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THE JUNE 1986 ERUPTION OF BEZYMYANNYI

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This paper presents the results of visual observations, particle-size analysis, seismological observations, and acoustic measurements carried out during a small-magnitude eruption of Bezymyannyi in June 1986. A model is proposed for the mechanism of the eruption. A specific character of the eruption is explained by a deeper localization of a gas-rich magma portion in the conduit.

INTRODUCTION

Bezymyannyi has been active since the cataclysmic explosion in 1956 after which a viscous lava dome, Novyi, began to grow in the summit crater [3]. In fact, the volcano has been in the state of a long-lasted extrusive activity consisting of the periods of reactivation in the form of single eruptions and the periods of relative quiescence. This type of activity is typical of many andesitic volcanoes from the circum-Pacific belt. The manifestations of their activities are extremely diverse: explosions of various size including lateral blasts, various types of pyroclastic flows, the extrusion of lava domes and blocks, and the outpouring or, to be more exact, the squeezing out of lava flows. Large-magnitude eruptions are often preceded by large rockslide avalanches and accompanied by disastrous mud flows (lahars). It is clear that the monitoring and study of these volcanoes is of great academic and practical importance.

Since 1956 Bezymyannyi has been kept under regular surveillance and many of the above mentioned events were observed during a period of more than 30 years. The volcano can be regarded as a convenient model that has been operating for many years and afforded an excellent opportunity for developing and testing a variety of concepts of physical volcanology and petrology. Each new eruption, whatever its scale, provides evidence and adds new facts to a large body of previously collected data; each new type of volcanic activity calls for the development and testing of new techniques that would be adequate and efficient to study it.

In early 1986 a dome-shaped bulge began to grow in the summit

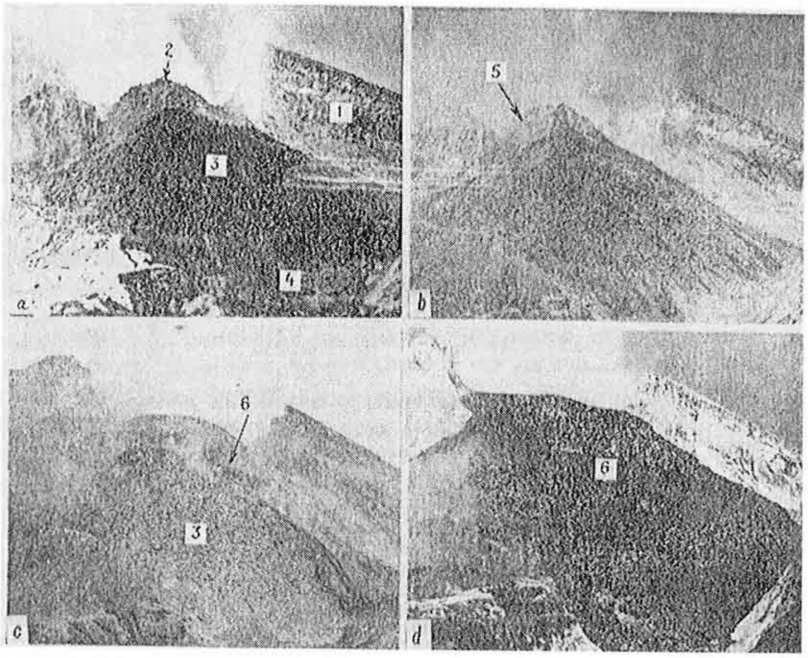

Figure 1 Dynamics of activity in the summit crater of the Novyi dome on June 20 (*a*), 22 (*b*), 24 (*c*) and 30 (*d*), 1986. 1 - Novyi dome; 2 - summit extrusion; 3 - 1985 lava flow; 4 - trench produced by explosion and collapse; 5 - lava bulge; 6 - new lava flow.

crater of the Novyi dome and a small-magnitude eruption took place in June. The aim of this paper is to describe and interpret the 1986 eruptive events from the evidence provided by visual observations, seismic and acoustic measurements, and the study of the grain-size distribution of the erupted material.

SEQUENCE OF ERUPTIVE EVENTS FROM VISUAL OBSERVATIONS

In late 1985 the extrusion of viscous lava ceased and for several months the volcano was in the state of moderate or strong fumarolic activity. In late March 1986 rockslide avalanches occurred and columns of tephra and gases rose. Those were the first indications of a renewal of eruptive activity. A flight over the volcano on April 16 revealed that the summit portion of the lava flow produced in December 1985 had been deformed: a dome-shaped bulge ~ 50 m high and ~ 150 m across at the base had been formed.

On May 12, 20 and 27 occasional but rather large landslides were observed. By the end of June an extrusive block ~ 80 m high rose in the place of the dome-shaped bulge. The volcano was relatively quiet except for occasional avalanches on the extrusive block. From 14 to 19 June the block rose to a height of 15-20 m. From June 18 rockslide avalanches grew more frequent and by June 21 reached the lower end of a trench that had been previously produced by explosions and collapse (Figure 1, *a*). The avalanche fronts carried large blocks up to 10 m in size. As they hit the slope, small dust clouds rose. A lava bulge emerged in the western part of the extrusive block by June 22 (Figure 1, *b*). Later, on June 22, some of the avalanches produced cauliflower ash clouds, obviously because they involved large amounts of a gas-rich hot material.

About midnight red hot cracks were seen in the collapsing extrusive block. By the night of June 24, the extrusion was heavily destroyed and overlapped by a viscous lava flow which had been squeezed out of a vent above the extrusive block. The lava flow advanced at a rate of about 5 meters per hour. On June 24 it was 120 m long (Figure 1, *c*). The front of the lava often collapsed and the dull red glare of the fragments was seen even in the daytime. The dust cloud produced by the avalanches propagated southward on June 22-24 and travelled along the eastern slopes of the Ziminy Mountains as far as 30 km. No columns of tephra and gases were generated during the period described.

From the noon of June 24 to 8:25 p.m. of June 25 the weather was too bad for visual observations. By the next night the lava flow was 250 to 400 m long and the rate of its advance was at least 8 meters per hour. From 25 to 29 June it grew as long as 500-550 m (Figure 1, *d*). Avalanches became more occasional, and the glare of the lava fragments in them grew duller. By July 1 avalanches ceased and the volcano was in the state of fumarolic activity. A month later fresh pyroclastic flow deposits were discovered at the foot of the cone.

Columns of fumarolic gases rose to a height of 0.5 to 1.5 km during a period of June 28 to July 2. The thermal energy released by the volcano in that period has been estimated to be 1.4×10^4 to 1.2×10^6 kW. It began to decline slowly with time [14].

GEOLOGIC EFFECT OF THE ERUPTION

The most important effect of the eruption in terms of erupted material was the development of a viscous lava flow and the deposition of pyroclastic material (Figures 2 and 3).

Lava filled the trench from side to side and flowed almost as far as the foot of the dome (see Figure 3). It was extruded during one eruptive event. Like in previous eruptions, lava was very viscous and the flow had a scaly surface. It was squeezed out of a vent in the summit crater on the Novyi dome. The front of the flow exhibited planar fracture joints produced by viscous shearing (see Figure 1, *d*); some lava blocks rolled down into the canyon at the foot of the dome. Apparently, the lava flow ranged between 10 and 20 m in

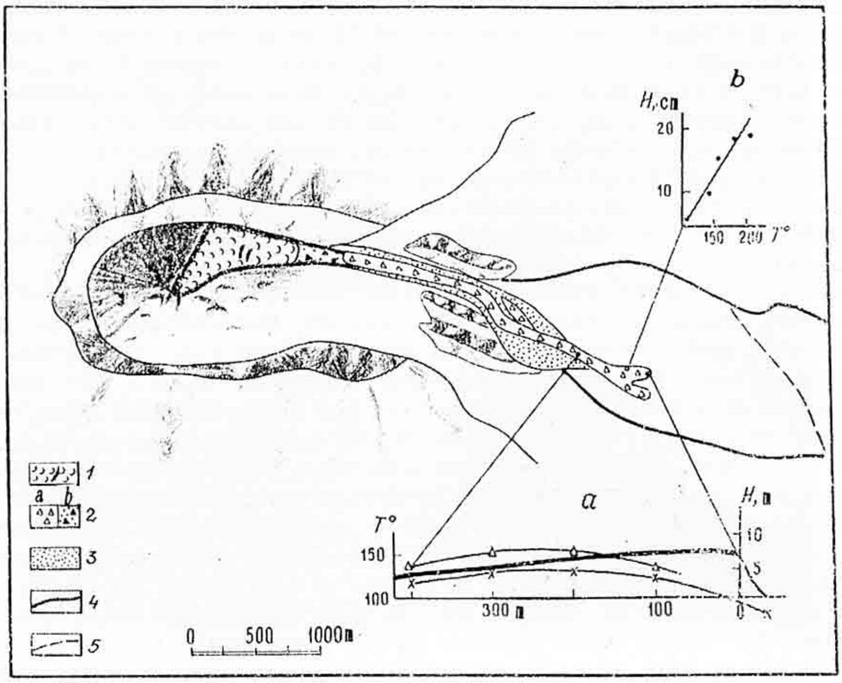

Figure 2 Schematic map showing the distribution of the products discharged during the June 1986 eruption of Bezymyannyi. 1 - lava flow; 2 - pyroclastic flow (*a*) and nuee ardent (*b*); 3 - pyroclastic surge deposit; 4 - limits of the 1985 pyroclastic flow deposit; 5 - extent of ash-fall deposit from clouds above pyroclastic flows. The insets show the results of temperature measurements: a - temperature profile along the north pyroclastic flow (crosses indicate temperature values at 10 cm below the flow surface, triangles at 15 cm, heavy line thickness); *b* - temperature variation from the surface to 20 cm depth.

thickness. The cracks displayed a transition from a denser internal material to a "frothy" marginal zone 1 to 1,5 m thick.

Pyroclastic flows laid down a deposit of pyroclastic material split into two tongues.

The north tongue consists of subrounded fragments and a matrix of medium-grained sand. The fragments have a maximum size of 3-4 m, the dominant size being 30-40 cm. The matrix accounts for 20-30 percent of the rock volume. The average natural density of the deposit (*d*) was found to be 1.49 g/cm^3 (six measurements). The tongue is about 100 m wide, has a steep front, and is 6-7 m thick (see Figure 3).

The south tongue contains 60-70 percent of matrix material and its average density was found to be higher, d = 1.75 g/cm^3 (three measurements) because of a larger amount of small fragments. The maximum size of fragments diminished to 1-2 m. The tongue is about 50 m wide has a gently sloping front, and reduces slowly in thickness from 1.5-2 m to a few centimeters.

These marked differences between the deposits suggest that they were laid down by two different pyroclastic flows. This supposition was confirmed later (see below).

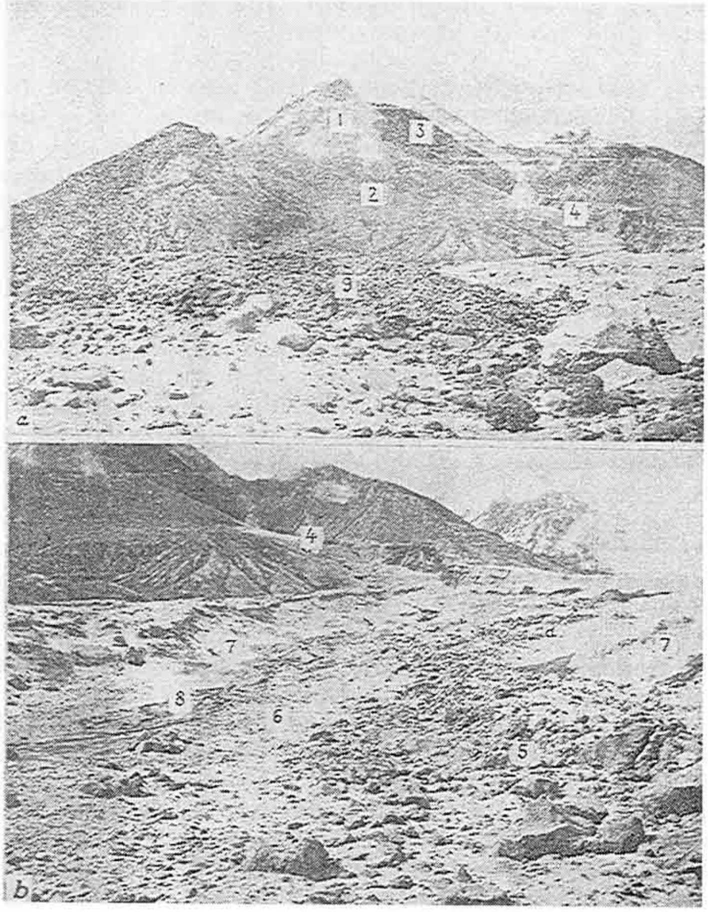

Figure 3 View of Bezymyannyi after the June 1986 eruption. *a* - general view; *b* - pyroclastic flow deposit. 1 - extrusive portion of Novyi dome; 2 - agglomerate mantle; 3 - new lava flow; 4 - erosion canyon followed by pyroclastic flow; 5 - block and ash flow: a - material "splashed" over the canyon side; 6 - vesicular andesite pyroclastic flow; 7 - pyroclastic surge deposit; 8 - fumarole on pyroclastic flow; 9 - front of block and ash flow.

According to one of the modern genetic classifications [2] and a working terminology of pyroclastic deposits [19], the north deposit seems to be a block and ash flow and the south deposit a vesicular andesitic flow. At the same time, a rather high vesicularity of fragments in the block and ash flow makes it similar to vesicular andesitic flows. So, it would be more correct to classify it as intermediate between the two types.

Many of the large blocks are seen to be broken by series of cracks. The character of the rupture surface and the fact that the cracks close with depth suggest that the blocks were plastic as they were carried by the flow and deposed. This supposition is supported by the traces of a plastic (draping) contact observed on some large blocks.

The pyroclastic flow moved along the canyon at the foot of the dome and about 500 m beyond it. It travelled to a distance of approximately 4 km from the crater. Where the flow met an obstacle and changed the direction, it bifurcated into two offshoots. One of them was formed as the flow left the trench and turned to move along the north side of the canyon and the other where the canyon turned sharply (see Figures 2 and 3, *b*). The first offshoot contain fragments most of which range between 15 to 20 cm in size and some are as large as half a meter. The matrix amounts to 60-70 percent of the rock volume. The offshoot deposit is a band 0.7-0.8 km long, 20 m wide and 0.5 m thick. The deposits extend somewhat further as a thin cover. The second offshoot is a pile of subrounded fragments including blocks of up to 3 m with 20-30 percent of a matrix material. According to the character of the deposits the first offshoot was laid down by a vesicular andesitic flow and the second by a block and ash flow. The height of the first flow above the canyon floor (the height of the canyon sides) was 40 m and that of the second 7-10 m. Apparently, a gas-rich pyroclastic material rushed down the canyon spatting over its sides and filled it to the brim.

Other types of pyroclastic deposits. Pyroclastic surges [2], [19] and ash-fall deposits from clouds above the pyroclastic flows [1] have been identified among the pyroclastic deposits.

Pyroclastic surges have been located on the right-hand side of the canyon as "spatters" of a sand and ash material splashed to a hight of up to 10 m above the flow surface. They also occur as patches on the grounds bordering the canyon and in small hollows away from it (Figure 4). The pyroclastic surge deposits often exhibit a dune-shaped topography; the material is loose, yields readily to pressure, and behaves as quicksand. The surges have a maximum thickness of 1 m. They consist of medium-grained sand and occasional fragments reaching a few centimeters in size; d = 1.15 g/cm^3 (average of 10 measurements).

The ash-fall material from clouds above the pyroclastic flows was deposited in the SSE direction as far as the north sides of the Ziminy Mts. (see Figure 2). The deposit varies in thickness from 0.6-0.7 cm near the pyroclastic flow to 0.3-0.4 cm at a distance of 2-2.5 km from

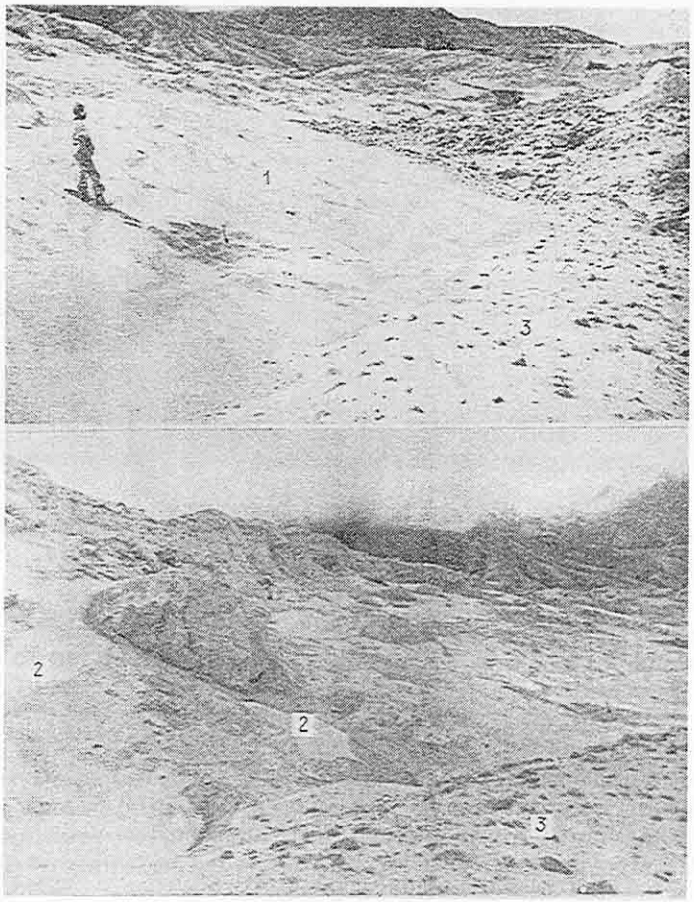

Figure 4 Pyroclastic surge deposits: 1 - dune topography, 2 - single patches; 3 - vesicular andesite pyroclastic flow.

its front. It consists of a light grey silt-size material including larger fragments of dark-colored minerals. The fact that the material was not deposited under the shelter of large blocks proves its ash cloud origin (Figure 5).

Figure 6 shows a section of pyroclastic deposits cut at a distance of 2 m from the side of the north flow. The figure also presents the cumulative curves of grain-size distribution. The section exhibits five layers including the lowermost 5 cm (layer 1) deposited from an ash cloud above a pyroclastic flow during the previous 1985 eruption described earlier by Alidibirov *et al.* [1]. The presence of the 1985 marker allowed us to identify the overlying deposits as products of

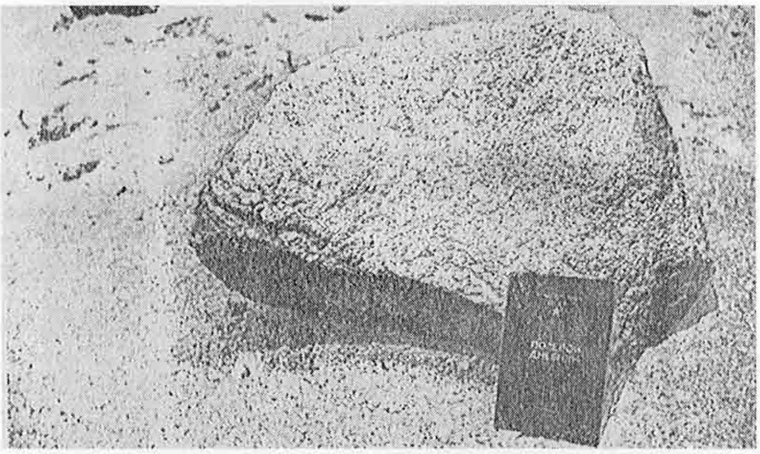

Figure 5 Ash-fall deposit from clouds above pyroclastic flows. No deposit under the shelter or a large block.

the 1986 eruption.

The upward succession of the layers with thickness in cm is as follows.

Layer 2. Well-sorted, fine-grained sand	2.5
Layer 3. Silt-size material	1.0
Layer 4. Medium-grained sand with a large number of fragments up to several centimeters	5.0
Layer 5. Silt-size material	0.5 - 1.0

We compared the grain-size distribution curves of the deposits, 2, 3 and 4 in Figure 6, with the curves for the matrix of the pyroclastic flows (curves A and B) and identified layers 3 and 5 as ash cloud deposits and the coarser material of layers 2 and 4 as pyroclastic surge. The regular alternation of two ash cloud layers and two surge layers reflects the sequential deposition of the materials of two pyroclastic flows. There is a short break between them during which the ash cloud material that travelled above the first flow had time to be deposited.

The ash particle fractions of the matrix materials from both flows are equal in size (< 2 mm). A large amount of fine rock fragments in the matrix of the south flow (*B*) and in layer 4, larger than in layer 2 and in the matrix of the block and ash flow (*A*), indicates a definite similarity between the respective deposits and suggests that the eruption of the block and ash flow occurred before the eruption of the vesicular andesitic flow. A grain-size difference between layers

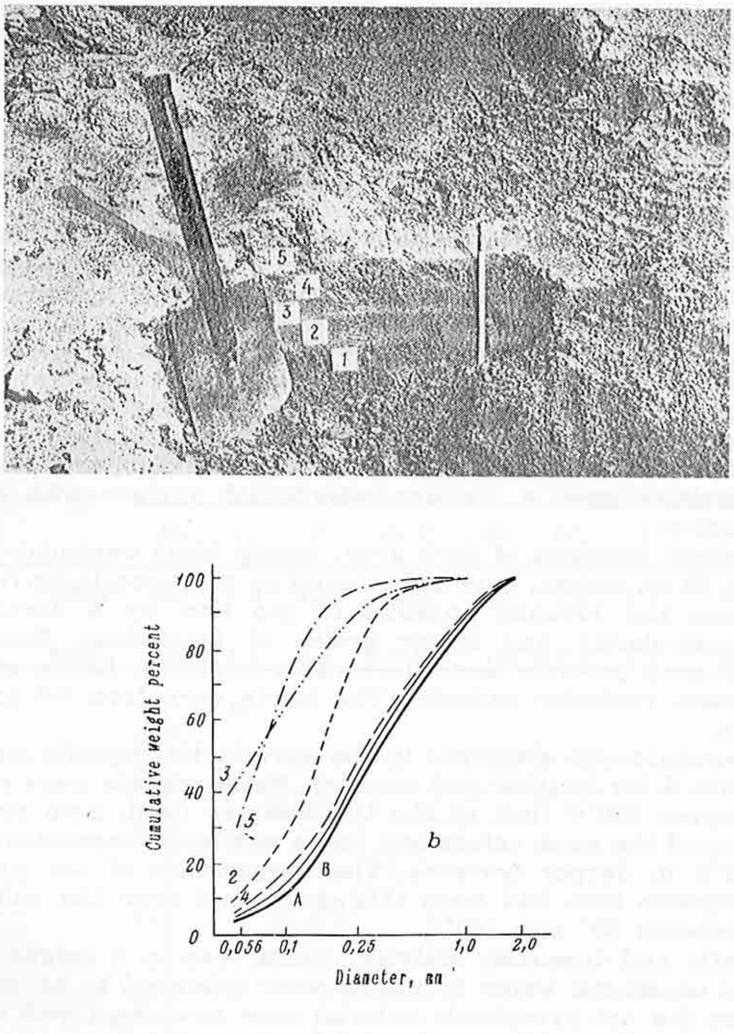

Figure 6 Pyroclastic deposits of the 1986 eruption. *a* - section at 3 km from the block and ash flow; *b* - cumulative size-frequency distribution of < 2 mm ash (layers 2 and 4 in the section) and matrix materials from: *A* - block and ash flow and *B* - pyroclastic flow of vesicular andesite. Figures indicate layers as they are numbered in the text.

2 and 4 may indicate that they belong to different types of pyroclastic surge deposits.

Description of the rocks. The pyroclastic flows consist of grey vesicular andesite containing abundant < 1–3 mm plagioclase crystals. Vesicles diminish in size toward the interior of the large blocks. The rocks look uniform in outward appearance.

Samples of lava have been collected on the flow front, where lava resembles the andesite from the pyroclastic flows, except that it is darker in color. It is dark grey to black andesite in the interior and greenish-grey, vesicular andesite in the outer, frothy zones.

Numerous vesicles in the rock samples from the pyroclastic flows often exhibit, at small magnification, fine, parallel glass threads stretching from one wall of the vesicle to another. As to the lava flows, such threads have only been found in the marginal vesicular andesite.

Ash particles from the unconsolidated deposits (pyroclastic flow matrix, pyroclastic surge, and ash cloud deposits) are almost totally represented by fragments of plagioclase and pyroxene crystals, plagioclase being much more abundant. Fine glass particles occur on the crystal faces and scarce minute glass needles are scattered. All particles exhibit a fresh glassy surface and very scarce are affected by oxidation. So this ash size fraction can be identified as juvenile, crystal-rich ash produced by the fragmentation of well-crystallized magma. The ash does not contain vesicular particles, and some of the glass particles have a concave, conchoidal surface with a typical glassy luster.

Occasional boulders of dark grey, nearly black vesicular andesite, less than 20 cm across, have been found on the pyroclastic flow. They differ from the juvenile andesite of the flow by a darker color, higher vesicularity, and larger grains of plagioclase. Some of the blocks of grey juvenile andesite contain lenticular bands of darker, nearly black vesicular andesite. The bands vary from 0.5 to 7 cm in thickness.

Temperature was measured in the pyroclastic deposits on June 30 (see Figure 2 for location and results). Measurements were restricted by the upper 350°C limit of the thermometer used. Both pyroclastic flows showed the same values and had a maximum temperature of more than 350°C in deeper horizons. The temperature of the pyroclastic surge deposits that had been thrown on and over the canyon side varied between 30° and 140°C.

Phreatic and fumarolic activity. Steam rose to a height of up to 30 m and occasional water fountains were observed to be as high as 1 m where the hot pyroclastic material came in contact with the water of the small, 0.5 m wide, creek at 3 km from the crater (see Figure 3, *b*). Small, secondary fumaroles were observed on the surface of the pyroclastic flows where large blocks had piled up and come in contact with the matrix. Some of the high-temperature fumaroles showed 350°C at depth.

ACOUSTIC AND SEISMIC OBSERVATIONS

The seismic network station Apakhonchich situated at 16 km from Bezymyannyi recorded two seismic signals during a period of June 20–30. They were accompanied by acoustic signals of infrasonic frequency. Judging by the signature and the time difference between the arrivals of the seismic and air waves, the signals are identical to the seismic events recorded during the eruptions of pyroclastic flows at Bezymyannyi in 1983-1985 [16]. Infrasonic oscillations of 0.3-1 Hz frequency are generated during the eruption and movement of pyroclastic flows as a result of large-scale turbulent pulsations in the eruption column as it undergoes convection above the flow. The simultaneous acoustic and seismic measurements indicated that the eruption of two pyroclastic flows occurred on June 25, one at 5h 50min and the other at 8h 56min. The mean amplitudes of the seismic and acoustic signals (A and ΔP), their periods (T) and durations (Δt) are presented in Table 1, and so are the energies (W) of the acoustic and seismic sources computed by a technique proposed by Firstov [16].

Table 1 Basic parameters of acoustic and seismic signals.

Date	Time, LT	Seismic signal				Acoustic signal			
		Δt, s	A, μm	T, s	W, W	Δt, s	ΔP, Pa	T, s	W, W
June 25, 1986	5h50m	120	1.0	0.5	5.6×10^6	85	1.0	1.5	7.5×10^6
	8h56m	120	1.2	0.8	5.0×10^6	110	1.5	1.2	16.8×10^6

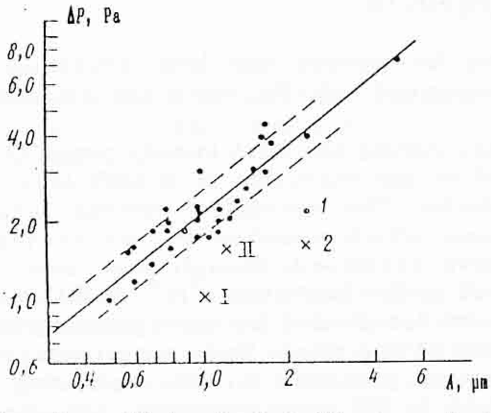

Figure 7 The ratio between the amplitudes of seismic (A) and acoustic (ΔP) signals. 1 - 1983-1984 pyroclastic flows [16]; 2 - 1986 pyroclastic flows I and II (numbered in the order of their formation).

As has been demonstrated by Firstov [16], pyroclastic flows of this kind feature a linear $\log\Delta P$ vs. $\log A$ relationship. Bearing in mind that the amplitude of an acoustic signal is controlled by the air stratification, we compared the air stratification during the 1986 eruption and that of the 1983-1984 eruptions using the records of the Klyuchi weather station. As we did not find any essential difference, we considered that the acoustic signals of the 1986 and 1983-1984 eruptions can be compared. One can see in Figure 7 that the data points of the 1986 eruption lie below the correlation region which means that the amplitudes of the acoustic signals produced by the 1986 pyroclastic flows were smaller than those of the 1983-1984 signals. Moreover, the amplitude of the signal from the first flow was lower than the signal amplitude from the second flow. The fact that all data points of the 1986 eruption are shifted from the correlation region indicates that there might be differences in the states of the atmosphere. This effect was even more pronounced in the behavior of the acoustic signals from the 1985 pyroclastic flows [16]: many data points deviated significantly from the correlation region. The amplitude of the acoustic signal is known to be determined by the heat loss from the surface of the pyroclastic flow, which means that it depends on its temperature, gas content, and grain size. On this basis we can suppose that block and ash flows which contain less matrix material and less gas than vesicular andesitic flows produce smaller eruption clouds and, accordingly, weaker acoustic signals. This conclusion was advanced earlier [16] from the study of the 1985 eruption. It follows that in 1986 the block and ash flow was erupted first and three hours later the eruption of the vesicular andesitic flow took place.

DISCUSSION OF RESULTS

Before proceeding to discuss the 1986 eruption, we will describe briefly the Bezymyannyi activity since the catastrophic eruption of 1956.

Recent activity. During the first twenty years (1956-1976) volcanic activity consisted in the extrusion of a stiff lava dome and later of its individual blocks. The extrusive process was accompanied by vigorous explosions which resulted in the eruption of pyroclastic flows. No lava flows developed, though some amounts of plastic lava were squeezed out in the late sixties [3]. Practically all eruptions of the last decade were terminated by the squeezing out of viscous lava flows on the slopes of the dome. Each eruptive cycle of the present-day activity usually proceeds in the following succession: slow extrusion of a block in the summit crater → ash explosions of various magnitude → one or several pyroclastic flows → viscous lava flow. The exceptions were the February 1984 eruption during which the pyroclastic flow stage was omitted and the 1985 eruption when a large rockslide avalanche triggered a lateral blast [1]. Commonly, eruptions occur once or twice a year. Data on the volumes of the material erupted during the last decade are presented in Table 2.

Character of the 1986 eruption. Quantitative estimates of the erupted materials, thermal energy, and other effects of the eruption are given in the Appendix. The 1986 eruption can be classified as a small-magnitude event as seen in Table 2. The volume of the

Table 2 Volumes of lava and pyroclastics discharged at Bezymyannyi in 1977-1986.

Date of eruption‡	*Volume, $\times 10^6$, m^3*		*Tephra to lava ratio*	*Refe- rence*
	Tephra	*Lava*		
March 1977	13.6	0.35	39	[13]
Sept. 1978	-	-	-	[13],[9]
Feb. 1979	17	0.48	35	[13]
Sept. 1979	6.5	0.56	12	[13]
Apr. 1980	19.1	0.59	32	[13]
Aug. 1980	-	0.72	-	[13]
June 1981	~10	-	-	[7]
June 1982	~3‡‡	~1.2‡‡	~2.5	[10]
May 1983	~10-15‡‡	-	-	[8]
Feb. 1984	-	-	-	[15]
Oct. 1984	~14	-	-	[15]
June 1985	37-50‡‡‡	-	-	[1],[6]
June 1986	~0.75	~3	~0.25	This paper

Note. Volumes of ash were not determined for lack of data. Dash means no data.
‡ Date of climactic stage (lava flow periods excluded).
‡‡ Estimates by the writers.
‡‡‡ Including avalanche debris.

pyroclastic material, 0.75×10^6 m^3, was smaller than the ejecta produced by the previous eruptions, whereas the lava flow ranks among the largest that have ever developed at Bezymyannyi. So the lava to pyroclastics ratio was larger than during the previous eruptions (see Table 2). Judging by its character, the 1986 eruption was typical of the eruptive activity during the past decade, yet it exhibited some special features. For example, there was no ash explosions which commonly began the climactic phases of all eruptions. Another unusual feature is that the eruption of pyroclastic flows occurred in the course of and not before the lava flow. A similar event took place in late July 1985, approximately a month after the outbreak of a large-magnitude eruption and the deposition of large pyroclastic flows, when a small pyroclastic flow was erupted as viscous lava continued to be extruded. According to A. B. Belousov's observation (personal communication), that flow developed from a vent in the middle of the dome flank, in the side of a trench produced by explosion and collapse. Another specific feature of the eruption was a rather rapid advance of the lava flow which developed and came to a halt within a week, whereas the extrusion of lava lasted a few months to a year during the previous events, e.g., in 1981-82, 1984 and 1985 [1], [2]. The speed of lava motion was greatest on June 24-25 when pyroclastic flows were erupted.

Mechanism of pyroclastic flow development. Another specific feature of the 1986 eruption was the development of two pyroclastic flows which differ from each other in many respects. Although the process of their development was not observed visually, the results of a later study by a combination of various techniques prove that there were two flows. As a matter of fact, pyroclastic flows of different properties were observed during some of the previous eruptions [1], [5].

Many of the modern classifications [2], [17], [19] subdivide pyroclastic flows into two groups based on a difference in the mechanisms of their formation. The first group comprises pyroclastic flows proper which are produced primarily by the explosion of gas-rich viscous magma. The second group includes nuees ardents (glowing avalanches) [17] and block and ash flows [19] that develop during the collapse of a growing dome or of a slowely extruded lava flow, largely due to the force of gravity. Naturally, both types of flows possess transitional properties in terms of their origin because both explosive and gravitational energies operate in both case, but their relative contributions vary greatly. This is reflected in the porosity of the resulting deposits which is higher in the case of pyroclastic flows proper [19]. For this reason we can use the results of particle-size analyses for the elucidation of the genetic aspects.

Having analyzed the particle-size data of different types of pyroclastic flows, Bardinzeff [17] demonstrated that pyroclastic flows were different from nuees ardents by a smaller particle size. He used the median diameter *Md*[a] of ash particles from the flow matrix as a measure of difference. He found $Md > 0.4$ mm ($< 1.25\phi$) for nuees ardents and $Md < 0.5$ mm ($> 1\phi$) for pyroclastic flows. So the 0.4-0.5 mm range is an overlap region of these types of pyroclastic deposits, which is another indication that the line of demarcation between them is very relative.

The median diameters of the ash particles from both of the 1986 pyroclastic flows measure about 0.3 mm. This value indicates that the flows were produced by explosions rather than by avalanches. Figure 8 shows the ash particle-size distribution of the 1986 flows in the coordinates of the sorting index σ[b] and *Md*. One can see that our

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[a] Md is the middlemost diameter that is larger than 50% of the diameters in the distribution and smaller than the other 50%. It is measured in millimeters or phi-units, ϕ, where $\phi = \log_2 d$, mm.

[b] $\sigma = (\phi_{84} - \phi_{16})/2$, where ϕ_{84} and ϕ_{16} correspond to 84% and 16% of the cumulative size-frequency distribution (see Figure 6).

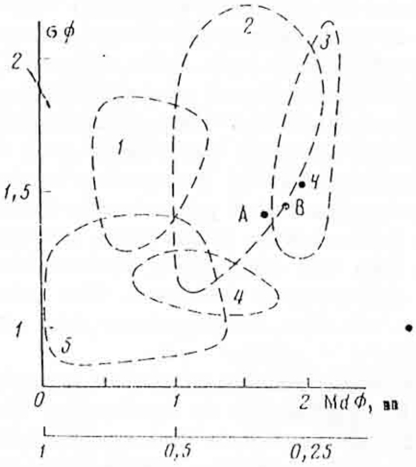

Figure 8 Ash-size distribution of pyroclastic deposits in the coordinates of sorting index σ and median diameter Md φ after [17] and data for the deposits of the 1986 eruption of Bezymyannyi. Data points are numbered as in Figure 6, *b*. 1 - nuee ardent; 2 - pyroclastic flow; 3 - pumiceous flow; 4 - pyroclastic surge; 5 - pumiceous tephra.

data points lie aside from the nuees ardents region in the field where pyroclastic and pumiceous flows overlap. So, on the basis of the particle-size data, the 1986 flows correlate with more porous pyroclastic flows whose formation was influenced essentially by the gas phase and which were definitely of juvenile origin in contrast to the resurgent origin of nuees ardents which may be derived from rather fresh material extruded earlier as blocks or as lava flows (often a few days before). Note that in spite of the very close grain-size characteristics of the two flows, the first (block and ash) flow is distinguished by a somewhat larger size of the particles and lies in the pyroclastic flow region in contrast to the second which lies in the pumiceous flow region.

The occurrence of numerous vesicles with threads and needles of residual glass in the andesite fragments is indicative of the juvenile nature of the pyroclastic material and of a high gas-saturation of magma. The origin of the vesicles with glass threads and needles can be explained by an abrupt expansion of gas bubbles in the near-surface environment when the remaining glass was still plastic. No andesite of this kind has been found in the interior of the lava flow. This is another argument against the generation of the pyroclastic flows by the collapse of a lava flow or of the extrusive blocks of the dome. The juvenile nature of the erupted materials is also supported by their megascopically uniform appearance and by the facts that the rocks were still very hot when samples were collected and that the pyroclastic flows were localized within a narrow canyon at the base of the cone. The latter circumstance distinguishes the 1986 eruption products from the rocks of the 1985 eruption which was accompanied by a large rockslide avalanche on the Novyi dome which resulted in an extensive mantle of block and ash deposits consisting of the materials produced by the previous stages of the dome formation [1].

It can be postulated that the 1986 pyroclastic flows owed their origin to small-magnitude inclined explosions and collapse of eruption clouds or to the redistribution of degassing magma. As no traces of explosive activity nor remnants of pyroclastic material were observed on the lava flow, the pyroclastic flows were probably erupted from a fissure on the slope, like the 1985 flow, rather than from the central vent. The observed differences between the two flows seem to be caused by variations of the temperature and gas content of the magma in the conduit.

Schematic interpretation of the eruptive events. The character of eruptive activity at Bezymyannyi is controlled to a great extent by a high gas content of the magma in the upper portion of the conduit and by a high viscosity of andesitic magma due to a large degree of its crystallization [4]. High viscosity first restrains the liberation of volatiles from the melt which tends to give off gases as pressure declines and crystallization develops and then prevents the gases to be freely transported in the magma. As a result, despite an extremely low solubility of gas at low pressure in the upper part of the conduit, the gas content in the magma system remains to be significant. This conclusion is supported by the pyroclastic character of the eruptions and by the vesicular, frothy constitution of the lava flow outer zones.

Commonly, the relatively high mobility of the gas phase and the decreasing solubility of gases toward the surface lead to the enrichment of the upper portion of the magma column with gases the content of which diminishes progressively with depth but remains thus far to be essential. The progressive stratification of the magma column in terms of gas content is the factor responsible for a change from explosive activity to the development of pyroclastic flows and to the extrusion of a vesicular, viscous andesitic lava flow. The proportion of ash, pyroclastic material, and lava must correspond with the volumes and energy of the magma batches that differ essentially in gas content just before the eruption takes place. After the eruption, the more degassed magma batch rises toward the surface and plugges the conduit. The plug restrains the degassing of the magma column and makes the system ready for a new eruption the outbreak of which squeezes out the plug as an extrusive block on the summit.

The process of the 1986 eruption can be visualized as follows. After the termination of the 1985 eruption, the upper portion of the conduit was filled with degassed magma the amount of which was larger than usual. This plug prevented gases from rising toward the surface and promoted their concentration at a deeper level of the conduit. Obviously, the products erupted in June 1986 were the "remnants" of the magma that had risen to the surface in 1985 and

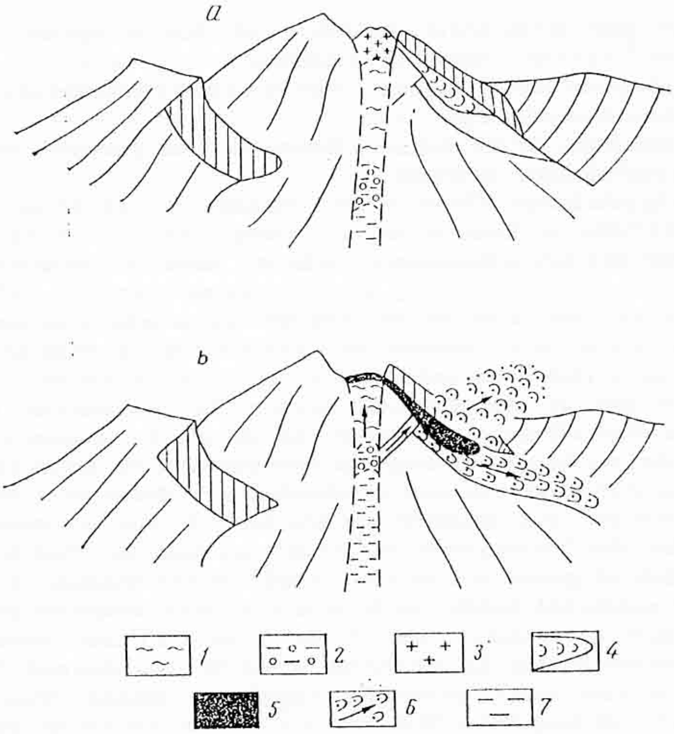

Figure 9 Schematic model of the June 1986 eruption of Bezymyannyi. a - opening phase; *b* - climactic phase. 1 - degassed magma zone (lava flow material); 2 - gas-rich magma zone (pyroclastic flow material); 3 - extrusive plug; 4 - lava flow of previous eruption; 5 - new lava flow; 6 - eruption cloud and pyroclastic flow; 7 - slightly degassed magma (material of next eruption).

was essentially depleted in volatiles. This accounts for the small volume of the erupted pyroclastic material and for the small magnitude of the 1986 eruption. The stratification of volatiles in the magma column turned out to be abnormal: the upper part of the column was lower in gas than the underlying magma batch (zones 1 and 2 in Figure 9). Further degassing led to the expansion of zone 2, largely downward, and to the increase of gas pressure in it. In spite of a high degree of crystallization and low gas content, the magma of zone 1 was still plastic and prone to viscous flow except for the uppermost portion. Eruption began when the gas pressure in zone 2 surpassed the yield point, the weight of the magma above, and the resistance of the plug in the vent. According to the model proposed, the lava flow was derived from the still plastic magma of zone 1 and issued immediately after the plug had been expelled on account of gas pressure in zone 2.

The unusually deep localization of the zone of maximum gas concentration in the magma conduit and the existence of a poorly permeable gas-depleted magma portion above it were the factors responsible for a specific behavior of the eruption which was characterized by the following features.

1. The stage of ash explosions which usually follows lava extrusion in the crater was missing.
2. The eruption of pyroclastic flows did not precede but occurred in the course of lava extrusion.
3. The pyroclastic flows were discharged not from the summit crater but from a fissure on the slope of the dome. This was promoted by the pre-existence of a large fault in the dome body and by a thick portion of not very plastic magma standing in the conduit above. The natural outcome of this situation was a large lava flow volume and a low ratio between the pyroclastic material and the lava.
4. The lava flow was extruded within a very short time and the rate of its motion was greatest when the pyroclastic flows were discharged. The climactic stage of the eruption occurred when gas-saturated magma broke through to the surface by squeezing out the magma plug like a piston and producing a viscous lava flow.

To conclude, the specific character of the eruption can be explained by the development of conditions that favored the maximum concentration of gases not in the "head" of the magma column but in its "body" somewhat below. It is still not clear whether the eruption was preceded by a slow rise of the magma in the conduit with a gradual redistribution of gases in it or it was caused by a rapid ascent of a new small portion of gas-rich magma from a crustal chamber. Proceeding from the results of our study of the chemical composition and petrography of the pyroclastic material and lava flow, we believe that the first alternative is more realistic.

APPENDIX: QUANTITATIVE ESTIMATES

Extent, volume, and mass. The lava flow area has been roughly estimated to be 0.3×10^6 m^2. By analogy with the previous lava flows of 1977-1980 [13], we assumed its average thickness to be 10 m. The volume of lava then comes to 3×10^6 m^3 and its mass 6 million tons assuming its density to be 2 g/cm^3. The area covered by the pyroclastic flows has been estimated to be ~ 0.25 km^2. Taking the average thickness to be 3 m, this gives a volume of ~ 0.75×10^6 m^3 or 1.1-1.3 million tons using natural density values. As the mass estimates have been based on the values obtained for the matrix of the pyroclastic flows, the maximum value seems to be more realistic. So the estimates of the total volume and mass of the erupted material are 3.75×10^6 m^3 and 7.3×10^6 tons.

It is more difficult to compute the volumes of the pyroclastic flows separately, because they overlap in many places. As the vesicular andesitic flow is half as large as the block and ash flow, we took their volumes to be 0.25 and 0.5 million m^3 and their weights to be 0.4 and 0.9 million tons, respectively.

The total area covered by the pyroclastic material has been estimated from the particle-size data and the mass estimates of the pyroclastic deposits. The resulting value was ~ 1.5×10^{16} m^2.

Rate of discharge. The rate of discharge of pyroclastic material can be estimated from the duration of its discharge which is approximately equal to the duration of the seismic signal. Using this approach, we got ~ 4×10^3 m^3/s or 7.5×10^3 ton/s for the first flow and ~ 2×10^3 m^3/s or 3.3×10^3 ton/s for the second flow, the average rate of discharge being 5.4×10^3 ton/s. This value is one or two orders of magnitude lower than those obtained for the catastrophic eruptions of similar volcanoes [4].

Heat and mechanical energy. Magma begins to expend energy due to expansion (frothing) as soon as it starts to give off gases and continues to do so until the eruption breaks out and possibly in the course of the motion of pyroclastic material on the surface. To estimate the amount of energy expended by expanding magma and gas is a difficult task since magma expansion is a complex process and many of its parameters are indeterminate. The surface of pyroclastic material grows in area due to its fragmentation while the flow is in motion. A rough estimate of the energy expended by the frothing magma has been obtained on the assumption that the expansion of gas bubbles occurs largely near the surface where the melt is substantially degassed and its surface tension σ approaches the surface tension of dry melt (σ=300-400 dyne/cm [11]). Hence the surface energy of the frothed andesite magma at the top of the magma conduit was found to be $n\times10^9$ J using the formula $E = \sigma S$, where S is the surficial area of the pyroclastics (the lava flow was not included in computation).

Seismic and acoustic energies have been computed using the values presented in Table 1 and found to be 1.27×10^9 J and 2.5×10^9 J, respectively.

The generalized coefficient of friction which is the ratio of the vertical component of the pyroclastic flow path to its horizontal component (H/L) is a measure of the mobility of pyroclastic material. It was found to be equal for both flows, 0.29-0.35, depending on the position of the eruptive vent which was unknown. This range of values agrees with the values of small pyroclastic flows [18]. Larger pyroclastic flows which travel at a greater speed show lower values. As the volume of the vesicular andesitic flow was half as large as that of the block and ash flow, its mobility was higher, probably due to its higher gas content.

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