	4.71	5.29	4.56	4.46	6.49	3.85
Na ₂ O	2.15	3.99	4.29	4.18	4.46	4.58	5.29	4.47	4.69	5.15
K ₂ O	0.83	1.25	1.37	1.80	2.05	1.84	1.84	1.86	1.54	2.21
H ₂ O ⁻	3.55	0.26		0.42	0.28	0.46	0.18	0.20		0.34
H ₂ O ⁺	4.49	0.24	0.32	0.10	0.13	0.18	0.33	0.40	0.30	0.20
P ₂ O ₅	0.23	0.18	0.15	0.11	0.19	0.33	0.23	0.21	0.22	0.18
Ignition loss	3.04									
Total	100.26	100.40	100.14	100.21	100.48	100.09	99.89	99.17	100.37	100.52

the plain in the southern part of caldera depression, where thermal springs occur in the Karymskaya river valley.

Karymsky volcano started to grow within the caldera about 5300 (6100 ¹⁴C) B.P. Its history can be divided into two main cycles, i.e., IKM and IIKM (not yet complete), divided by a 2300-year repose period. During the IKM cycle, in turn, two stages of activity are divided by an inactive period of about 800 years (Fig. 3, Table 1).

Early during the IKM cycle (eruptive stage IKM₁; Fig. 5), the caldera was filled and a volcanic cone was built. The character of tephra indicates that eruptions

were frequent but weak. (Strong eruptions of Karymsky volcano are defined as those involving 0.5–0.05 × 10⁹ tonnes of material, and weak eruptions as those of less than 0.05 × 10⁹ tonnes.) The tephra are mainly basaltic andesite (52–56% SiO₂ content, Table 3, Fig. 3). No lava flows of this composition are exposed on flanks of the volcano; any that were erupted are buried by younger material. Lava of this composition is present at the small lava cone "Lagerny" in the southern part of caldera. Tephra correlations indicate that this cone was active concurrently with initial activity at Karymsky volcano, i.e., basaltic andesite vented through several conduits, not only through Karymsky volcano. In the

Table 2. (continued)

Period of increased activity I KM (6100–2800 yrs ago)										
Components	Eruption 4300 yrs ago					Eruption 4200 yrs ago				
	Tephra PM ₂	Lava flows III			Tephra	Tephra	Lava flows IV			Tephra PM ₃
	348/1	411	422	413/1	278/33	278/30	407	421	381	278/29
SiO ₂	60.88	63.00	61.98	59.08	59.62	60.58	60.08	59.16	59.50	59.84
TiO ₂	0.88	0.88	0.91	0.80	0.81	0.64	0.87	0.82	0.53	0.83
Al ₂ O ₃	16.68	16.32	15.94	16.62	16.84	17.75	16.32	16.67	16.53	16.94
Fe ₂ O ₃	2.43	3.42	1.31	1.84	2.93	2.68	2.32	2.84	2.12	2.23
FeO	3.68	2.10	4.88	5.60	4.36	3.10	4.48	4.60	4.42	3.59
MnO	0.17	0.16	0.24	0.15	0.14	0.14	0.19	0.13	0.17	0.17
MgO	2.27	2.01	1.53	2.74	3.20	2.18	3.66	2.90	3.03	2.07
CaO	5.48	4.56	4.86	7.03	5.78	5.97	6.06	7.30	6.49	5.23
Na ₂ O	4.64	4.67	4.28	3.86	4.08	4.27	4.08	3.99	4.33	4.28
K ₂ O	1.75	2.05	1.73	1.37	1.45	1.56	1.56	1.54	1.77	1.63
H ₂ O ⁻	0.36	0.32	0.13	0.24	0.57	0.70	0.25	—	—	1.36
H ₂ O ⁺	1.00	0.42	0.33	0.36	0.17	0.51	0.46	—	—	1.18
P ₂ O ₅	0.22	0.23	0.19	0.31	0.19	0.18	0.12	0.19	0.19	0.20
Ignition loss										0.44
Total	100.41	100.14	99.72	100.00	100.14	100.26	100.45	100.14	99.63	99.99

Period of increased activity 1 KM (6100–2800 yrs ago)										
Components	Deposits of eruptive phase KM ₂ (4100–2800 yrs ago)									
	Tephra			Lava flows V				Tephra PM ₄	Tephra	
	285/11	285/10	285/8	350	349	358	351	285/6	285/5	285/3
SiO ₂	58.26	58.74	56.76	57.24	59.12	61.04	63.12	57.24	56.36	58.24
TiO ₂	0.83	0.83	0.85	0.90	0.74	0.82	0.85	0.89	0.89	0.92
Al ₂ O ₃	16.56	16.76	18.29	17.08	16.28	16.83	16.61	16.62	17.06	16.91
Fe ₂ O ₃	2.30	2.98	2.15	2.45	2.01	2.07	1.87	3.07	2.56	2.41
FeO	4.31	4.11	4.89	5.89	5.17	2.23	3.65	4.14	4.94	4.83
MnO	0.17	0.11	0.13	0.21	0.15	0.08	0.18	0.11	0.13	0.20
MgO	3.96	3.40	4.47	3.64	2.87	1.47	2.37	4.74	4.02	3.79
CaO	6.51	6.25	5.50	7.52	6.85	6.64	4.79	6.63	7.22	6.73
Na ₂ O	3.60	3.69	3.75	3.65	4.50	4.59	4.46	3.51	3.47	3.65
K ₂ O	1.35	1.35	1.31	1.50	1.44	1.56	1.88	1.35	1.31	1.35
H ₂ O ⁻	0.59	0.68	0.46	0.28	0.18	0.02	0.26	0.82	0.62	0.81
H ₂ O ⁺	1.07	0.39	1.47	—	0.30	0.76	0.10	0.30	0.77	0.56
P ₂ O ₅	0.09	0.12	0.19	0.08	0.37	0.07	0.21	0.11	0.22	0.09
Total	99.60	99.41	97.92	100.44	99.98	100.18	100.35	99.53	99.56	100.49

middle of the IKM₁ stage, the composition changed to more silicic andesite, and group I lava flows were erupted (volume about 0.25 km²). After a 300-year-long recess of volcanic activity, a strong eruption (PM₁ tephra, group II lavas) took place at 5200–5100 (4500–4400 ¹⁴C) B.P. Tephra of this eruption are widespread eastward (Fig. 6), where this horizon serves as a marker (Braitseva et al. 1985). Lava flows of this eruption are the thickest on the volcano (up to 80 m); they almost completely filled the southeast part of the caldera. These flows are characterized by contrast in microrelief with large and extensive transverse ridges. This concluding eruption of the first eruptive stage (IKM₁) was

the strongest in the entire history of the volcano (Table 3, Fig. 5).

After 800 years of repose, activity of the volcano resumed with two moderate-strength eruptions (PM₂-III, PM₂-IV) at the beginning of stage IKM₂ at about 4300 (3800 ¹⁴C) B.P. and 4200 (3700 ¹⁴C) B.P. Both eruptions were only about a quarter as strong as the culminating eruption of the preceding stage (Fig. 3, Table 3), but tephra of the PM₃ are comparable in volume with tephra of PM₁. The axis of the ash fall of this eruption was westward (Fig. 6).

Following these comparatively strong eruptions, further eruptive activity of the IKM₂ stage was similar

Table 2. (continued)

Period of increased activity I KM (6100-2800 B.P.)							Tephra in soil during repose period			
Components	Deposits of eruptive phase KM ₂ (4100-2800 B.P.)									
	Lava flows VI		Lava flows VII			Scoria avalanche	Tephra sc			
	428	418	368	356	397			429	351/1	283/13
SiO ₂	58.06	59.26	58.14	57.42	59.02	56.78	53.26	56.08	65.84	
TiO ₂	0.80	0.81	0.83	0.93	0.85	0.85	1.00	1.05	0.83	
Al ₂ O ₃	16.35	17.14	16.63	17.31	16.40	16.65	16.52	16.85	17.72	
Fe ₂ O ₃	2.13	1.77	2.47	2.51	0.81	2.53	5.34	2.97	2.24	
FeO	4.34	4.94	4.25	5.03	5.89	5.75	4.25	5.48	5.14	
MnO	0.20	0.18	0.25	0.20	0.17	0.11	0.23	0.18	0.18	
MgO	4.21	3.39	4.98	4.03	3.08	3.68	4.49	3.45	3.52	
CaO	6.99	6.80	6.92	6.96	6.91	7.97	9.13	7.59	7.61	
Na ₂ O	3.92	4.00	3.27	3.79	4.39	3.84	3.26	3.65	3.38	
K ₂ O	1.45	1.54	1.57	1.38	1.36	1.50	0.79	1.36	1.26	
H ₂ O ⁻	—	—	—	0.46	0.28	—	0.45	0.53	0.99	
H ₂ O ⁺	1.18	0.04	0.40	0.25	0.44	—	—	0.08	0.77	
P ₂ O ₅	0.16	0.23	0.17	0.12	0.21	0.14	0.20	0.23	0.20	
Ignition loss							1.00	0.61		
Total	99.79	100.10	99.83	100.39	99.81	99.80	99.92	100.111	99.68	

Period of increased activity II KM 500 B.P. - present time										
Components	Tephra	Eruption 400 yrs ago		Eruption 200 B.P.		Tephra PM ₁₀	Eruption 1935?		Tephra	
		Tephra PM ₇	Lava VIII	Lava IX	Tephra PM ₉		Tephra PM ₁₁	Lava X	348/5	348/4
SiO ₂	56.14	62.44	63.48	63.74	61.40	57.52	60.80	63.24	61.84	61.16
TiO ₂	1.20	0.90	0.85	0.85	0.93	0.80	0.95	0.87	0.95	0.95
Al ₂ O ₃	16.52	16.48	15.97	16.04	16.03	17.61	16.77	16.00	17.73	17.68
Fe ₂ O ₃	2.64	1.65	2.27	2.03	2.52	2.68	1.80	2.27	1.73	2.00
FeO	6.84	3.97	3.68	3.51	4.11	4.19	4.88	3.58	4.15	4.28
MnO	0.16	0.19	0.20	0.20	0.16	0.17	0.16	0.18	0.15	0.15
MgO	3.86	2.10	1.99	1.88	2.16	2.82	2.37	2.87	2.94	2.99
CaO	6.21	4.88	4.34	4.41	5.29	6.92	5.19	5.19	4.37	4.58
Na ₂ O	2.80	4.61	4.74	5.02	4.53	3.68	4.46	4.46	4.24	4.24
K ₂ O	1.31	1.95	1.93	2.03	1.73	1.33	1.84	1.84	1.75	1.75
H ₂ O ⁻	0.40	0.36	0.34	0.39	0.34	0.36	0.34	0.34	0.20	0.16
H ₂ O ⁺	1.25	0.31	0.37	0.31	0.78	0.14	0.20	0.20	0.17	0.39
P ₂ O ₅	0.21	0.09	0.18	0.16	0.29	0.30	0.29	0.29	0.23	0.12
Ignition loss						1.08				
Total	99.54	99.98	100.34	100.57	100.27	99.60	100.05	100.05	99.85	100.45

1, Analyses were made at the Central Chemical Laboratory of the Institute of Volcanology, Analysts: L. G. Baitsaeva, N. G. Gusakova, T. V. Dolgova, L. A. Kartashova, G. F. Knyazeva, G. V. Lets, G. P. Novoseletskaya, T. G. Osetrova. 2, Analyses of tephra and lava within indicated subdivisions are given in age sequence. 3, See lava and tephra analyses of historical eruptions in Ivanov B. V., 1970; Khrenov et al., 1982. 4, Analysis SL-12 presented to authors by O. B. Selyangin

in character to the activity during beginning of the KM₁ interval: many weak eruptions following each other in rapid succession. Within a general sequence of gray weakly stratified coarse ash, some of these eruptions are represented by separate intercalated gray volcanic sand and pumice (PM₄ and PM₅); volume of the materials is 0.01-0.001 km³. In the same stage, lava flows of

groups V, VI, and VII were erupted, with volumes of 0.025, 0.012, and 0.02 km³, respectively. They form the upper lava flows on the southern flanks of the volcano. The IKM₂ stage culminated with an explosive eruption of scoria about 2800 B.P. Bombs and lapilli of this scoria cover the volcanic cone and its flanks; their thickness reaches 1-1.4 m close to the volcano. This scoria

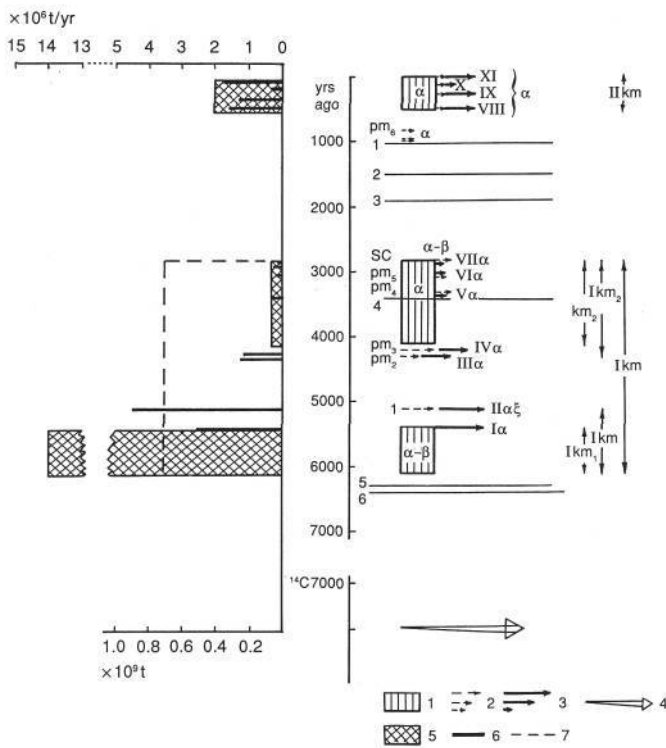


Fig. 5. Eruption dynamics of Karymsky volcano. 1, phases of intense explosive activity; 2, separate explosive eruptions, with volumes: a, 0.1-0.05 km³; b, 0.05-0.01 km³; c, 0.01-0.0001 km³; 3, lava flow groups, with volumes: a, 0.5-0.25 km³; b, 0.25-0.05 km³; c, 0.05-0.01 km³; 4, caldera-forming eruption (not to scale); 5, eruptive intensities for the major eruptive phases; 6, total mass erupted during the strongest eruptions; 7, average eruptive intensity during the IKM cycle. I-XI, age groups of lava flows; PM₁-PM₆, SC, layers of pumice and scoria of separate explosive eruptions. IKM, IIKM: cycles of activity of the volcano; IKM₁, IKM₂, eruptive stages of activity within the IKM cycle; KM₁ and KM₂, eruptive phases; 1-6, horizons of transitional tephra

cover subdues the surface microrelief of lava flows in the southern flanks. Total volume of the scoria is about 0.015 km³.

During the IKM₂ stage, silicic andesite (59-63% SiO₂) gradually gave way to more mafic varieties (57-59% SiO₂). Scoria of the final eruption is basaltic andesite. The transition from andesite to basaltic andesite took place virtually without change in eruptive dynamics. A similar lack of change in eruptive behavior characterized the end of the KM₁ phase (Fig. 5), when basaltic andesite was, in contrast, abruptly replaced by andesite (Table 1). In both transitions, the eruptive intensity was neither interrupted nor increased.

By the close of the IKM cycle of activity (about 2800 B.P.) the volcanic cone had grown to nearly its present shape. The subsequent prolonged repose period is expressed by a buried soil zone. Some weak explosive eruptions are marked by two layers of coarse andesitic ash and pumice (PM₆) in the upper part of the soil. Volumes of the tephra from these eruptions are in the range 0.001-0.008 km³. During the volcanic inactivity,

vegetated areas enlarged considerably; shrubs covered the flanking lava flows and also the cone itself up to 1000-m elevation.

New activity of the volcano (the IIKM cycle) started about 500 B.P. The volcanic activity became more episodic: separate moderate-strength eruptions, or series of eruptions, were interrupted by short (tens of years) repose intervals, expressed by thin soil horizons. Eruptions were either explosive or effusive-explosive: outbursts produced pumiceous tephra (PM₇-PM₈) or coarse gray ash, accompanied by the young (VIII, IX) and historical (X, XI) lava flows. The characteristically fresh microrelief of flow surfaces distinguishes it from the 2800 B.P. scoria-covered flows. The strongest eruptions occurred at 400 and 200-250 B.P., and historically in 1961-1981 (Fig. 2) with eruptive volumes of 0.15, 0.12, and 0.19 km³, respectively.

To generalize, the volume of material erupted was maximal during the initial IKM cycle (IKM₁) and decreased sequentially later during this cycle. At the beginning of cycle IIKM, productivity increased again by a factor of almost four, but remained lower than during the beginning of cycle IKM. The eruptive volumes during the IIKM cycle have been only half the average for the IKM cycle (Fig. 5, Table 3). Such a trend accords with the general decrease in productivity at many volcanoes with time (Magus'kin et al. 1982). Including the repose periods, after which accumulated energy was released in eruptions, productivity was 2.1 x 10⁶ t/a for the IKM cycle, but only 0.4 x 10⁶ t/a for the IIKM cycle. Volcano productivity during the IIKM cycle is close to that in the second half of the IKM cycle (0.4 x 10⁶ t/a for the IKM₂). Thus, the volcano retained its energetic potential at the same level as in the end of the last repose period. The average intensity for the entire history of the volcano (6100 years) is 2 x 10⁶ t/a, or 15 x 10⁶ t/a including the preceding repose period.

Interpretation of the past activity permits an approximate forecast of future eruptions. High eruptive activity of the volcano during the last 500 years and increased volumes of erupted magma during the same time in comparison to the second half of the previous IKM cycle (Fig. 5) show that the volcano has not yet completed its cycle of activity. Thus, activity is not likely to stop in the near future. Considering the duration of eruptive phases with intense activity (700-1300 years), we suggest that high rates of volcanic activity will continue for at least the next 200 years. The character of eruptions will be similar: weak to moderately explosive eruptions involving ejection of andesitic tephra (commonly pumiceous) and formation of lava flows. Andesite may be replaced by basaltic andesite, as occurred at the end of the KM₂ phase, although the character of eruptions will not change significantly. The volcanic hazards from lava flows will be limited by the caldera boundaries (radius 2.5-5 km), and the thickness of tephra within the caldera will be 5-40 cm, reaching 100-120 cm at the base of the cone downslope from an explosion. At a distance of 4-5 km beyond the caldera, maximum tephra thickness will reach 20-25 cm, and 2-4 cm (coarse ash) at a distance of 10 km.

Table 3. Volumes and masses erupted by Karymsky volcano at different stages of its activity

Main events in history of volcano (see index values in Figs. 2, 3)		Duration, years		Pyroclastics		Lavas		Total amount of material		Rate of evacuation of material $m \times 10^6$ t/y
				V, km ³	$m \times 10^9$, t	V, km ³	$m \times 10^9$, t	V, km ³	$m \times 10^9$, t	
IIKM	PM _{11-12, X, IX}	500		0.06	0.07	0.15	0.30	0.21	0.37	1.9-2.1
	PM _{7-10, IX, VIII}			0.07-0.09	0.08-0.1	0.23-0.30	0.50-0.60	0.30-0.39	0.58-0.70	
	Σ			0.13-0.15	0.15-0.17	0.38-0.45	0.8-0.9	0.51-0.60	0.95-1.07	
PM ₆ and coarse ashes of relative repose period		2300		0.02	0.02	—	—	0.02	0.02	
IKM ₂	KM ₂	1300		0.17	0.24	0.06	0.13	0.23	0.37	0.3
	PM _{3-IV}	1500		0.1-0.15	0.1-0.15	0.05	0.11	0.15-0.20	0.21-0.26	0.53-0.57
	PM _{2-III}			0.03-0.04	0.03-0.04	0.09-0.1	0.20-0.22	0.12-0.13	0.24-0.26	
IKM	Σ			0.30-0.36	0.37-0.43	0.20-0.21	0.44-0.46	0.50-0.56	0.82-0.89	
IKM ₁	PM _{1-II}	700	1000	0.1	0.1	0.4	0.8	0.5	0.9	10.4-10.9
	KM ₁			4.7	9.5-10	13.6-14.3				
	Σ			5.2	10.4-10.9					
Σ	IKM	2500						6.23-6.38	11.22-11.79	3.4-3.6
Σ	KM	5300						6.3	12.5	2

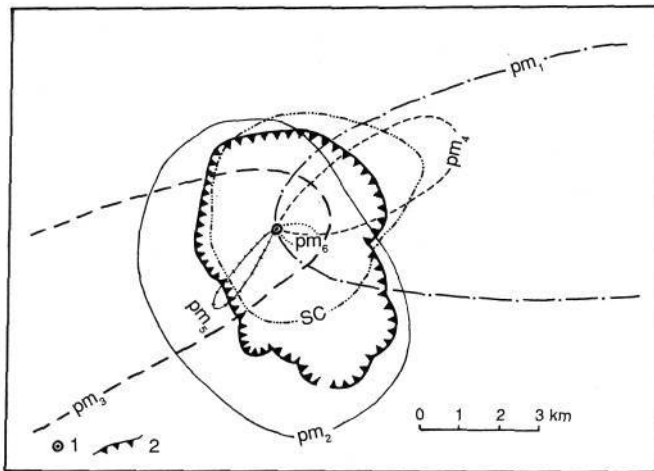


Fig. 6. Distribution of tephra during the main explosive eruptions (bounded by the 10-cm isopach). 1, crater of the volcano; 2, caldera rim scarp. Symbols for tephra layers as on Fig. 2

We suggest that the discharge rate will eventually decrease, as it did during the second half of the IKM cycle. Productivity of the complete IIKM cycle will be lower than productivity for the IKM cycle, reflecting a decreasing eruptive capacity of the volcano, and leading to a longer repose interval before the beginning of the next eruptive cycle (IIKM?), or to the cessation of volcanic activity.

Conclusions

1. The Karymsky caldera, within which Karymsky volcano is nested, collapsed about 7700 ^{14}C B.P. as a result of eruption of 12.5-16 km^3 of pumiceous pyroclastic material. Volumes of the caldera and erupted magma are subequal. The caldera-forming eruption is comparable in style and in composition of ejecta to the 1883 eruption of Krakatau.
2. Karymsky volcano began to grow within the caldera about 5300 (6100 ^{14}C) B.P., after a 1600-year repose period. About 6.3 km^3 (12.3×10^9 t) of lava and pyroclastics have been erupted since, at an average discharge of 2×10^6 t/a.
3. Two peak eruptive cycles (IKM, IIKM) were separated by 2300 years of low activity. The initial stage of IKM activity (6100-5100 B.P.) was characterized by the maximum discharge rates, most explosive eruptions, and changes in eruptive compositions from basaltic andesite to dacite. The second stage of IKM activity (4300-2800 B.P.) was characterized by decreasing intensity of eruptions and by andesitic compositions that changed to basaltic andesite during the final eruption.

4. The IIKM activity, which started about 500 B.P., is characterized by discrete, weak to moderate andesitic eruptions separated by short repose periods.
5. The most explosive eruptions occurred at 5400, 5200-5100, 4300-4200, 400, 250-200 B.P., and in 1962-1981.
6. Analysis of the eruptive dynamics suggests that high levels of activity of similar character to recent eruptions will continue for at least the next 200 years.

References

- Arslanov KhA (1978) Corrections to radiocarbon ages. *Geokhimiya* 8:1157-1164 (in Russian)
- Braitseva OA, Yegorova IA, Sulerzhitsky LD (1979) Tephrochronological study of the Karymsky Volcano. *Vulkanologiya and Seismologiya* 1:48-59 (in Russian)
- Braitseva OA, Litasova SI (1982) Age of Karymsky and the Maly Semiachik Volcanoes. *Vulkanologiya and Seismologiya* 3:92-96 (in Russian)
- Braitseva OA, Melekestsev IV, Flerov GB (1984) Holocene volcanism of the Tolbachik regional zone of scoria cones. In: Great Tolbachik fissure eruption in Kamchatka, 1975-1976. Moscow, Nauka, pp 177-223 (in Russian)
- Braitseva OA, Sulerzhitsky LD, Kirianov VYu (1985) Holocene tephra layers in the Eastern Volcanic zone of Kamchatka. *Vulkanologiya and Seismologiya* 5:80-90 (in Russian)
- Braitseva OA, Litasova SI, Sulerzhitsky LD (1989) Radiocarbon dating and palynological study of tephra on flanks of Karymsky and Maly Semiachik Volcanoes. *Vulkanologiya and Seismologiya* 1:92-96 (in Russian)
- Firstov PM, Lemzikov VK, Feofilaktov VD (1978) The seismic regime of Karymsky Volcano in 1975 and several questions on the forecasting of the time of thermal eruptions. *B Vokanol Stantsii (Kamchatka)* 54:27-34 (in Russian)
- Ivanov BV (1970) Eruption of Karymsky Volcano in 1962-65 and volcanoes of the Karymsky group. Moscow, Nauka, 135 p (in Russian)
- Khrenov AP, Dubik YuM, Ivanov BV (1982) Eruptive activity of the Karymsky Volcano (1970-1980). *Bull Vulkanologiya and Seismologiya* 4:29-49 (in Russian)
- Kirianov VYu, Yegorova IA, Litasova SI (1986) Volcanic ashes on Bering Island (Komandor Islands) associated with Holocene eruptions in Kamchatka. *Vulkanologiya and Seismologiya* 6:18-28 (in Russian)
- Magus'kin MA, Enman VB, Seleznev BV, Shkred VI (1982) Displacements on Karymsky Volcano from geodetic and photogrammetric data during 1970-1981. *Vulkanologiya and Seismologiya* 4:42-49 (in Russian)
- Masurenkov Yu P (ed) (1980) A volcanic center: structure and dynamics of the Karymsky center. Moscow, Nauka, 298 pp (in Russian)
- Newhall CG, Dzurisin D (1988) Historical unrest at large calderas of the world. *US Geol Survey Bull* 1855, 1108 pp
- Polyak BG, Melekestsev IV (1981) Productivity of volcanoes. *Vulkanologiya and Seismologiya* 5:22-37 (in Russian)
- Vlodavets VI (1947) Volcanoes of the Karymsky group. *Kamchatsky Volcano station, Trudy* 3:3-40 (in Russian)