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## Special Issue

## The 1996 Eruptions in the Karymsky Volcanic Center and Related Events

**Guest Editor S. A. Fedotov**

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*Continued on back cover*

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# Volcanic Activity in the Karymsky Center in 1996: Summit Eruption at Karymsky and Phreatomagmatic Eruption in the Akademii Nauk Caldera

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This paper presents the results of investigating the 1996 eruptive activity of volcanoes in the long-lived Karymsky volcanic center of Kamchatka, where eruptions began simultaneously at Karymsky volcano and in the Akademii Nauk caldera. Renewed effusive and explosive activity occurred at Karymsky after a 14-year period of dormancy and produced ~30 million tonnes of andesitic material over the year. The long history of eruptive activity at this volcano is forecast for the next few years. Simultaneously with this activity, which is typical for Karymsky, a subaqueous explosive eruption occurred 6 km to the south in a lake filling the Akademii Nauk caldera, the first event during historic times. A cone of basalt and basaltic andesite pyroclastic material, with a crater 650 m across, grew during an 18-hour period of activity in the northern part of Lake Karymskoe. The volume of this material is estimated as 0.04 km$^3$, and the weight as >70 million tonnes. The impact of the eruptions on the environment are discussed, the revived hydrothermal activity (new hot springs) in the caldera are described, and breach floods from the lake and other hazards are estimated.

## INTRODUCTION

The Karymsky long-lived volcanic center is situated in the central part of the east Kamchatka volcanic belt and is among the most active areas of the region. It is elongated from the south as an ellipse with axes of 50 and 35 km and consists of two (volcanic edifices of different ages and shapes (stratovolcanoes, calderas, maars, and monogenetic cones). The active volcanoes are Karymsky and Malyi Semyachik. The other, much larger, edifices are several old, partially destroyed volcanoes and calderas: Dvor, Odnobokiy, Akademii Nauk, etc. (Fig. 1).

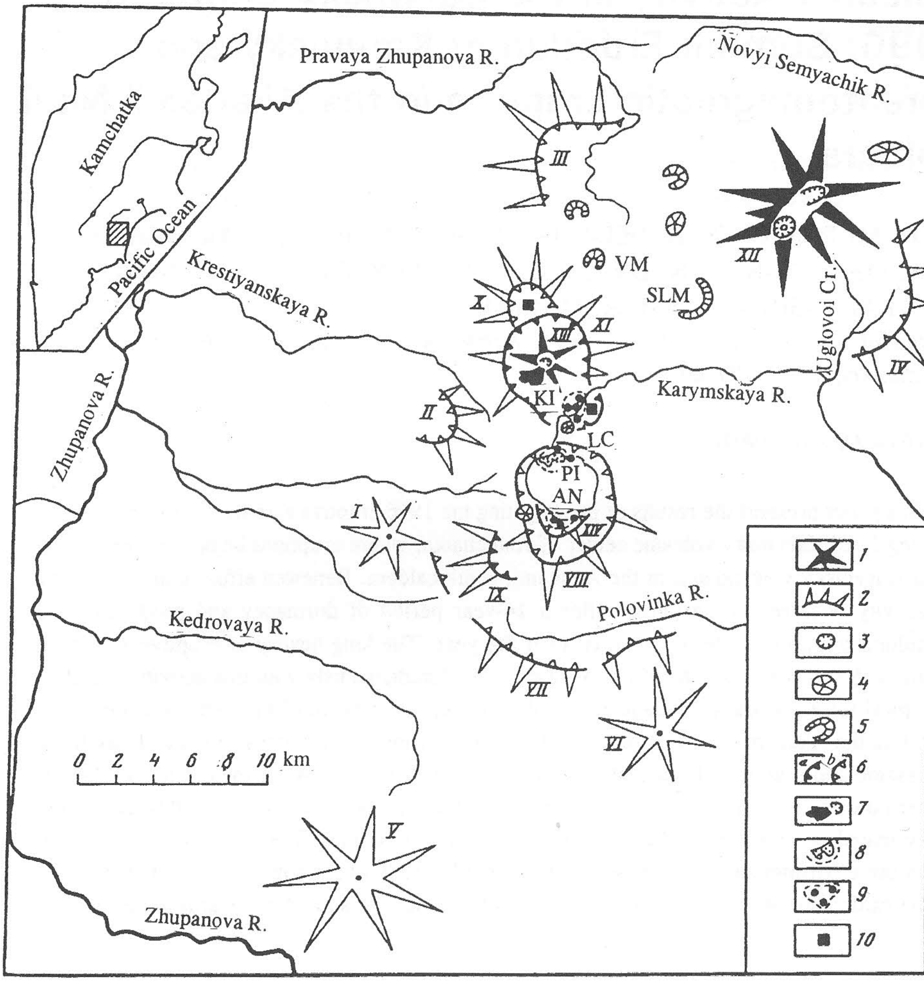


**Figure 1** Location map of major volcanic structures in the Karymsky area: *1* - active volcanoes; *2* - middle–late Pleistocene volcanoes; *3* - craters; *4* - cinder cones and lava domes; *5* - maars; *6* - fault (*a*) and erosion (*b*) scarps of calderas; *7* - Karymsky lava flows, 1996; *8* - Tokarev crater in the Akademii Nauk caldera – the center of the subaqueous phreatomagmatic eruption of January 2–3, 1996; *9* - groups of Karymsky (KI), Piip (P), and Akademii Nauk (AN) hot springs; *10* - Institute of Volcanology Observatory. Volcanoes: I - Krainii, II - Razlatyi, III - Sobolinyi, IV - Stena, V - Zhupanovskie Vostryaki, VI - Ditmar, VII - Polovinki caldera, VIII - Odnobokiy, IX - Belyankin, X - Dvor, XI - Pra-Karymsky, XII - Malyi Semyachik, XIII - Karymsky, XIV - Akademii Nauk, LC - Lagernyi Cone, SLM - Sukhoe Lake Maar, VM - Valentina Maar.

The last eruption of Karymsky terminated in 1982 [9]. Its eruptive activity recommenced after a 14-year dormancy on the night between January 1 and 2, 1996, after a powerful swarm of volcanic and tectonic earthquakes. The main distinction of the new eruptive cycle in this volcanic zone was the simultaneous reactivation of its two centers: a subaqueous eruption in the Akademii Nauk caldera and a summit eruption at Karymsky Volcano.

The volcanic history of this area was a long and very complex process. The Karymsky caldera, which is 5 km across, was formed during the Holocene, after a large caldera-forming eruption 7800 years ago. A young cone started to grow in it ~5000 years ago [1], [2]. Currently this is a typical central-type stratovolcano composed of lava flows intercalated with pyroclastic material. Prior to the 1996 eruption, its crater was located at an altitude of 1546 m, had an ellipsoidal form in view, and was 120×160 m in size.

A historic record of the Karymsky eruptions is available for the whole period since the year of 1771. More than 20 long-term eruptions were recorded during the subsequent two centuries, with maximum periods of 10 years' dormancy between them. The most powerful explosive eruption occurred on May 11, 1963, when a huge ash fall occurred in Petropavlovsk-Kamchatskiy (125 km south of the volcano). Generally, explosive or explosive plus effusive eruptions take place at this volcano. The typical volcanic rocks are andesite and dacite. A sequence of lava flows can be observed in the caldera, beginning with dacite flow of the 1908 eruption. The last eruptive cycle was observed in 1970–1982 [9], [12], when lava flowed episodically in small streams, and moderate or weak explosions occurred at the summit crater. This cycle was followed by a period of dormancy, the longest in this century, which continued up to and including 1995.

The Akademii Nauk caldera is situated south of the Karymsky caldera. It was given this name in 1939 by V. I. Vlodavets [3], one of the founders of Russian volcanology. This volcano first appeared ~50,000 years ago. No eruptions were recorded during historic times. The age of the caldera was estimated by a fission-track method to range between 28,000 and 48,000 years [5], [8]. Considering the low accuracy of this technique of absolute age determination, it should be noted that the crest of the caldera shows traces of Late Pleistocene glacier working, and that the age of the caldera could be at least 20,000 years. At the present time the caldera is occupied by a typical caldera lake 3.8 km across and 66–70 m deep, with a water surface area of 10.7 $km^2$. Prior to the eruption concerned, the only evidence of volcanic activity was a group of the Akademii Nauk hot-springs on the southern shore of the lake, which flowed 12.5 m above the lake's water-table. The hot springs produce Cl–Na water with a maximum salinity of 1.3 g/l and a temperature in the subsurface system of >250°C [7].

## DESCRIPTION OF ERUPTIVE ACTIVITY

An eruption at Karymsky had been expected since March 1995, when precursor volcano-tectonic earthquakes began to be recorded by the seismic network of the Geophysical

Survey of the Russian Academy of Sciences. On the night between January 1 and 2, 1996, eruptive activity began. The unique feature of this activity was the fact that eruptions occurred simultaneously at the summit crater of Karymsky and, unexpectedly, in the caldera lake of the Akademii Nauk volcano [12]. A team of volcanologists from the Institute of Volcanology carried out observations from the beginning of the eruption to January 1997 and later.

At 19 hr 30 min (local (winter) time) of December 31, 1995, a large tectonic earthquake of M = 5.8 occurred in the south of the Kronotskiy Gulf. Shaking of intensity III–IV was felt in the Petropavlovsk-Kamchatskiy area on the afternoon of January 1, 1996. At 21 hr 57 min a large crustal earthquake of M = 7.0 occurred. During the two days that followed, seismic activity remained too high to monitor the development of the earthquake swarm and eruptions [15], [17].

Prior to the main shock of January 1, 1996, and for a week thereafter, the level of the earthquake swarm was too high to provide high-quality information at the Karymsky seismic station located on the slope of the Karymsky volcano. The beginning of the Karymsky eruption and of the Akademii Nauk subaqueous eruption could hardly be discerned in the records from the remote stations. The seismic events associated with the volcanic activity and the outbreaks of the eruptions were masked by seismotectonic activity. The most important seismological data will be discussed in a separate paper.

Hunters from the Kedrovaya hunting center saw the first lights at the Karymsky cone after midnight on January 1–2. The beginning of the eruption may have been a slow event. By 10 hr in the morning of January 2 an ash cloud stretched for a distance of 60–70 km from the volcano in a southern direction toward Cape Shipunskiy.

**January 2 airborne observations.** Eruptions were observed from a helicopter in the afternoon, for an hour from 15 hr 20 min to 16 hr 20 min. It was found that Karymsky resumed its eruptive activity after a 14-year repose period, and that an eruption, unusual for the modern volcanism of Kamchatka, was under way in the north of Lake Karymskoe, located in the Akademii Nauk caldera (Fig. 2).

An explosive crater, 20–25 m across, was formed on the slope of Karymsky 80 m below the south-western rim of the old summit crater. Ash-loaded gas was being emitted almost continuously from it, the resulting ash cloud being driven by the wind to the south-east (Fig. 3). A 2–3 km wide ash-fall belt was clearly seen on the snow-covered eastern slopes beyond Lake Karymskoe, and a continuous eruption cloud trailed at a height of 2–2.5 km in the same direction oceanward. No activity was seen at the rim of the old crater, apart from fumarolic gas emanations.

Simultaneously, a huge steam–gas column, 300–400 m across at the base, rose to a height of more than 2.5 km from Lake Karymskoe for 6 km to the south. Hot water could be seen swirling and splashing a few meters up in the northern part of the lake. The ice that usually covered the lake at this time of the year had melted. Vigorous ash-loaded explosions occurred on average every 8–10 minutes at the base of the eruption column

(Fig. 4); base surges propagated from their vents [4] and were accompanied by tsunami waves as high as 10–15 m. The tsunami forced flood waves through the canyon-shaped head of the Karymskaya River, into the southern part of the Karymsky caldera, where the flood covered the floodplain of the river and the flat floor of the Karymsky geothermal field (see Fig. 1); the water layer was as deep as 2.2–2.5 m. The water flow was dammed where the river valley was very narrow (near the Observatory of the Institute of Volcanology) and rose as high as 2.5 m to a 600-meter isohypse; the water stream there was as wide as 100 m, producing a temporary back-water lake.

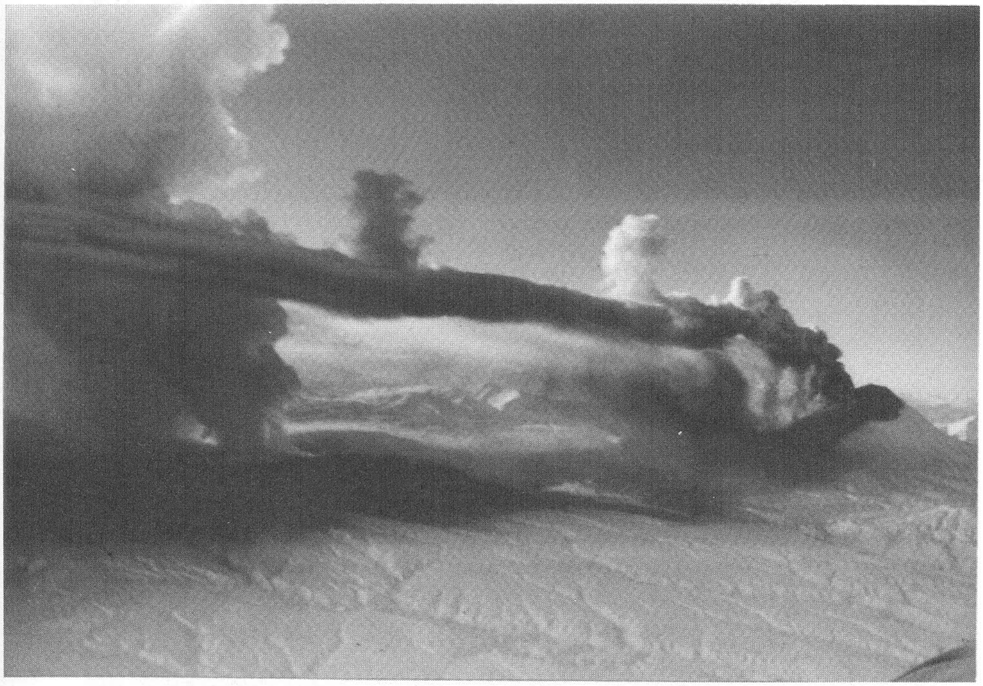

**Figure 2** Two simultaneous eruptions in the Karymsky volcanic area, on January 2, 1996. Right – the summit Karymsky eruption, left – the phreatomagmatic eruption in Lake Karymskoe (Akademii Nauk caldera). The distance between the craters is 6 km. Photo by V. A. Podtabachnyi.

The large local earthquakes of January 1 and 2 apparently accompanied the reactivation of a long-lived crustal fault trending roughly in a N–S direction. Judging by the surface ruptures and dislocations in the seasonal snow cover, which were accentuated by numerous snow avalanches and landslides, the surface intensity of the earthquakes might have been as high as grade IX.

**January 3 airborne observation and onset of fieldwork.** Toward midday of January 3 a new summit crater was formed at Karymsky; it was connected with the south-

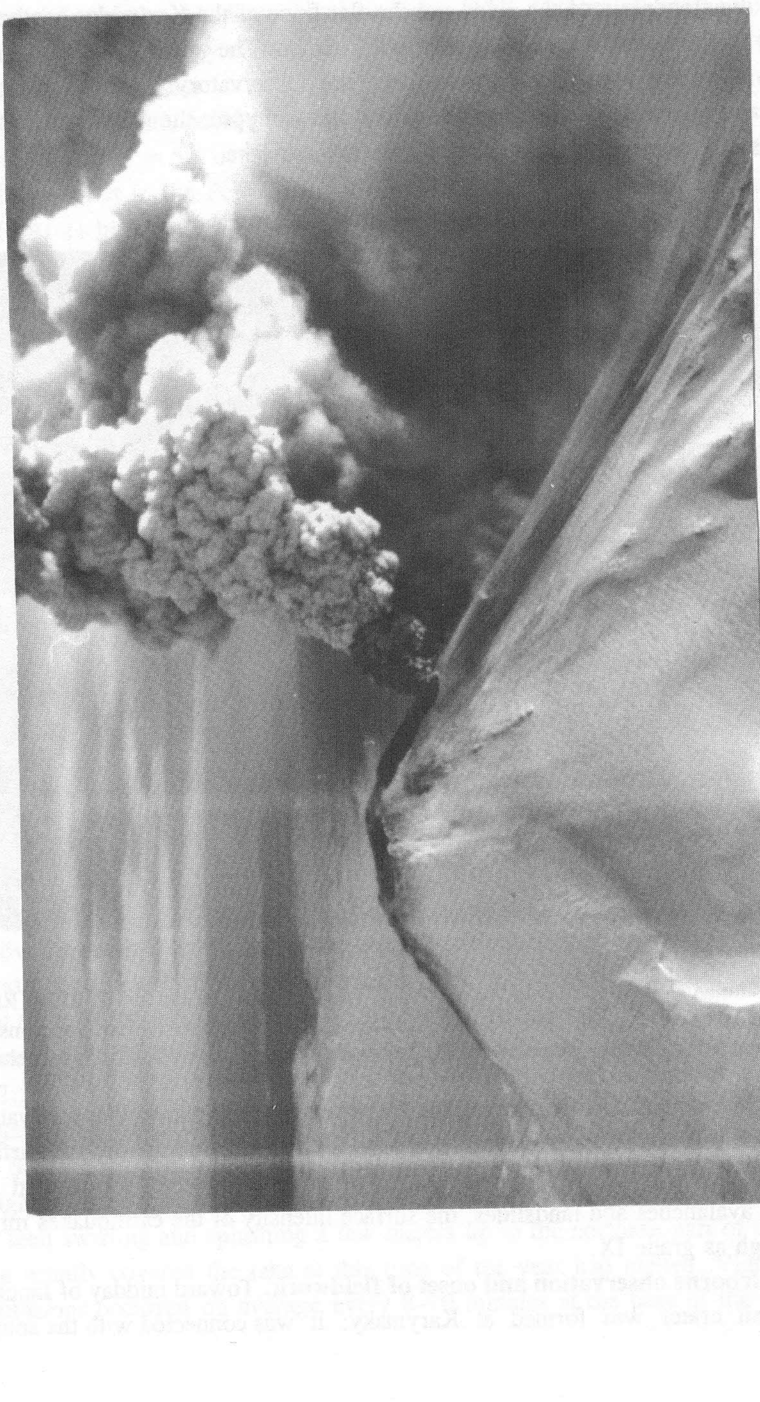

**Figure 3** Continuous ash emission through the explosive crater at the beginning of Karymsky eruption, January 2, 1996. Photo by Ya. D. Muraviev.

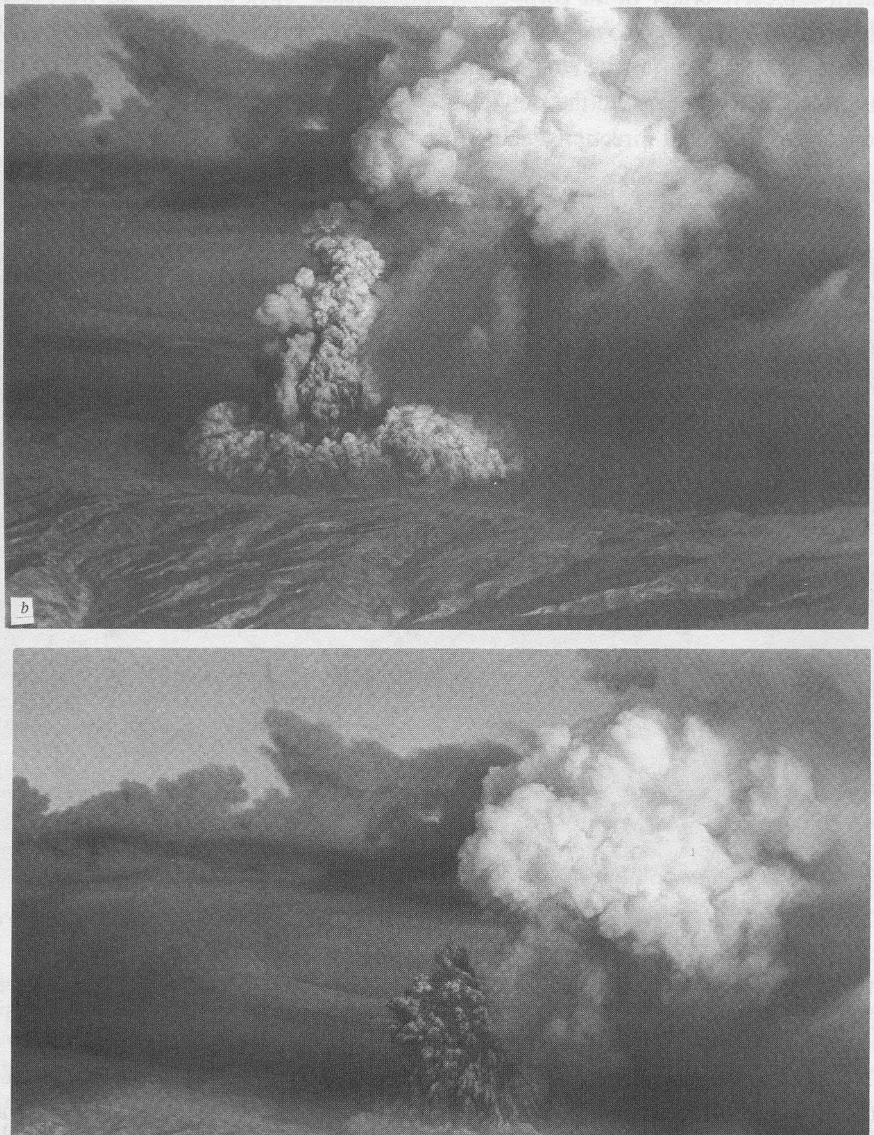

**Figure 4** Development of a vigorous phreatomagmatic explosion in Lake Karymskoe (Akademii Nauk caldera), January 2, 1996, afternoon: *a* – early explosive phase: finger-like jets of pyroclastics, water, and steam rise to a height of 1 km. Right – white wind-carried base-surge cloud of the previous explosion; *b* – development of the same explosion: the column is ~1.5 km high, next base surge propagates from its base. Photo by S. A. Fedotov.

western explosive crater in the form of an amphitheater open to the south-west and with a diameter of ~90 m. Subvertical vulcanian-type explosions occurred there every 3–5 minutes, with a column rising to a height of 1.0–1.3 km (Fig. 5) and a cloud drifting in a SE direction. In contrast to the previous day, the slopes of the Karymsky caldera were covered with ash in all directions apart from north-eastwards.

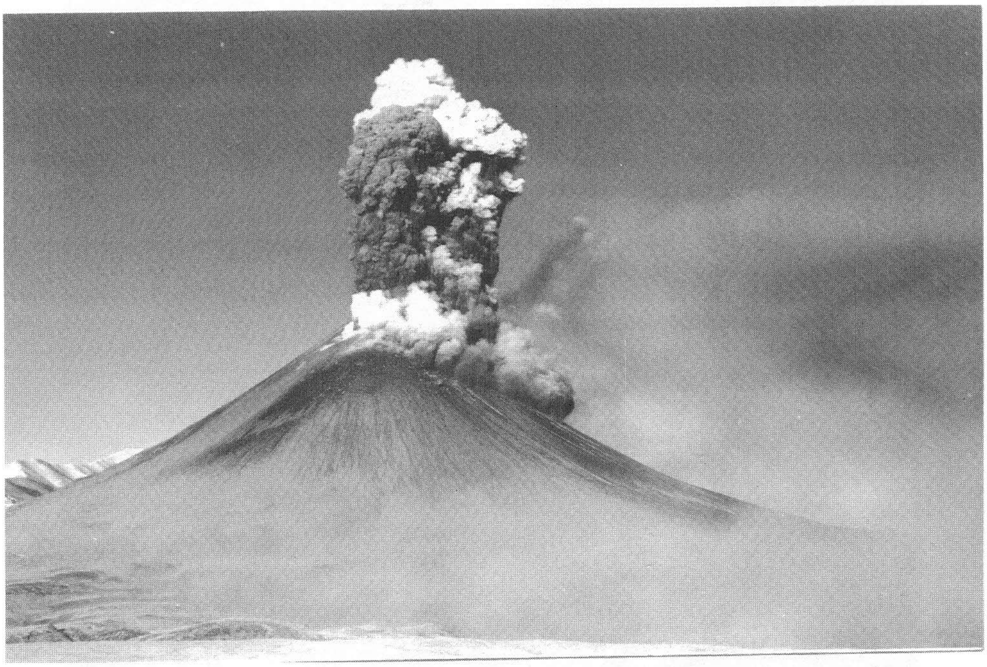

**Figure 5** Powerful vulcanian explosion at Karymsky, morning of January 3, 1996. The relative height of the cone is 700 m. View from the south. Photo by V. A. Podtabachnyi.

By 11 hr in the morning, pyroclastic material was deposited as a black belt at the head of the Karymskaya River (Fig. 6) and formed a new peninsula, where steam and gas emanated weakly from five vents; from the helicopter the steam emanating from three vents was seen to be a single stream. The vents were arranged along one line, obviously marking a feeder fissure. Most of the lake area was steaming. Numerous impact prints from bombs as large as 5–6 m across could be seen in the snow of the nearest northern slopes, as well as a belt of tephra deposits. The belt of explosive deposits was traceable for a distance of 800 m from the lake shore.

Late in the afternoon of January 3, systematic field observations commenced, firstly with a camp pitched in the Dvor caldera, and, from January 17 onwards, at the Karymsky

Observatory (see Fig. 1). Before describing the dynamics of the 1996 eruptive activity in the Karymsky volcanic center, we will first dwell on the eruption in the Academii Nauk caldera because of the unusual character and short duration of this event and we will then discuss the results of observations on the Karymsky eruption, which is still in progress.

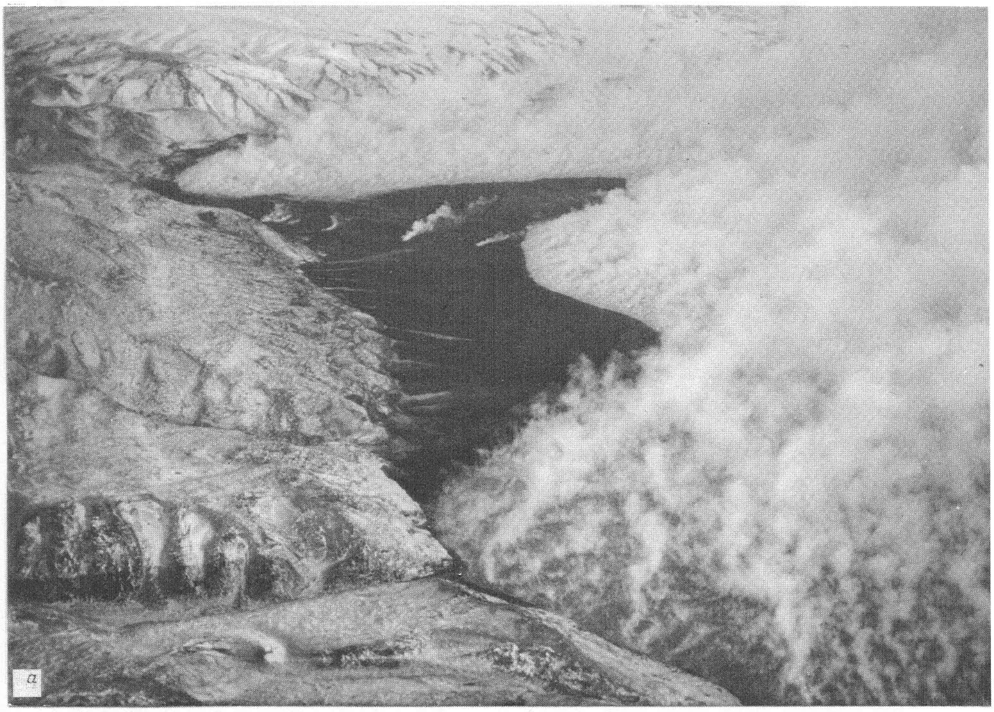


**Figure 6** New peninsula in Lake Karymskoe (Akademii Nauk caldera) formed on January 2–3, 1996, during the subaqueous phreatomagmatic eruption: *a* – the view a few hours after the outbreak. The lake is seen to be steaming strongly; the water temperature rose from zero to 25°C and higher. A chain of steam jets, ~400 m long, marks the feeder fissure. Afternoon of January 3, 1996 (photo by S. A. Fedotov); *b* – peninsula formed around the main crater by the deposits of the subaqueous eruption in the north of the lake after a 3.5-meter drop in the water level produced by a break through a dam at the source of the Karymskaya River on May 15, 1996. The crater diameter is 650 m. A small crater (4) is seen on the peninsula. The lake shores are pumice bluffs washed out by a tsunami on January 2–3, 1996. Photo by A. V. Sokorenko.

## SUBAQUEOUS ERUPTION IN THE ACADEMII NAUK CALDERA

Airborne observations of January 2 and 3, 1996, revealed that the eruption in the northern part of Lake Karymskoe was a short-lived event. It was not recorded instrumentally because the abundance and the high intensity of seismic events that took place on

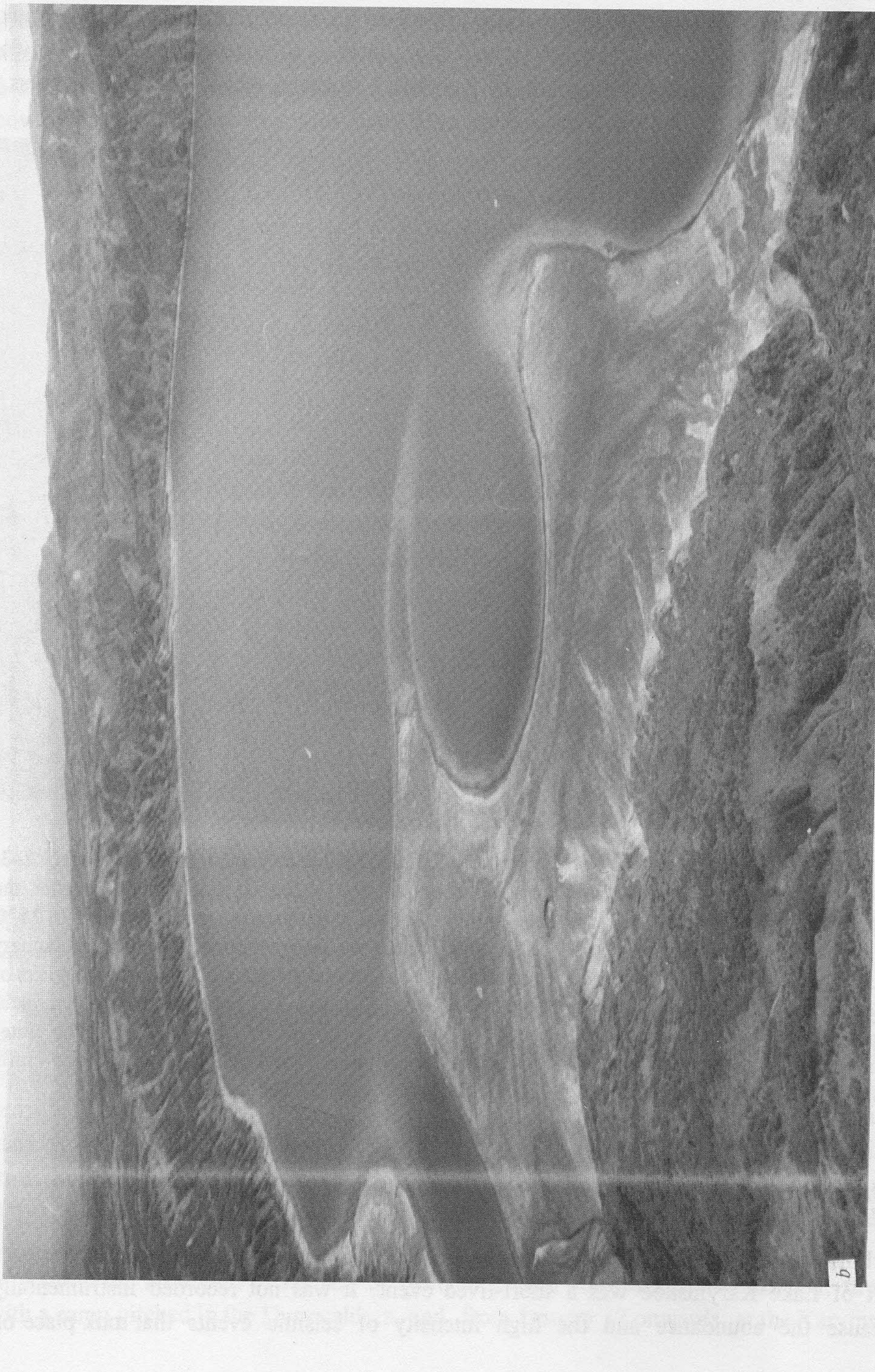


Figure 6, *b*

January 1 and 2 masked the general picture. However, A. G. Kovalenkov reported that during his flight over the Karymsky volcano on January 2 he had not seen anything unusual on the lake at noon.

As witnessed by A. V. Sokorenko (from the top of the Vilyuchik cone, 170 km from Karymsky) and by N. P. Smelov (from the head of Avacha Bay), a white eruption column arose in the Karymsky area between 14 hr and 14 hr 10 min. As a group of observers was waiting for a helicopter near the Institute of Volcanology building, they saw a white cloud between 14 hr and 14 hr 30 min through a pass between the Avacha and Koryaksky volcanoes. Initially the cloud was at a high level and then spread and decreased in height by about one-third.

This suggests that the eruption began in the lake between 13 and 14 hr. No subaqueous explosions were observed by 11 hr of January 3. In the afternoon water continued to swirl above the middle of the newly formed underwater crater. Therefore major explosions continued in the lake for less than 21 hours. The decrease in the steam–gas emissions from the new crater suggests that the lake eruption ceased at night and continued for ~18 hours. As a result of the subaqueous eruption, a circular belt of pyroclastic deposits was formed on the northern shore of the lake, as a peninsula, surrounding the main eruption vent – a crater ~650 m across (Fig. 7). In the south, the crater rim was as little as 3–5 m below the water surface. The outer southern slope of the edifice plunged steeply into the lake, to a depth of 50–52 m. In the north, the base-surge and tsunami deposits formed a gently dipping beach abutting against the shore scarp of the caldera. This part of the peninsula was 17–18 m above the lake-water level.

Numerous tsunamis vigorously eroded the lake shores, especially the northern one, where its surface was lowered by 2.7 m at a distance of 850 m from the vent. This was clearly seen where a geodetic benchmark had been destroyed right down its base.

By the morning of January 3, the products of the eruption buried the head of the Karymskaya River, which flowed out of the lake and produced a dam through which lake water flowed slowly at a rate of 20–30 l/s. According to hydrogeological measurements, the water level in the lake became 1.88 m higher during the next 4.5 months. On May 15 water flowed over the dam, breached it by erosion, and flowed through the river valley into the ocean, where it discharged ~35 million m$^3$ of acid water (pH = 3.1) over 3–5 days. The flood was big enough to remove the earth at the head of the river to a depth of 1 m compared to the pre-existing base level of erosion.

After January 3 a new flood covered the area of the Karymsky hot springs: in May the water level of this ephemeral lake was 0.9–1.0 m higher than on January 2–3 and measured ~3.5 m at the closing gauge line near the observatory. This flood was outlined by a 601-meter isohypse of the local topography. The dam material at the head of the river was removed to the area of the hot springs. Because the flow velocity declined rapidly when the river left the canyon, the coarse sand that it carried covered the upper half of the thermal area, disturbing the activity of and blocking many hot springs. At the ocean coast the water in the river mouth rose 1.5–1.7 m higher than the autumn low level.

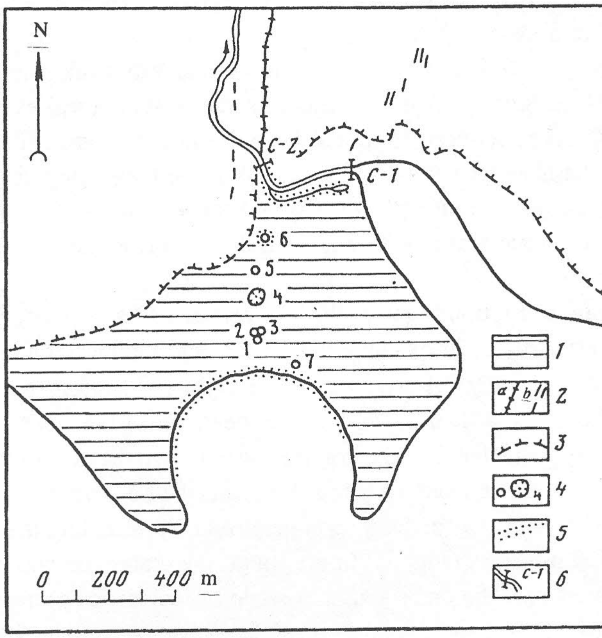


**Figure 7** Sketch showing the area of subaqueous eruption in the north of Lake Karymskoe: *1* – peninsula of the pyroclastic edifice; *2* – fault along the eastern side of the Karymskaya River canyon (*a* – northward continuation of the feeder fissure, *b* – fractures produced by ground deformations); *3* – lake shore outline eroded by the tsunami; *4* – subsidence craters; *5* – geothermal fields and the Piip hot springs; *6* – hydrometric gauge lines at the head of the Karymskaya River.

**Volume of erupted material.** The task of estimating the volume of the erupted rocks was aggravated by the severe vertical and horizontal deformations in the eruption area. We calculated the total volume of the discharged material $V_s$ using the equation

$$V_s = V_w + V_p + V_r + V_t + V_m, \quad (1)$$

where $V_w$ is the change in the lake volume caused by a rise in the water level due to the accumulation of erupted products minus the amount of snow that melted at lake shores and the amount of pyroclastic soil removed in the shore zone; $V_p$ is the amount of pyroclastic material that made up the emergent part of the new volcanic edifice to the date of the eruption termination; $V_r$ is the volume of the runoff and evaporation from the lake during the eruption; $V_t$ is the volume of tephra deposited outside the lake; $V_m$ is the volume of material removed by floods and lahars on January 2 and 3.

The systematic geodetic measurements of 1972–1995 indicated that the water line of the lake was 623.91 m above sea-level during that period of time. The first post-eruption leveling done on February 29, 1996, yielded a significantly higher lake-water level, some 627.13 m above sea-level. The calculated results of gauging and meteorologic measurements in January and February showed that on January 3, 1996, the lake level was 626.5 m above sea-level, that is ~2.6 m higher than the pre-eruption level.

The water level rose in the lake because of the addition of erupted material, material from the tsunami-eroded lake shores, and snow melt-water that flowed into the lake from its shores, also because of the vertical movements of the lake floor.

According to leveling data [15], the uplift and downward land surface movements that occurred along the northern shore of the lake were as high as 30–40 cm and generally balanced each other. The exact volumetric total rise and subsidence of the lake floor is not known and is probably not greater than 1-2 million $m^3$.

According to our estimation, the amount of snow-melt water in the 100-meter shore belt around the 12-kilometer perimeter of the lake was ~1 million $m^3$. The volume of the soil and pyroclastic material averaging 60 m in width and 3 m in thickness that was removed by the tsunami from a 3-km segment of the northern shore was 0.7 million $m^3$.

Therefore, the contribution of the non-eruptive component to the increased lake volume was ~2 million $m^3$. This value, the lake area of 10.7 $km^2$, and the rise in its level of 2.6 m give a value of ~26 million $m^3$ for the quantity $V_w$ in equation (1).

The volume of water discharged from the lake to the Karymskaya River valley was estimated by calculating the water discharge at the closing gauge line near the Karymsky Observatory.

The maximum rate of water discharge was indirectly estimated to be as high as 500 $m^3/s$. The flood drowned a considerable area of the Karymsky hot springs; the fish that lived in the lower reaches of the river (below the cascades) perished and their remains were transported to the ocean at the mouth of the river.

Autumn measurements of the lake-water discharge made at several gauge lines yielded the following relation between the river discharge ($Q$) and effective cross-sectional area ($F_{ef}$):

$$Q = 1.32F_{ef} - 4.1\,[m^3/s]. \quad (2)$$

With an $F_{ef}$ value of ~130 $m^2$ at the closing gauge line, the water discharge from the 2nd to the 3rd of January averaged 170 $m^3/s$, that is, the river could carry ~11 million $m^3$ of water for the 18 hours of the eruption.

The volume of the water that evaporated from the lake during the eruption was calculated, relying on data reported in [14] concerning the variation in water vapor content in the air as a function of its state: the maximum water content was reported for the cumulus varying from 0.7 to 1.8 $g/m^3$, and occasionally it was as high as 5 $g/m^3$. Considering that evaporation occurred from a lake surface that was warmer than the surrounding air, we took the maximum water vapor density in the eruption cloud to be 10 $g/m^3$. The average volume of steam produced by the phreatomagmatic explosions was taken to be 1.25 $km^3$, with the eruption column having a base area of 0.25 $km^2$ and a height of 5 km (including drifting cloud). The total number of these explosions was $\geq 100$, and the total volume of evaporated water had a maximum value of 1.25 million $m^3$, or a 0.11–0.12-meter water layer over the entire lake area. The resulting $V_r$ value was 12 million $m^3$.

Because the bulk of the ash fell back into the lake, only a small amount of ash was deposited around it. The thickness of the tephra decreased rapidly away from the vent; it was 20–30 cm near the northern shore and a few millimeters thick at a distance of 1–1.5 km. The total tephra volume $V_t$ could hardly be larger than 1 million $m^3$.

Almost the same amount of the pyroclastic material $V_p$ built up the emergent part of the new edifice, with an area of 0.45 $km^2$ on the newly formed peninsula and an average thickness of 2 m of the pyroclastic layer that exposed above the surface of the water.

The solid constituent of the flood surges and lahars $V_m$ was substantially less and measured not more than 0.5 million $m^3$ in the material deposited in the Karymsky hot-spring area. Part of the lahar material was the Holocene soil–pyroclastic cover that was washed out by a tsunami at the northern shore of the lake.

The substitution of the above values in (1) yielded a value of $\sim 40$ million $m^3$ for the total volume of the material produced by the subaqueous eruption.

**The post-eruption situation.** The phreatomagmatic explosive eruption produced a cone at the lake floor which was partially spread level over the floor and partially rose above the water (see Fig. 6). As mentioned above, the resulting edifice dammed the source of the Karymskaya River, and the water slowly rose until the dam was breached on May 15.

The maximum water level of 628.38 m had dropped to 624.94 m (by 3.44 m) by May 20. The lake lost $\sim 35$ million $m^3$ of water in less than 5 days. By the end of the summer the water level had declined to 624.1 m below sea-level (by 0.8 m) and was almost equal to the level before 1996 (making allowances for vertical deformation). As a result, the hot springs, which were earlier inferred from some indirect indications [7] were exposed.

By the end of the eruption, a number of small, sagging craters were formed on the surface of the new peninsula (Fig. 7); by mid-January they were filled with hot water at 75 °C. Six of them seem to be arrayed along the reactivated long-lived fault which had formerly produced the present-day canyon at the head of the Karymskaya River. The seventh crater is located beside this array, above the faults that extend from the middle of the crater toward the Lagernyi cone (Figs 8 and 9) at an angle of 15–17° NNE from the feeder fissure. The craters are 4–6 m in diameter, except for crater 4 whose diameter is 35.5 m. This is the crater where a phreatic explosion took place and produced a small mound on its western rim.

After the lake broke through the dam on May 15 and the water level decreased by 3.44-meter, five craters dried up. Greenish water at a temperature of $\sim 20$ °C remained in the large crater (4). Fumarolic activity was observed in crater 6 and up to 10 m from its edge and eastwards.

**Figure 8** Fractures in the side of the Karymskaya River valley, along a fault produced by the injection of a basalt dyke and the strong seismotectonic movements of January 1–2, 1996. Vertical displacement is >1 m. Photo by A. V. Sokorenko.

A funnel-shaped hollow with active gas emanations and hot water rising through the basal alluvium was discovered later, during the inspection of the Karymskaya River channel after the lake drained, at the first turn in the river source area.

By the end of the summer the eruption material of the new peninsula had cooled at the surface, and the hot springs were grouped together in a 150–200-meter zone along the feeder fissure. They resembled major seepages at the inner rim of the main crater and along the foot of the deposits exposed by the river in its source area. The water accumulated to form a hot creek. According to our water-balance measurements, water with an average temperature of 58°C flowed into the river at a rate of ~0.21 $m^3$/s. In the main crater the hot-water discharge might have been as high as 130–150 l/s. The maximum temperature of ascending springs was 92–97°C. No appreciable changes occurred in the temperature and flow rate of the springs for the nine months preceding the measurements of April 1997.

Apparently, a new group of hot springs appeared in 1996 within the new eruption edifice. It was proposed that it be named after B. J. Piip on the occasion of his 90th birthday; he was the founder of the Institute of Volcanology and the author of the first fundamental publication on the Kamchatkan hot springs.

**Figure 9** Small fractures 2 km from the subaqueous crater, on the northern continuation of the eruption fissure at the surface of the Lagernyi cone lava flow in the south of the Karymsky caldera. Vertical displacements are 0.2–0.3 m. Photo by A. V. Sokorenko.

The volcanic and tectonic events that occurred in the Akademii Nauk caldera revived the activity of the pre-existing hot springs, the Akademii Nauk group, where hydrothermal activity renewed in a thermal area 100–200 m west of the main group of springs. Several kettles and pulsing hot springs originated here, one of which behaves as a geyser with an eruption period of 15–17 minutes, the period varies with changes in the weather. The maximum height of its column is 2.5 m.

**Mineral composition of eruption products.** The erupted material varies greatly in composition (Table 1). The fresh pyroclastic materials (ash, bombs, and tuff) consist mainly (95–99%) of basalt with 50.5–52.5% $SiO_2$. The rhyolitic material was deposited during the closing phase of the eruption. This consisted mostly of large bombs (max. 75% $SiO_2$) encased in basalt (Fig. 10). According to different estimations, rhyolite varies from 0.3 to 4% of the total volume of the erupted rocks. Both the basalt and the rhyolite were in an obviously plastic state. The products of the subaqueous eruption contained lake-floor lithic debris, including metasomatic rocks, which are the products of hydrothermal alteration, and contain a large amount of sulfides and clay minerals.

The basalts are dark to black, ranging from compact to vesicular varieties. The rock-forming (essential) mineral is plagioclase. There are occasional grains of olivine and pyroxene.

The rhyolites are gray and light-gray vesicular rocks (see Table 1), almost devoid of crystalline material. Rhyolite occurs as single bombs and as inclusions in basalt jackets. There are bombs in which the basalt layers have a plastic contact with the dacite layers. The vesicles range between a few millimeters and 4 cm in size. In some samples the vesicles are empty, in others the vesicles are infilled with fresh froth-like basalt scoria. There are bombs, with vesicles filled with a black clayey material. This material may have been entrapped as incandescent rhyolite rose through lake water rich in suspended solid particles. According to Gill's classification [16], the basalts can be referred to a medium-potassium series, whereas in terms of their $FeO^*/MgO$ ratio they can be placed at the boundary between a calc-alkaline and a tholeiitic series. As far as the rhyolites are concerned, they fall in the field of high-potassium rocks and have a distinct tholeiitic $FeO^*/MgO$ ratio.

The distribution of the erupted material and the stratigraphy of the deposits composing the new peninsula suggest the following pattern of the eruption behavior.

The eruption began with a powerful phreatic explosion caused by the breakthrough of basalt magma and juvenile gases through a feeder fissure and a deep fault. The lake ice melted, and fragments of the lake-floor rocks, up to 4–5 tonnes in weight, were hurled as far as 1.3–1.5 km from the vent. The high temperature of the explosive gases is indicated by thermal damage of the bark of the older dwarf trees (Fig. 11) on the northern shores of the lake some 600–800 m from the vent (the damage effect corresponds to a short-term thermal episode at $T$ of 300–400°C). Slightly charred bark remained at the back of the tree trunks, the front of the trunks had their bark completely removed by the pyroclastics of the base surges.

For a short time after the explosions (a few tens of minutes) a continuous stream of pyroclastics was discharged: a finely-pulverized andesitic ash (Sample AN-6 in Table 1). This was a mixture of basalt ash and fine pumice-like rhyolite material or lithic debris. Part of this material was deposited on the snow covering the adjacent shores,

**Table 1** Chemical composition (wt. %) of rocks erupted in the Akademii Nauk caldera.

| Sample | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | FeO | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $H_2O$ | LOI | $P_2O_5$ | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AN-1 | 50,48 | 0,60 | 20,84 | 2,08 | 4,77 | 0,10 | 5,48 | 11,63 | 2,21 | 0,48 | 0,00 | 0,71 | 0,14 | 99,52 |
| AN-2 | 52,20 | 0,78 | 19,00 | 2,13 | 6,48 | 0,06 | 4,62 | 11,12 | 2,51 | 0,56 | 0,06 | 0,00 | 0,20 | 99,72 |
| AN-3 | 67,10 | 0,56 | 17,40 | 0,89 | 2,50 | 0,05 | 0,96 | 2,86 | 5,40 | 1,57 | 0,20 | 0,00 | 0,10 | 99,59 |
| AN-4 | 52,00 | 0,80 | 18,90 | 2,75 | 6,02 | 0,06 | 5,28 | 10,90 | 2,51 | 0,60 | 0,20 | 0,00 | 0,20 | 100,22 |
| AN-5 | 61,50 | 0,37 | 18,80 | 1,81 | 1,87 | 0,05 | 1,48 | 8,48 | 2,22 | 1,02 | 0,40 | 2,20 | 0,15 | 100,35 |
| AN-6 | 57,92 | 0,60 | 17,25 | 2,83 | 4,32 | 0,13 | 2,40 | 6,40 | 2,97 | 1,33 | 1,20 | 2,84 | 0,22 | 100,41 |
| AN-7 | 51,80 | 0,70 | 18,70 | 1,99 | 6,31 | 0,12 | 6,38 | 10,50 | 2,46 | 0,60 | 0,14 | 0,16 | 0,20 | 100,06 |
| AN-9 | 54,30 | 0,68 | 16,50 | 2,58 | 2,38 | 0,05 | 2,52 | 9,80 | 0,24 | 0,23 | 1,44 | 9,26 | 0,30 | 100,28 |
| AN-10 | 56,40 | 0,74 | 16,70 | 2,38 | 5,46 | 0,16 | 4,35 | 9,20 | 3,15 | 1,13 | 0,00 | 0,13 | 0,22 | 100,02 |
| AN-11 | 56,40 | 0,67 | 17,30 | 1,98 | 5,72 | 0,07 | 4,25 | 9,66 | 2,37 | 0,86 | 0,00 | 0,25 | 0,30 | 99,83 |
| AN-12/1 | 52,28 | 1,06 | 18,90 | 1,24 | 7,24 | 0,14 | 4,94 | 10,38 | 2,90 | 0,69 | 0,00 | 0,00 | 0,09 | 99,72 |
| AN-12/2 | 74,50 | 0,30 | 13,52 | 0,35 | 1,72 | 0,00 | 0,24 | 1,04 | 3,60 | 3,88 | 0,21 | 0,81 | 0,06 | 100,17 |

**Note.** AN-1, AN-2, AN-4 – basalt bombs from the surface of the new peninsula; AN-3 – lake-floor metasomatic rocks removed by the subaqueous eruption; AN-5 – pumice of late Holocene Karymsky eruptions from the soil–pyroclastic cover on the lake shore (sand-size fraction); AN-6 – fine ash erupted during the outbreak; AN-7 – volcanic sand of the main eruptive phase; AN-9 – fragment of altered country rock; AN-10, AN-11 – ash at different distances from the crater; AN-12/1 – basalt cover of a rhyolite bomb; AN-12/2 – pumice-like rhyolite core of a bomb. The samples were collected by V. A. Budnikov, Ya. D. Muraviev, and V. M. Okrugin. Analyses were made at the Central Laboratory of the Institute of Volcanology, analyst L. A. Kartasheva.

whereas its bulk was removed by floods and lahars to the area of the Karymsky hot springs, or settled on the lake floor.

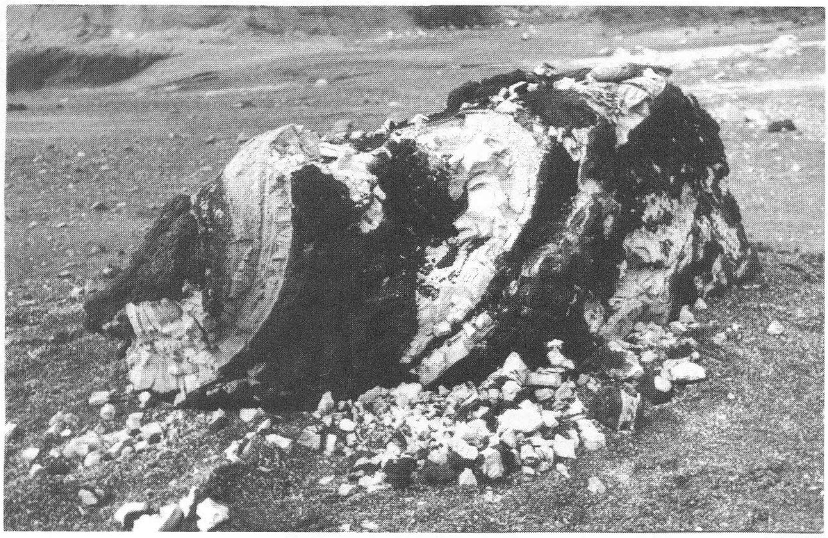

**Figure 10** Rhyolite bomb in a basalt jacket, size >1 m. Photo by A. V. Sokorenko.

During the helicopter flight of January 2, it was discovered that there was no ice on the lake surface and that powerful ash-loaded explosions occurred every 6–10 minutes from under the lake water (Fig. 4). S. A. Fedotov estimated that the rate of discharge of material through the feeder fissure might be higher than 830 tonnes/s. Ash-loaded base surges and tsunamis rolled over the shores, eroded them, and deposited a layer of pyroclastic material. Large explosions were accompanied by smaller ones that were distributed along the zone of seismotectonic deformations. As the explosive activity began to attenuate, volcanic sand started to be deposited; its particle size gradually increased up to scoriaceous lapilli. This material approximated the composition of basalt (e.g. Sample AN-7 in Table 1) and dominated the eruption products. A layer of rounded basalt bombs and their fragments, ranging between 7 and 30 cm in size, was deposited on the surface of this material. This sequence of events is clearly documented in crater 4, where layers deposited by individual explosions accompanied by base surges and tsunamis are traceable.

The number of large explosions was estimated visually and stratigraphically to be >100. The volume of material discharged by a single explosion might be as large as 400,000 $m^3$ or more. The total volume of material produced by the lake eruption was ~40 million $m^3$. In the middle of winter this material heated the upper 15-20 m of the lake water by an average of 25°C.

**Figure 11** Elder trunk on the side of the Akademii Nauk caldera at a distance of 800 m from the vent of the subaqueous eruption. The bark at the front has been removed by base-surge pyroclastics and is burnt by hot gases at the back. Photo by A. V. Sokorenko.

A distinctive feature of the first month of field observations was a great number of physically felt local earthquakes. Its maximum intensity was estimated at II to V (modified Mercally scale). From January 3 to February 9 15 seismic events were felt in the Observatory Building, located at the foot of Karymsky Volcano, as single abrupt shocks arriving from below. The maximum magnitudes were 5.0–5.6. The reaction of Karymsky Volcano to these shocks was not recorded. Visual activity of Karymsky Volcano was not associated with these shocks.

The unusual features of this eruption and its products posed many questions which could not be answered unambiguously. They concern the source (or sources) of magmas, the juvenile nature of the basalts and rhyolites, the mechanism of the eruption, the relation between the Akademii Nauk and Karymsky volcanoes, and other problems. Some of the answers are offered in the other papers of this journal issue, and some call for long-term specialized studies.

## ERUPTION AT KARYMSKY: DYNAMICS AND COMPOSITION

The explosive–effusive eruption at the Karymsky summit crater generally repeated the behavior characteristic of the Karymsky activity during the twentieth century (vulcanian–strombolian eruptions, lava flows, medium-grained ash falls and long eruptive phases [6], [13]). The following phases of different volcanic activity can be distinguished in the dynamics of this eruption (Fig. 12).

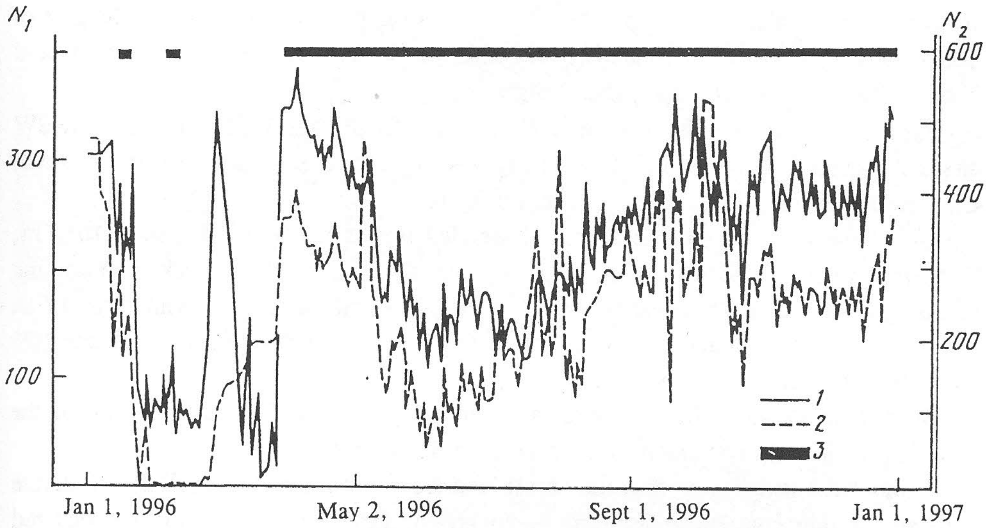


**Figure 12** Variation of seismicity ($N_1$ is the number of events per day) and explosive activity ($N_2$ is the number of explosions per day) at Karymsky during 1996: *1* – daily number of explosive earthquakes at Karymsky during the year; *2* – distribution of the daily number of ash ejections during the same period; *3* – lava flow.

**Explosive phase (January 2–11).** This eruption of Karymsky Volcano was speeded up by the active seismic events of January 1 and obviously began at about midnight, between January 1 and 2, 1996. By the evening of January 3 a new crater had been formed as an amphitheater, ~90 m across, open to the south-west. The absolute height of its floor is 1480 m. Subvertical explosions of the vulcanian type occurred in it to heights of 1.0–1.2 km. Electric charges (lightning) were seen at night at the base of the eruption column. On January 2 and 3 ash-loaded gas was ejected spasmodically from the crater: 3–5 explosions 0.3 to 1.2 km in height took place every 3–5 minutes. Each explosive cycle was followed by 5–10 minutes of slowly declining steam-gas emission, and the cycle was then repeated.

At 13 hr on January 4 small pyroclastic flows and rock avalanches began to roll down the SW slope. Some of them reached the side of the caldera (Fig. 13). Incandescent material was occasionally ejected to a height of 100–150 m. In the afternoon an ash-loaded cloud drifted to the south-west and west, and a visible ash fall occurred at a distance of 40–50 km from the volcano. The ash cover had its maximum thickness at a distance of 3 km from the volcano, on the SW rim of the Karymsky caldera; the ash deposit was up to 30 mm thick by the third day of the eruption.

The weather was bad until January 13, but the roar and explosions, emanating from the volcano, indicated that the eruption was still under way. Explosive activity usually intensified in the afternoon, from 13 to 22 hr: ash-loaded gas columns rose to heights of 1000–1300 m, and red-hot avalanches rolled down the volcano slopes. Explosions and blasts were rare in the morning and at night.

**Explosive–effusive phase (January 12–14).** The first block lava flowed on to the SW slope on January 12–14. Its movement was especially active on January 13: the sound of the lava movement could be heard from a distance of 1 km.

Over these three days the lava front descended from a height of 1465 m to 1050 m. The first lava flow was 600–650 m long, 60–80 m wide, and 6–12 m thick. The volume of one part of the lava was calculated to be 300–350$\times 10^3$ $m^3$ on the assumption of an average width of 50 m and a thickness of 10 m. The average rate of lava discharge ($Q_l$) over the three days was 1.35 $m^3/s$.

By that time a small field of pyroclastic flow deposits had formed to the left of the lava flow (Fig. 14). The crater had a maximum diameter of 120 m.

**Explosive phase and occasional small lava flows (January 15–April 5).** Moderate explosive activity continued after a short-term lava outflow. Powerful explosions occurred once every 5–7 days. They were accompanied by pyroclastic surges and red-hot avalanches collapsing simultaneously on all slopes. The lava blocks thrown out of the crater were as large as 3–5 m. On January 16 and 21 very powerful explosions took place, with the explosion columns as high as 1.5–2 km. The first explosion occurred at 10 hr 53 min. Coarse volcanic sand with a minor amount of admixed resurgent material, as well as lapilli (pellets of fragmented andesite–dacite lava) 11–12 mm in size, were deposited at a distance of 3.5 km from the crater. Similar material was deposited at the same distance by the second explosion which took place at 9 hr 24 min of January 21. This time the material contained less resurgent particles. As evidenced by the form and composition of the lapilli, lava fragmentation occurred in the vent and resulted in its widening.

On January 17 to 22 the volcano operated in an explosive mode with 5–6 explosions per hour and explosion columns rising to a height of 500–900 m. On average one powerful explosion occurred per day and scattered the ejecta over all of the slopes; red-hot rock avalanches rolled down to an elevation of 1000–1100 m on the cone. At that time the summit crater was 130–150 m across (on the upper rim).

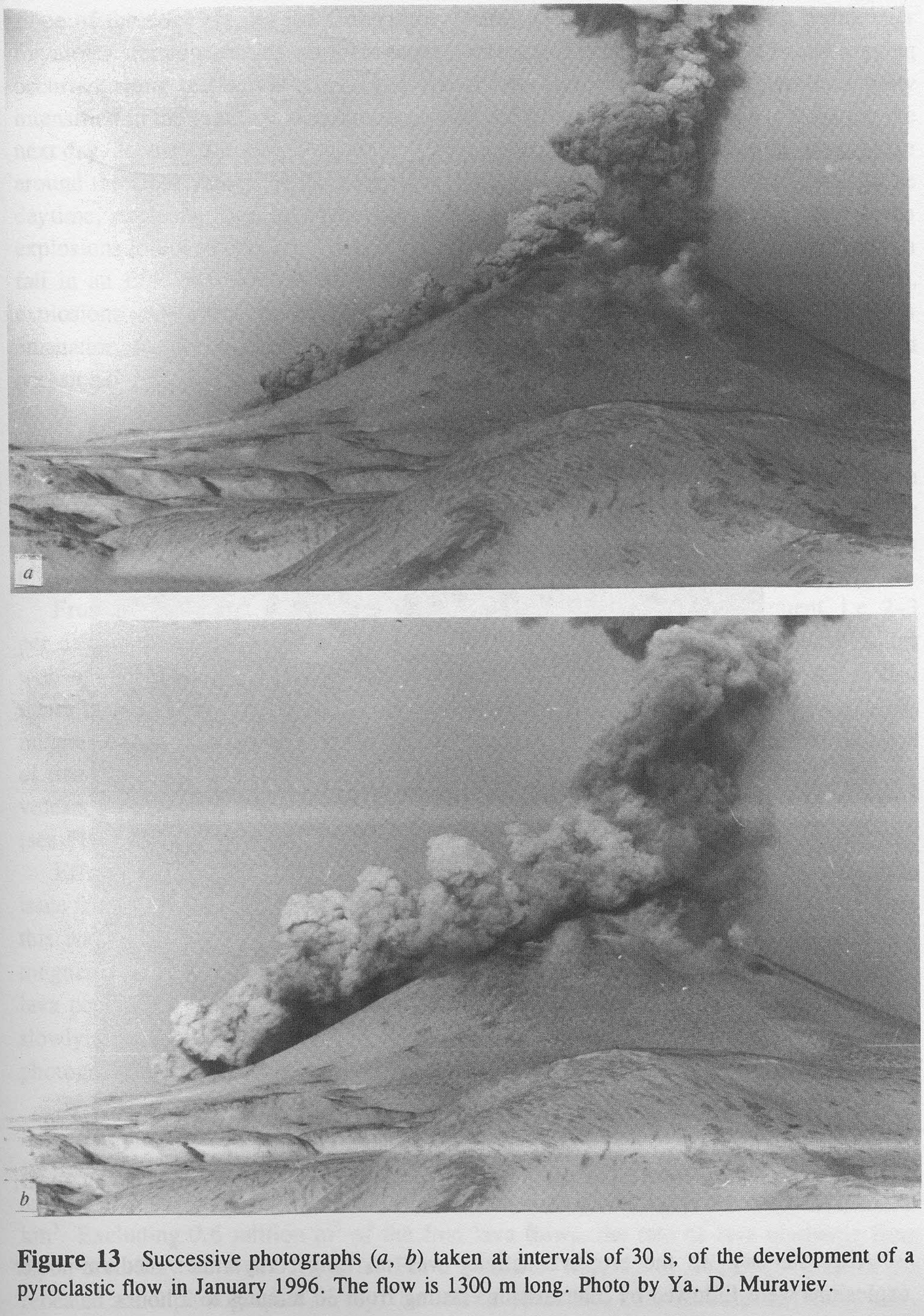


**Figure 13** Successive photographs (*a*, *b*) taken at intervals of 30 s, of the development of a pyroclastic flow in January 1996. The flow is 1300 m long. Photo by Ya. D. Muraviev.

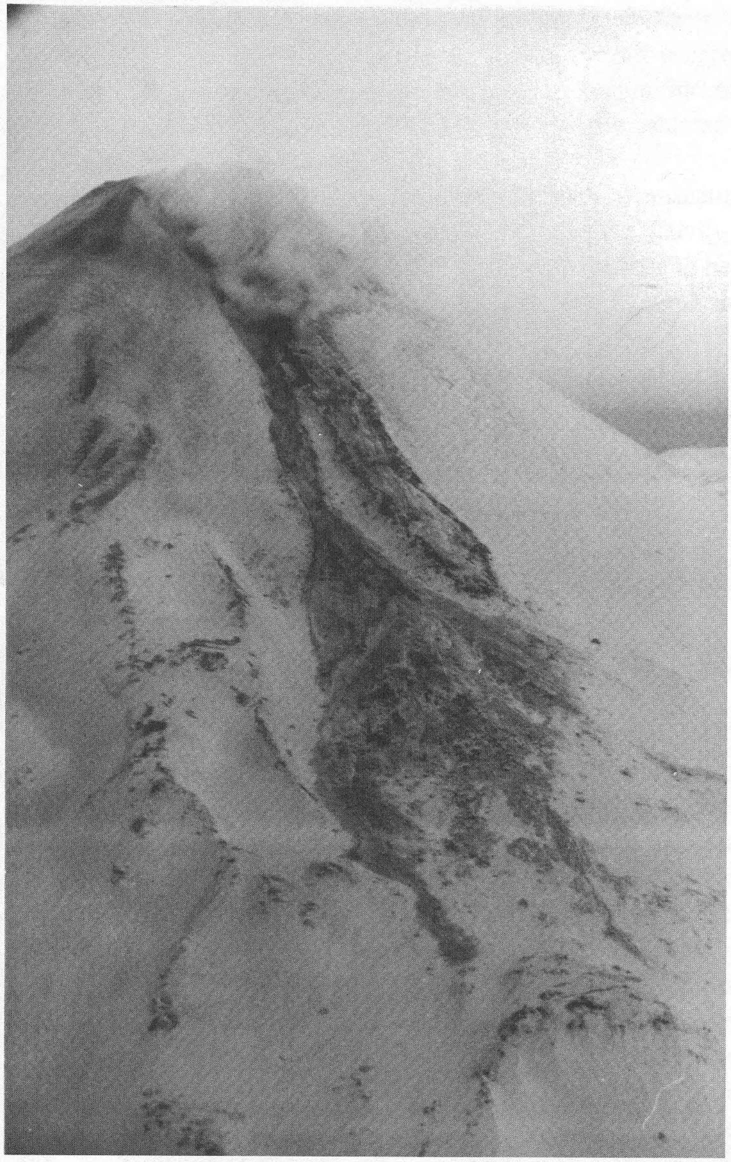

**Figure 14** Lava flow (right) and a fan of pyroclastic deposits in January 1996. Photo by Ya. D. Muraviev.

After January 22 the eruptive activity was no longer rhythmic: medium-power explosions were followed by intermissions lasting from 30 minutes to 2 hours.

At 16 hr of January 27, two horizontal fissures emerged on to the snow on the SE slope of the cone (facing the Observatory), 200–250 m below the summit; a day later fumaroles started steaming on their eastern sides. A possible explanation is that sagging occurred along the buried rim of the old crater. At the same time fumarolic activity intensified in the crater: it was steaming over the whole of the surface (Fig. 15). On the next day, January 28, a high content of hydrogen sulfide was observed in the atmosphere around the Observatory; in the evening it could be smelt even inside the building. In the daytime, explosive activity intensified abruptly, with a peak at 15–16 hr when seven explosions followed one another with columns rising to a height of 1–1.5 km and an ash fall in an ESE direction toward the Zhupanovo town. During the days that followed, explosions grew rarer and resembled blasts (ash ejections followed by attenuating gas emanation during 10–12 minutes). A high steam and gas column was observed through occasional holes in the clouds.

During a break in the snowstorm on February 5 a new lava flow was seen on the SW slope from Lake Karymskoe. This lava flowed above the previous lava flow as far as its middle and had a volume of not more than $250 \times 10^3$ $m^3$. At the end of February this lava flow was immobile and showed orange, yellow, and bluish green sublimates around the active fumaroles. The average rate of lava discharge on February 5–7 was 0.96 $m^3/s$. The total volume of the two lava flows was not more than 0.6 million $m^3$.

From the 5th to the 11th of February the ash ejections became less frequent, i.e. 2–3 per day. On February 12–15 explosive activity subsided to occasional single explosions with one- or two-day intermissions. During the next week on average one ash-loaded steam column was ejected daily to a height of 300–500 m and was followed by a 7–10-minute steam–gas blast. On February 22 explosive activity intensified again. At first one or two explosions occurred every hour, and from February 29 to early January 1997 the volcano operated in a fairly continuous explosive mode with 10–20 explosions per hour (see Fig. 12).

**Effusive–explosive phase (April 6, 1996–January 1997).** On April 6 lava began to issue from the crater and continued to flow up till January 3, 1997, and later. At that time this was the largest lava flow that descended from an elevation of 1465 m as a few tongues to elevations of 870–880 m (Figs 16 and 17, *a*). The average thickness of these lava portions is 20–25 m in the lower half of the flow. The lava tongues moved very slowly, varying between 2 and 25 m/day. The maximum velocity was 50 m/day. An aerial photographic survey was carried out in the eruption area on May 25 and on August 13.

By May 25, 1996, the lava flow descended to an elevation of 893 m and was 1500 m long. The flow had a maximum width of 300 m at an elevation contour line of 1100 m. Its thickness ranged between 10 m at the vent and 26 m at the front. The lava field had an area of 259,730 $m^2$ together with a small cone around the vent and a volume of 0.0045 $km^3$. Excluding 0.6 million $m^3$ of the first lava flows, the rate of lava discharge from April 6 to May 25 was 0.39 $m^3/s$. For a period of May 25 to August 13 (date of the repeated aerial photographic survey) the volume of the lava field increased to 0.0068 $km^3$.

The rate of lava discharge during that period averaged 0.36 $m^3/s$. The front of the lava flow descended to an elevation of 878.7 m. The length of the lava field remained almost the same, but its width increased to 360 m.

**Figure 15** Steam and gas emission from the Karymsky crater at the end of January 1996. Photo by Ya. D. Muraviev.

Later, as the lava flowed over its channel, the volume and area of the lava field grew below the elevation of 1200 m. As lava issued from the fissure, it first moved along a well-developed channel with district lateral levées. The width of the actively moving flow was 5–7 m at the vent and 10–15 m in the central segment. At elevations of 1100–1200 m the lava flow sometimes broke through or flowed over the levées of the channel, formed by previous flows, and produced new advancing lava tongues. By the end of November the next lava portion broke through a bend in the central segment of the lava channel and slowly descended as far as the front of the lava flow that had come to a halt in October, but did not travel beyond the existing lava field. A helicopter flight on January 3 , 1997, revealed that a new tongue of lava had begun to increment the lava flow from the east at elevations of 1050–1250 m (Fig. 17, *b*).

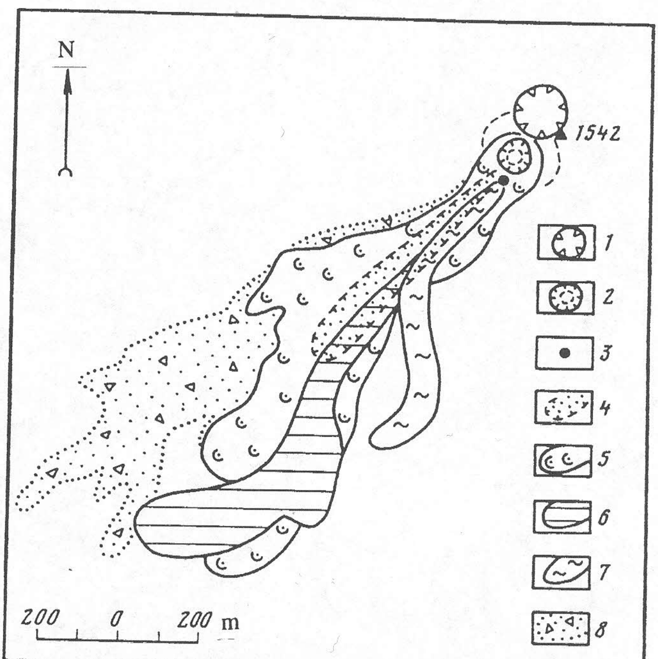


**Figure 16** Sketch of lava flows at Karymsky in 1996: *1* - old crater; *2* - active crater; *3* - lava bocca; *4–7* - lava flow growth (*4* - January 1996, *5* - April 6 to August 13, *6* - September–October, *7* - January 3, 1997); *8* - lithic and pyroclastic avalanche deposits.

According to repeated measurements of additions to the front of the lava flow on September 4, 9, and 16, the rate of lava discharge was 0.34 $m^3/s$, a value similar to the rate measured during the summer. For this reason the rate of lava discharge through the fissure was taken invariable for the eruptive period that followed. On this basis the volume of lava discharged during the first year of the eruption (by January 3, 1997) was estimated to be roughly 11.1 million $m^3$.

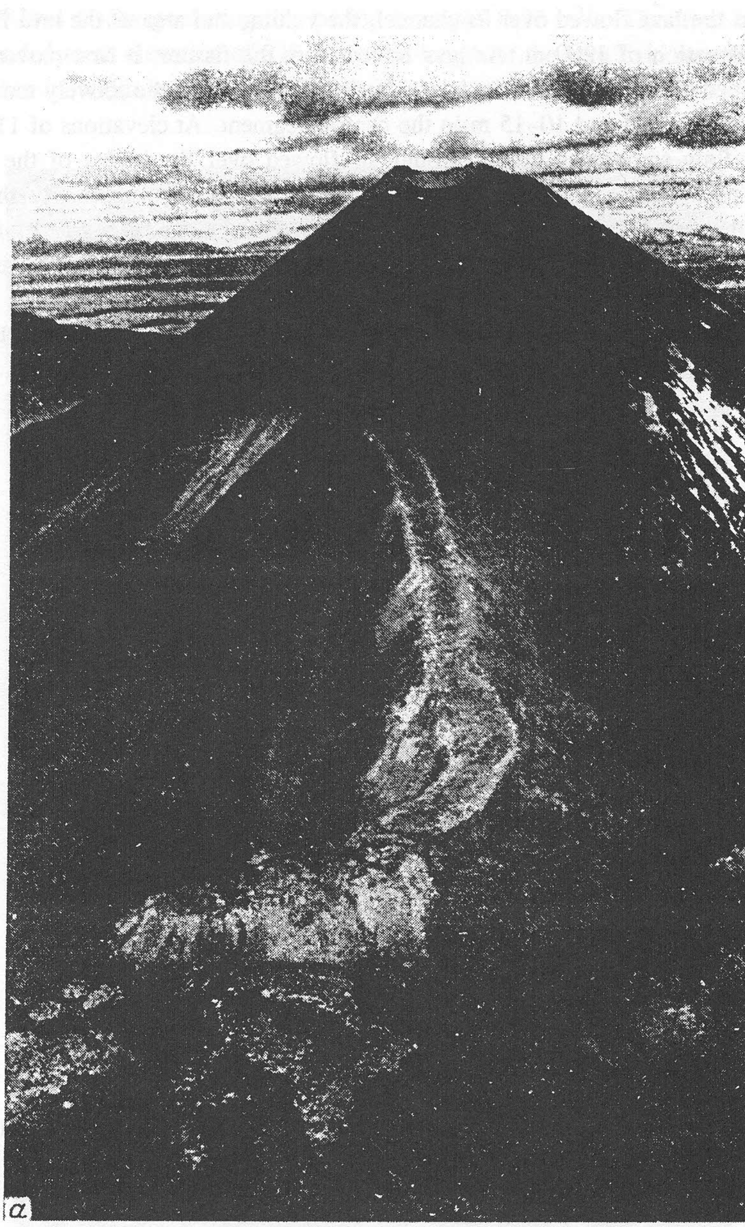

**Figure 17*a*** Development of lava flows at Karymsky: *a* – October 6, 1996 (Photo by A. V. Sokorenko).

Figure 12 displays variations in the explosive activity in 1996, based on the results of monitoring ash ejections and the daily dynamics of volcanic earthquakes under the volcano. Explosive activity was highly variable during the early half of the year with a peak at the beginning of the eruption and a decline in mid-February. Further on the magnitude of the variation decreased, and the number of ash ejections remained at a steady high level to the end of the year.

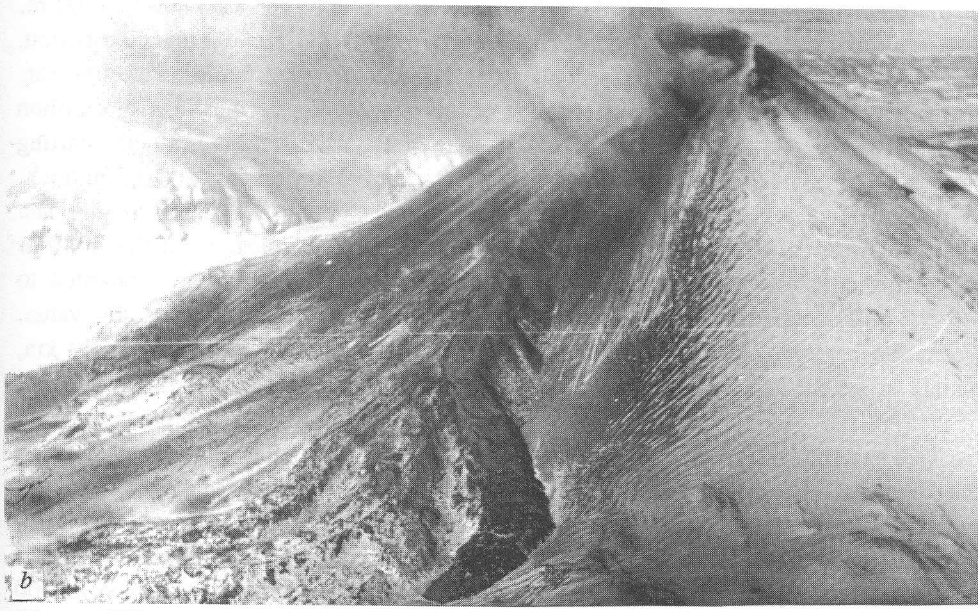

**Figure 17*b*** Development of lava flows at Karymsky: *b* – January 3, 1997 (Photo by V. A. Budnikov).

The early explosions and roaring blasts were accompanied by the ejection of bombs, lapilli, and ash. Bombs were as large as 1 m and sometimes more than 1.5 m across. They were hurled to a maximum height of 300–350 m and scattered within a range of several hundred meters. Most of them landed on the cone and some rolled down the slope to its foot, within about 1 km from the crater. On January 16 and May 5 bombs were hurled as far as 1.5 km from the vent. However, most of the explosions were silent moderate or weak ash ejections.

Seismic activity consisted of volcanotectonic and explosive volcanic earthquakes. Tremors were recorded during some of the volcanic explosions.

Synchronous samples of these parameters showed a good correlation between them (~0.80). This allowed us to estimate, with an acceptable accuracy, that the total number of ash ejections during the year was ~85,000 with an average number of 230 explosions per day.

The amount of explosive material removed by the Karymsky eruption of 1996 was calculated using the following techniques:

(1) by S. A. Fedotov's [11] empirical formula

$$Q_a = (H/1.87)^4 \times 10^{-9}, \quad (3)$$

where $Q_a$ is the amount of ejected ash; and $H$ is the height of the eruption column;

(2) using the measurements of the thickness and weight of the pyroclastic material at different distances from the volcano.

According to visual observations, the number of explosions was distributed in terms of the maximum height to which the ash was ejected, as follows: 5% - up to 1300 m, 10% - up to 1000 m, 25% - up to 500 m, and 60% <300 m. Based on this distribution, the total weight of the ejected ash, calculated by formula (3) was 2.5 million tonnes/year. It was assumed that the continuous eruption of the first 2–3 days removed ~0.6 million tonnes of material more, assuming a discharge rate of 2–3 tonnes/s. For a month, starting from January 4, small pyroclastic flows deposited a fan 0.3 $km^2$ in area and 0.5 m thick. With an average density of 1500 $g/m^3$, this material had a volume of 1.5 million $m^3$. The total weight of the rocks erupted during 1996, including the explosions of the first few days, further explosive activity, and pyroclastic flows and avalanches, amounted to 5.0–5.5 million tonnes. The calculation by the second method yielded a comparable value.

At the beginning of the eruption, ash falls covered a distance as great as 60 km, mainly in the SE and SW directions. Later ash was dispersed in all directions. Because of its very fine particle size, this ash was deposited more uniformly with distance from the vent as compared to the previous ash deposits. Table 2 lists the results of calculating the amounts of ash deposited at different distances from the volcano, based on measurements of the thickness of the ash. The total area covered by the ash was ~9000 $km^2$, and the total weight of the pyroclastic material, including pyroclastic avalanches and bombs on the slope, was 6.3 million tonnes. It should be noted that as much as 300 thousand tonnes of ash deposited in a 1.0–1.5-km zone around the northern shore of Lake Karymskoe can be attributed to the eruption in the Akademii Nauk caldera.

**Table 2** Ash distribution at Karymsky Volcano in 1996.

| Radius (km) | Area ($km^2$) | Thickness (cm) | Average density ($kg/m^3$) | Weight (thousand tonnes) |
|---|---|---|---|---|
| 1.5 | 7 | 6.0 | 60 | 500 |
| 4.0 | 50 | 2.0 | 22 | 1100 |
| 10.0 | 250 | 1.0 | 10 | 2500 |
| 50.0 | 8520 | 0.3 | 3 | 250 |
| Total | 8850 | – | 5 | 4350 |

To sum up, the amount of loose products erupted by the volcano in 1996 was 5.5–6 million tonnes as calculated by two independent methods. The explosive index was ~20%.

The total volume of the material erupted by Karymsky during 1996 was 16 million $km^3$. Assuming the average density of the lava flows to be 2200 $kg/km^3$, the total weight of the lava and pyroclastic material produced during this period was 30.4 million tonnes.

**Table 3** Chemical composition (wt. %) of ash erupted by Karymsky in 1996.

| Sample | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | FeO | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $H_2O$ | LOI | $P_2O_5$ | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LC-43 | 62,48 | 0,63 | 16,21 | 2,95 | 3,00 | 0,10 | 1,92 | 5,52 | 3,58 | 1,30 | 0,44 | 1,96 | 0,25 | 100,34 |
| LC-44 | 60,37 | 0,87 | 17,89 | 2,60 | 3,83 | 0,05 | 2,04 | 6,40 | 3,66 | 1,28 | 0,28 | 0,52 | 0,19 | 99,98 |
| LC-5 | 61,00 | 0,95 | 15,90 | 2,19 | 4,03 | 0,05 | 2,12 | 6,16 | 3,52 | 1,43 | 0,30 | 1,90 | 0,35 | 99,90 |
| 0301 | 61,26 | 0,84 | 19,05 | 0,92 | 3,86 | 0,10 | 1,72 | 5,50 | 3,70 | 1,82 | 0,26 | 1,18 | 0,19 | 100,40 |
| LC-1 | 62,00 | 0,90 | 15,10 | 1,01 | 7,49 | 0,10 | 2,38 | 5,06 | 3,64 | 1,57 | 0,12 | 0,00 | 0,45 | 99,82 |
| LC-2 | 61,40 | 0,95 | 15,40 | 1,38 | 7,46 | 0,13 | 2,12 | 5,40 | 3,83 | 1,54 | 0,14 | 0,00 | 0,45 | 100,20 |
| LC-4 | 62,20 | 0,96 | 16,10 | 2,00 | 4,20 | 0,10 | 2,12 | 5,94 | 3,87 | 1,55 | 0,16 | 0,00 | 0,50 | 99,70 |
| 2201 | 61,06 | 0,98 | 17,94 | 3,96 | 2,65 | 0,14 | 2,44 | 6,28 | 3,23 | 1,44 | 0,09 | Не обн. | 0,20 | 100,41 |
| 1802 | 62,40 | 0,81 | 15,89 | 2,50 | 3,88 | 0,05 | 2,02 | 5,16 | 4,11 | 1,89 | 0,00 | 0,80 | 0,22 | 99,73 |
| 2202 | 63,00 | 0,80 | 14,50 | 2,94 | 2,80 | 0,05 | 1,74 | 5,68 | 4,05 | 1,88 | 0,42 | 1,82 | 0,23 | 99,91 |
| 2902 | 63,20 | 0,80 | 14,90 | 3,06 | 2,64 | 0,08 | 1,71 | 5,62 | 3,79 | 1,76 | 0,46 | 1,54 | 0,24 | 99,80 |
| 0103 | 62,50 | 0,72 | 16,53 | 2,48 | 3,04 | 0,07 | 1,58 | 5,22 | 3,99 | 1,76 | 0,28 | 1,50 | 0,28 | 99,75 |
| 2403 | 63,50 | 0,89 | 15,83 | 2,34 | 4,41 | 0,13 | 1,63 | 3,96 | 3,53 | 1,73 | 0,18 | – | 0,24 | 99,52 |
| 0804 | 63,05 | 1,01 | 16,42 | 2,20 | 4,32 | 0,12 | 1,19 | 4,47 | 3,58 | 1,69 | 0,20 | – | 0,25 | 99,69 |
| 1804 | 61,96 | 0,96 | 16,60 | 2,17 | 4,95 | 0,14 | 2,16 | 4,75 | 3,63 | 1,74 | 0,17 | – | 0,25 | 99,64 |

**Note.** LC-43 – volcanic sand of first eruptions deposited at 1 km from the crater; LC-44 – ash fall of January 2-3, 1996; LC-5 – first ash fall 3 km south of the crater; 0301 – fine ash from the Dvor caldera (3.2 km from the crater); LC-1 – lapilli produced by explosion at the vent of a lava flow, January 16, 1996; LC-2 – lapilli produced by an explosion of January 21, 1996; 2201 – ash fall of January 21, 1996; 1802, 0804, 1804 – ash samples (the first two figures denote the date, the second, the month). The samples were collected by V. A. Budnikov and Ya. D. Muraviev. Analyses were made at the Institute of Volcanology, analyst L. A. Kartasheva.

**Table 4** Chemical composition (wt.%) of lavas erupted by Karymsky in 1996.

| Sample | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | FeO | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $H_2O$ | LOI | $P_2O_5$ | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1702/1 | 60,70 | 0,82 | 17,30 | 1,78 | 4,20 | 0,10 | 2,06 | 6,80 | 4,17 | 1,45 | 0,10 | - | 0,25 | 99,73 |
| 1702/2 | 61,80 | 0,89 | 16,20 | 1,59 | 4,37 | 0,14 | 1,95 | 6,56 | 4,22 | 1,50 | Не обн. | - | 0,25 | 99,64 |
| 1702/3 | 62,00 | 0,86 | 15,20 | 4,22 | 2,35 | 0,12 | 2,02 | 6,22 | 4,30 | 1,76 | 0,00 | 0,36 | 0,26 | 99,67 |
| 308 | 62,40 | 0,96 | 15,96 | 2,22 | 4,02 | 0,11 | 2,14 | 5,46 | 3,94 | 1,77 | 0,07 | 0,41 | 0,26 | 99,72 |
| 0603 | 62,28 | 0,89 | 16,64 | 1,99 | 5,47 | 0,07 | 1,88 | 4,62 | 3,06 | 1,39 | 0,52 | 0,49 | 0,24 | 99,54 |
| 1604 | 59,64 | 0,94 | 17,50 | 2,38 | 3,69 | 0,10 | 2,46 | 6,66 | 3,88 | 1,67 | 0,00 | 0,35 | 0,24 | 99,51 |
| 2404 | 62,00 | 0,92 | 16,54 | 2,30 | 5,38 | 0,13 | 1,92 | 5,00 | 3,68 | 1,63 | 0,14 | 0,00 | 0,25 | 99,89 |
| 2005 | 61,48 | 0,89 | 16,54 | 2,65 | 5,56 | 0,12 | 1,79 | 4,62 | 3,53 | 1,68 | 0,18 | 0,53 | 0,25 | 99,82 |
| 1007 | 62,52 | 0,89 | 16,92 | 2,60 | 4,75 | 0,05 | 1,87 | 4,54 | 3,63 | 1,68 | 0,00 | - | 0,25 | 99,70 |
| 0409 | 62,00 | 0,91 | 17,15 | 1,60 | 5,27 | 0,08 | 1,91 | 5,52 | 4,25 | 1,58 | 0,00 | 0,00 | 0,21 | 100,48 |
| 0909 | 61,40 | 0,65 | 16,79 | 2,76 | 4,84 | 0,10 | 2,16 | 6,14 | 3,85 | 1,38 | 0,00 | 0,00 | 0,21 | 100,28 |
| 1609 | 60,56 | 0,70 | 17,62 | 1,18 | 5,90 | 0,10 | 1,90 | 6,62 | 3,90 | 1,32 | 0,10 | 0,00 | 0,22 | 100,19 |
| 1/97 | 58,20 | 0,84 | 19,22 | 2,04 | 3,86 | 0,10 | 2,40 | 6,75 | 3,94 | 1,46 | 0,08 | 0,39 | 0,22 | 99,59 |
| 2/97 | 59,50 | 0,88 | 17,83 | 2,67 | 3,48 | 0,11 | 2,36 | 6,64 | 3,74 | 1,46 | 0,11 | 0,51 | 0,22 | 99,51 |
| 3/97 | 59,85 | 0,92 | 17,41 | 3,06 | 3,36 | 0,10 | 2,32 | 6,26 | 4,00 | 1,60 | 0,07 | 0,33 | 0,23 | 99,51 |

**Note.** 1701/1, 1701/2 - first lava flow (dense and vesicular varieties, respectively); 1702/3 - bomb; 308 - pyroclastic flow; 0603-1609 - lavas and bombs of different dates (first two figures denote the date, second, the month): 0603 - bomb (dense), 1604 - lava of flow 3, 2404 - bomb (vesicular, pumice-like), 2005 - new portion of lava flow 3, 1007 - new portion of lava flow 3 (dense), 0409 - lava flow, August portion, 0909, 1609 - fresh lava flows; 1/97-3/97 - fresh lava flow of January 3, 1997 (massive porphyritic and glassy vesicular, respectively). The samples were collected by V. N. Andreev, V. I. Andreev, V. A. Budnikov, V. E. Bykasov, and Ya. D. Muraviev. Analyses were made at the Institute of Volcanology, analyst L. A. Kartasheva.

## COMPOSITION OF ERUPTED MATERIAL

The solid rocks erupted by Karymsky in 1996 approximate the composition of andesite and are not essentially different from the material that was erupted by the medium-sized explosive and effusive eruptions of the previous eruptive cycle [12]. The material produced by the 1996 eruption consisted of ash, bombs, and lava. In contrast to the material of the subaqueous eruption in the Akademii Nauk caldera, the Karymsky ash and lava had a fairly uniform composition (Tables 3 and 4).

**Petrography.** *Lava.* The lava of the new eruptive cycle is represented by both a dense and a vesicular variety. The rock of the lava flows is dense and dark in color with numerous light-gray plagioclase phenocrysts and a vesicular scoriaceous matrix. The lava fragments are black and smooth, forming rounded blocks, 0.5–1.5 m in size, with plagioclase crystals and brown ferruginous, locally vesicular block fragments, with a maximum size of 4 m. The main rock-forming mineral is plagioclase; its content ranges between 20 and 25%, some of the grains being as large as 3–5 mm. Very scarce olivine and pyroxene crystals were noted.

The dense rocks of the lava flows are massive and have a porphyritic or a glomerophyric texture. The phenocrysts account for ~5 vol.% and consist of plagioclase (3%), clinopyroxene (1.5%), and magnetite (0.5%). The glomerophyric clusters consist of the same mineral (plagioclase) or of different mineral assemblages (plagioclase + clinopyroxene, plagioclase + magnetite, clinopyroxene + magnetite, and plagioclase + clinopyroxene + magnetite). The maximum size of the clusters is 3 mm.

Plagioclase occurs as tablets or laths, ranging between 0.3 and 2.5 mm in size. There are some crystal fragments and grains with uneven boundaries, as if eaten away at the edges; some crystals show bifurcating ends. The crystals are zoned and polysynthetically twinned. There are frequent irregularly shaped inclusions of the groundmass and fine clinopyroxene crystals.

The location of groundmass inclusions is often controlled by plagioclase zoning. Clinopyroxene occurs as pale-greenish tinted prismatic crystals ranging between 0.3 and 1.5 mm in size. They show distinct cleavage in two directions. There are some simple and polysynthetic twins.

Magnetite occurs as octahedral crystals, 0.1–0.4 mm in size, both as phenocrysts and as glomerophyric clusters with other minerals.

The groundmass is microlitic and consists of pale-brown glass (50–55%), plagioclase and clinopyroxene microlites, and ore mineral (magnetite) fines. The size of the microlites is 0.01–0.015 mm.

The texture of the vesicular lava is also porphyritic. The volume of the vesicles is 7–10%. The vesicles have an irregular form and range between 0.1 and 3 mm in size. The phenocrysts have the same mineral composition as those of the dense lava.

*Bombs.* The bombs are highly vesicular (>50%), the vesicles ranging between fractions of and a few millimeters. The texture is porphyritic or glomerophyric.

The phenocrysts account for 1.5 vol.% and consist of plagioclase (1%) and clinopyroxene (0.5%). The accessory minerals are orthopyroxene and apatite. The glomerophyric clusters consist of plagioclase alone or of plagioclase and pyroxene.

Plagioclase occurs as colorless tabular zoned crystals 0.3 to 2.0 mm in size. The crystals are polysynthetically twinned. There are small amounts of glass inclusions and fine pyroxene crystals. Clinopyroxene occurs as prismatic crystals and irregular grains which are pale greenish-gray in color and 0.2–0.4 mm in size. Simple and polysynthetic twins are common. One grain of orthopyroxene was found. It has a prismatic form, a 0.2-mm size, and is pleochroic from pale green to pale brown. The apatite occurred as scarce colorless prismatic crystals with a hexagonal cross-section and a maximum size of 0.15 mm.

The groundmass has a hyaline texture. It consists of dark red to brown glass. The vesicles are surrounded by black dendritic formations. In some parts of thin section, the glass shows a flow texture which is accentuated by the changes in its color.

*Ash.* Here we describe three most characteristic ash samples (Table 5). Sample 1 consists of ash deposited by the new Karymsky eruption. It was collected on the 3rd of January, 1996, on the Dvor volcano, 3.2 km from the active crater. The ash particles are <0.25 mm in size, the dominated size being <0.1 mm. Some 95% of the ash fraction between 0.25 and 0.1 mm consists of finely pulverized particles, <0.01 mm in size, which are stuck together to form pumice-like aggregates that are light gray in color, in which black rock fragments, colorless and gray plagioclases, and brownish red altered fragments can be discerned. The fragments are angular and fairly rare.

**Table 5** Particle size (%) of Karymsky ash, 1996–1997.

| Sample | Sampling date | Fraction (mm) | | | | | |
|---|---|---|---|---|---|---|---|
| | | > 2.0 | 2.0–1.0 | 1.0–0.5 | 0.5–0.25 | 0.25–0.06 | <0.06 |
| | | | | Dvor volcano* | | | |
| 1 | 3/1/1996 | | – | – | – | 80.0 | 20.0 |
| | | | | Observatory** | | | |
| 2 | 21/1/1996 | – | 3.0 | 32.0 | 42.0 | 20.0 | 3.0 |
| 3 | 3/1/1997 | 0.5 | 1.5 | 13.0 | 35.0 | 38.0 | 12.0 |

* 3.2 km from the crater.
** 3.6 km from the crater.

The ash of Sample 2 was deposited by the explosion of January 21 on the 20th day of the eruption. It was collected in the area of the Observatory and is very different from the ash of Sample 1 and from all of the ash samples collected during 1996. This ash is distinguished (especially its 2.0–1.0-mm fraction) by the flattened form of all of its solid fragments. It also contains many altered shapeless pumice-like fragments. Similar flattened fragments were found in the ash deposited by the 1981 eruption of Alaid Volcano (the eruption lasted from April 28 to June 4). These facts and the deposition of lapilli pellets along the ash-fall axis indicate that the Karymsky vent was widened by the explosions of January 16 and 21 and that the lava was fragmented at the location of the source of the lava flow.

The bulk of the fragments are dark rock fragments and dark brown (to black), vesicular, shapeless glass fragments, that is, fresh juvenile fragments of dark brown glass. This ash also contains chips of colorless, transparent, sometimes opaque plagioclase and occasional fragments of altered brown and reddish-brown rocks.

The amount of plagioclase chips increases with the decreasing size of the fragments: there is more plagioclase in the ash fraction of 0.5–0.25 than in the 2.0–1.0-mm fraction and also more particles of the 0.5–0.25-mm fraction consist of plagioclase as compared with 1.0–0.5 mm fraction.

The ash of sample 2202 collected on February 11 near the Observatory consists largely of particles $<0.1$ mm in diameter. These are fragments of plagioclase ($\sim 50\%$), single dark-green prismatic pyroxene and hornblende crystals (?), and altered rock fragments (10–15%). The ash that fell on February 28 and March 1 appeared to take on a pink tint when it fell on the white snow. This effect seems to have been produced by a somewhat larger amount of altered reddish particles and also by the fact that the ash was moistened by melting snow. When dry this ash reverted to its usual color, almost loosing its pinkish tint.

Very fine ash alone ($<0.25$ mm) fell on January 3 in the Dvor caldera (table 5). There were almost no particles larger than 0.25 mm, even though at a distance as little as 3.2 km from the vent they must have been present in the sample. A possible explanation is that at the closing phase of the ash fall only very small particles were brought there from the periphery of the ash cloud as the wind changed its direction.

Comparison of the ash deposited near the Observatory on January 21, 1996, and on January 3, 1997, shows that there was little difference between their particle sizes: the latter had fewer particles 2.0 to 0.5 mm in diameter (15% instead of 35% in the former) and more particles of $\leq 0.5$ mm (85% compared to 65%). This was caused by a difference in the eruption dynamics.

The rock of the lava flows resembles, both macroscopically and chemically, that of the tephra. According to Gill's classification [16], the andesites of Karymsky Volcano can be attributed to the medium-potassium series. In terms of the Fe/Mg ratio they can be placed at the boundary between the calc-alkaline and the tholeiitic series. Different areas of lava sometimes show a poorly expressed trend of a decreasing $SiO_2$ content. This effect appears to have been caused by the rise of new, more basic magma portions. The same trend can be noted in the more silicic composition of the pyroclastic material as compared to the lava flows.

## RESULTS AND DISCUSSION

The beginning of 1996 was marked by eruptions at two volcanoes in the Karymsky volcano-tectonic area: an unusual very short subaqueous eruption in the Akademii Nauk caldera and typical long-term eruptive activity at Karymsky Volcano. The period from December 31, 1995 to January 1, 1996, was characterized by powerful deep tectonomagmatic activity which resulted in the breakthrough of deep-seated magma to the surface through the volcanic vent of Karymsky Volcano on the night between the 1st and 2nd of January and through a feeder fissure and a fault in the northern part of the Akademii Nauk caldera in the daytime of January 2, 1996.

A medium-sized vulcanian–strombolian eruption occurred at Karymsky after a 14-year period of dormancy. The volume of lava erupted during the first year of activity was 11.1 million $m^3$. With an average lava density, the weight of the lava flows has been estimated to be 24.4 million tonnes.

The total volume of the material erupted over one year was 0.02 $km^3$, the total weight of the lava and pyroclastic material amounting to 30.4 million tonnes. The explosivity, as calculated on the basis of the lava/pyroclastic ratio was ~20%, which means that the explosive index of 60–80%, typical of the previous Karymsky eruptions [9], [13], was not attained.

Using the value of 1 MJ/kg that was earlier proposed by S. A. Fedotov [10] for the heat content of erupted material, we calculated the total thermal energy of the 1996 Karymsky eruption to be $\sim 30.4 \times 10^9$ MJ.

As regards the dynamics of the effusive activity, firstly there was a peak with the initial lava flow, which had an average rate of lava discharge of 1.35 $m^3/s$. The subsequent periods of lava flow did not show any significant differences in their average lava discharge rates: 0.39 $m^3/s$ from January 12 to May 5, 1996; 0.36 $m^3/s$ from May 5 to August 13, 1996; and 0.34 $m^3/s$ from August 13, 1996, to January 3, 1997.

As with the preceding Karymsky eruptions, the material erupted in 1996 from the summit crater of the volcano was of andesite composition. The mineral composition was plagioclase and ortho- and clinopyroxene, and magnetite, with sulfides, apatite, and zircon as accessory minerals. Almost all of the samples were found to contain microscopic inclusions of a silicic pumice-like material (up to 74% $SiO_2$).

According to the outward appearance of the samples, the rocks of the lava flows erupted during the first six months were aphyric and rather crystalline, while the products of the latter half of the year were more crystalline, which seems to be common for the Karymsky lava evolution during long eruptions. This trend was also reported [12] for the previous eruptive cycle.

It is probable that prolonged eruptive activity will occur at Karymsky over the next few years. From the behavior of the previous eruptions, the most likely activity will consist of mild or medium-sized explosions with episodic small lava flows. Paroxysmal explosions may occur if an extrusive dome grows in the crater.

A short but vigorous subaqueous eruption occurred in the Akademii Nauk caldera during the outbreak of the next eruptive cycle at Karymsky. It started with a short phase of phreatic explosions and became phreatomagmatic during the subsequent phase. Explosions ejected compositionally bimodal magmas: mostly basalt and a small amount of rhyolite during the final phase. The total volume of the erupted products was ~40 million $m^3$. It is significant that the short eruption in the lake removed a more than twice as much material than Karymsky Volcano over the year.

The volcanotectonic events in the Akademii Nauk caldera intensified the hydrothermal activity. Several mud pots and pulsating springs, including one geyser, showed renewed activity in a thermal area 120 m west of the Akademii Nauk Springs. Numerous hot springs started operating around periphery of the lake. A new large group of hot springs (called the Piip Springs) came into being along the feeder fissure between the underwater crater and the source of the Karymskaya River. The total flow rate of these springs was measured to be 350–400 l/s, with the water temperature ranging between 60 and 92°C.

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