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Eruptions at Bezymyannyi in 1993-1995

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Data on pyroclastic deposits, visual observations, and seismicity were used to reconstruct the sequence of eruptive events at Bezymyannyi in 1993. The eruption consisted of three episodes of block-and-ash pyroclastic flows which traveled for distances of 7, 8, and 5 km, respectively. The eruption column rose to a height of 13 km. The second episode of pyroclastic flows was accompanied by a partial collapse of the dome 0.006 km^3 in volume. A powerful vertical explosion and a lava flow occurred at the end of the eruption. The explosion deposited dense andesite lapilli over an area > 50 km SE of the volcano. The total volume of the erupted material was 0.07 km^3. A brief description is given of the subsequent volcanic activity till September 1995: lava flowed episodically, no significant explosions took place.

Introduction. A volcanic dome (named Novyi) began to grow on Bezymyannyi after a powerful explosive eruption on March 30, 1956, and continues to grow now [5]. During the early period, rigid obelisks were squeezed out continuously; further on, the growth of the dome was discontinuous, and since 1977 viscous lava flows were squeezed out along with rigid blocks [4]. The growth of the dome was accompanied, throughout its history, by weak and medium-size explosive eruptions with fine ash ejections and by the deposition of small block-and-ash pyroclastic flows and the associated ash-cloud surges. Most of the pyroclastic flows were deposited between two SE-trending spurs of the dome known as the Northern and Southern Ridges. Eruptions were as frequent as one or two per year. Some of the explosive eruptions were fairly large: pyroclastic flows traveled as far as > 7 km beyond the ends of the Northern and Southern Ridges. The largest eruptions occurred in 1977 (pyroclastic flow traveled 7.5 km [7]), in 1979 (flow covered a distance of 7.6 km [7]) and in 1985 {pyroclastic material flowed as far as 12.5 km [6]). The flows erupted before 1984 did not produce any notable digging effects on the slopes, whereas those of 1984 and 1985 eruptions cut a trench on the dome's slope, which was used as the main channel by the subsequent flows during several years.

Large older portions of the dome began to crumble and fall as debris avalanches concurrently with the intensification of the digging effect of new pyroclastic flows. The largest avalanche took place during the eruption of 1985 [1], [6]. By 1989 the morphology of the dome had been modified greatly as a result of the eruption of numerous lava flows. This shifted southward the main path of pyroclastic flows, and a new trench, parallel to the eastern one, was dug. The old trench began to be filled gradually with a debris material (pyroclastic-flow deposits and colluvium from the slopes of the dome).

After the relatively large eruption of 1985, merely weak explosive-effusive events occurred producing shorter than 6-km pyroclastic flows. The last eruption that was recorded before 1993 took place in March 1992 [3]. It consisted of a few weak explosions which were followed by a short-term lava flow. The aim of this paper is to reconstruct the character and sequence of events relative to a comparatively large explosive-effusive eruption that occurred at Bezymyannyi in October 1993 and to describe briefly its subsequent activity up to September 1995.

Chronology of eruptive events was based on the evidence of visual observations, a space-mission picture, courtesy of American colleagues, and seismic data from the Podkova Station located 25 km NE of the crater (Fig. 1).

The first eruptive cloud was noted above the Bezymyannyi area at - 4 p.m. (hereinafter local time) on October 21, 1993. At 11 p.m. fine ash fall began and lasted 6 hours in Nikolskoe Village (Komandorskie Is, bearing N 97° E from Bezymyannyi, distance 515 km). On October 23 visual observations were forestalled because of bad weather. A picture returned from a meteorological orbiter on 3:25 p.m. showed distinct three cloud trails (Fig. 1). Two of them (I with azimuth 100° and II with azimuth 150° from the crater) stretched over distances of > 300 km. Cloud I was decayed and its density suggested its earlier origin with respect to the other two clouds which originated as a result of individual eruptive events. Cloud III (azimuth 170°, extension - 100 km) was shorter than I and II and judging by its high density was the last to form.

Generally the propagation of eruptive clouds depends on the temperature and wind stratification of the atmosphere. The state of the atmosphere during the eruption was studied using the results of upper-air sounding which is done at the Klyuchi weather station two times a day (11:30 a.m. and 11:30 p.m.). Figure 2 shows the temperature stratification and the wind direction and velocity for October 21 (11:30 a.m.) and 22 (11:30 p.m.). In the morning of October 21 the wind had the same directional all heights (azimuth 280°). This direction was coincident with a direction from Bezymyannyi to Nikolskoe Village. On the assumption of the horizontal homogeneity of the atmosphere, the speed of the eruption cloud motion must have been 20 m/s to reach Nikolskoe in 7 hours. One can see in Fig. 2, *c* that the wind had this velocity at heights 5 and 13 km. We believe that the eruption cloud rose to a height of 13 km because according to visual

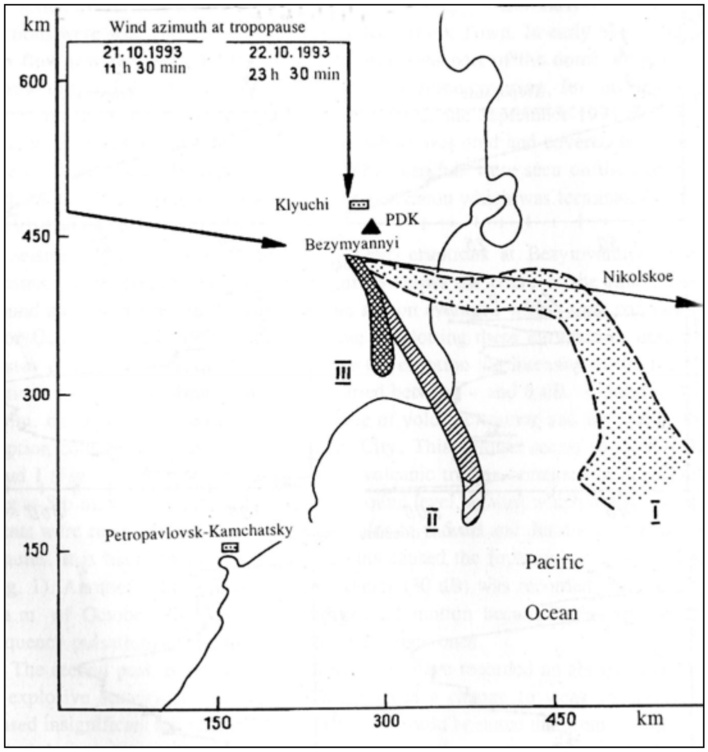

Figure 1 Sketch of eastern Kamchatka and adjacent Pacific area showing the distribution of eruption clouds during the 1993 eruption of Bezymyannyi based on a picture returned from a meteorological satellite at 3:25 p.m. on October 22. I—III - eruption cloud propagations. PDK -Podkova seismic station.

observations its height was not less than 8 km. The change of the western to the southern direction of the cloud was compatible with the change of the wind direction at the tropopause height. Assuming the wind velocity to be 20 m/s, the periods of the cloud developments can be evaluated as follows: > 5 hours for cloud I (its end was decayed), > 3.5 hours for cloud II, and 1.5 hours for cloud III.

On October 23-24 ash ejections were seen from the weather monitoring site located at the Khapitsa River (30 km east of the volcano): ash-loaded column broke through the

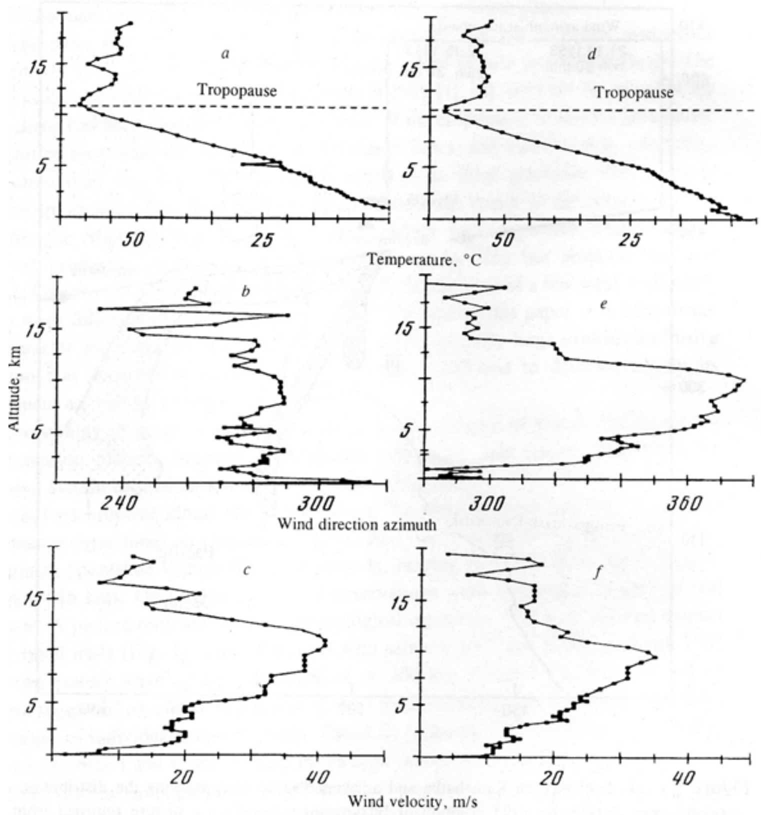

Figure 2 Atmospheric state from upper-air sounding at the Klyuchi meteostation at 11:30 a.m. on October 21, 1993 *(a-c)* and at 11:30 p.m. on October 22 *(d-f).*

clouds that masked the cone and rose to heights of 8-12 km. During the four days that followed the weather was too bad to see anything, but the eruption was known to be under way because mild ash falls occurred in Klyuchi City on October 28 and 29. Weak explosive activity continued and terminated in mid-November. A visit to the volcano on November 12 revealed that the SE part of the dome had been partially destroyed and a viscous lava flow was slowly squeezed out at its summit. There was no data for the period that followed until August-October 1994. In late August and early October mild ash ejections were seen above the volcano from Kozyrevsk Town. In early September a new lava flow was recorded. Its lava filled the destroyed part of the dome and moved as a narrow tongue for a distance of 700 m down the slope covering, for the first time, the debris mantle of the dome. In late September 1995, the September 1994 lava flow was covered by a new broad undated lava flow, which was cold and covered by snow at the time of observation. On September 21 small avalanches were seen on the upper portion of the dome. They were indicative of new reactivation which was terminated in October 1995 by an explosive eruption.

Seismic signals that accompanied volcanic eruptions at Bezymyannyi reflect the dynamics of its eruptive activity [9]. Figure 3 shows the curve of the rms variation of ground motion rate at the Podkova seismic station averaged with a time constant of 900 s for October 21-24, 1993. The technique of plotting these curves was described by Firstov *et at.* [10]. One can see that before the eruption the intensity of the rms ground motion rate (ground vibration intensity) varied between 4 and 8 dB. A jump to 35 dB at 4 p.m. on October 21 records the beginning of volcanic tremor and the rise of the first eruption column that was seen in Klyuchi City. This column seems to have drifted as cloud I (Fig. 1). With some variations the volcanic tremor remained to be intensive as long as 8 p.m. when it declined to the background level, against which individual eruptive events were recorded as peaks with magnitudes of 4-5 dB and durations of a few tens of minutes. It is likely that these eruptive events caused the formation of clouds II and III (Fig. 1). Another high peak of volcanic tremor (30 dB) was recorded from midnight to 3 a.m. of October 23. Thereafter the ground motion became pulsatory, with high-frequency pulsations overlapping the low-frequency ones.

The second peak of volcanic tremor seems to have recorded an abrupt intensification of explosive activity and the later signal marked a change to weak explosions which caused insignificant ash falls in Klyuchi City. It should be noted that tremor surges as long and violent as that, indicative of an abrupt rise in the rate of pyroclastic discharge from the vent, had never been observed at Bezymyannyi before.

Pyroclastic deposits. The pyroclastic material deposited during the eruption can be classified into three main types: block-and-ash flows, ash-cloud surge deposits, and tephra.

The juvenile material of the pyroclastics is represented mainly by greenish gray, perfectly crystallized vesicular andesite. Its color inside the large blocks varies from greenish dark gray to almost black indicative of a long cooling period. The juvenile material of the pyroclastic flows and surges occurs as particles of an irregular "lumpy" form, where the crystals are enclosed in thin jackets of transparent glass and welded with one another merely in a few points. The glass and dark-colored minerals have a fresh unoxidized habit with numerous communicating interstices between the crystals. Part of the juvenile material is represented by a porous variety occurring as angular block-shaped particles.

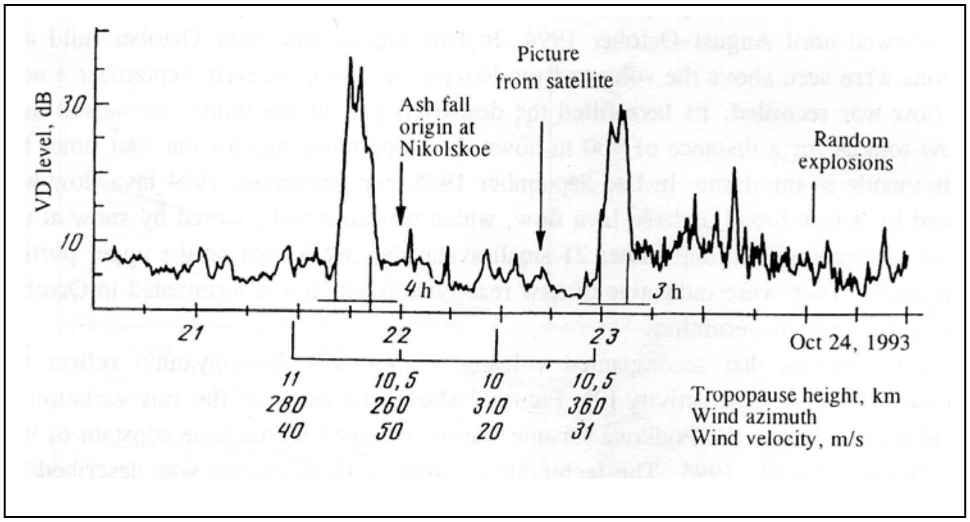

Figure 3 Root-mean-square ground motion velocity (vertical component) measured at Podkova seismic station on October 21-24, 1993, and averaged using a 900-second time constant. VD denotes volcanic tremor.

The resurgent material is usually more compact, mainly crimson-colored because of numerous oxidized dark-colored minerals.

Pyroclastic flows and surges. The pyroclastic flow deposits of this eruption consist of varying-density andesite fragments as large as 1-2 m (max. 5-7 m) and a fine-grained matrix. They can be classified as block-and-ash flows [11]. They range between 1 and 10 m in thickness and between 10 and 100 m in width. The Inman sorting coefficient is 1.7-3.2 phi, the median diameter ranging between 1.1 and 2.1 phi. At the foot of the dome, at a distance of 2-3 km from it, we found several small gravel-sand flows with thickness of a few tens of centimeters, a median diameter of 1.1 phi and a sorting coefficient of 2.6 phi. These deposits seem to have been produced by the gravitational sorting of the material of block-and-ash flows as they moved down the trenches on the slope of the dome. Generally, where the volume of a pyroclastic flow is larger than the volume of the trench, only the lower, more compact and coarser material of the flow is transported, while the upper finer material is splashed out of the trench, moves independently, and is deposited as a material transitional to ash-cloud surge deposits.

The pyroclastic flow and surge deposits occur at the eastern foot of the volcano as a field consisting of three tongues: (1) the northern tongue covered a distance of 2 km and is 0.25 km^2 in area and 0.002 km^3 in volume, (2) the central tongue traveled for 8 km and is 3.5 km^2 in area and 0.01 km^3 in volume, and (3) the southern tongue covered a distance of 4 km and is 0.75 km^2 in area and 0.008 km^3 in volume (Fig. 4). The total volume of the flows has been evaluated as 0.002 km^3. The erupted pyroclastic material separated into three tongues as it flowed down the slope. The northern tongue consists of the pyroclastic material that moved along an old trench. The material of the central and southern tongues initially moved as one flow and then separated into two tongues as it ran into the Southern Range. Each of these tongues consists of several portions of pyroclastic material that were deposited successively one upon another and differ in lithology.

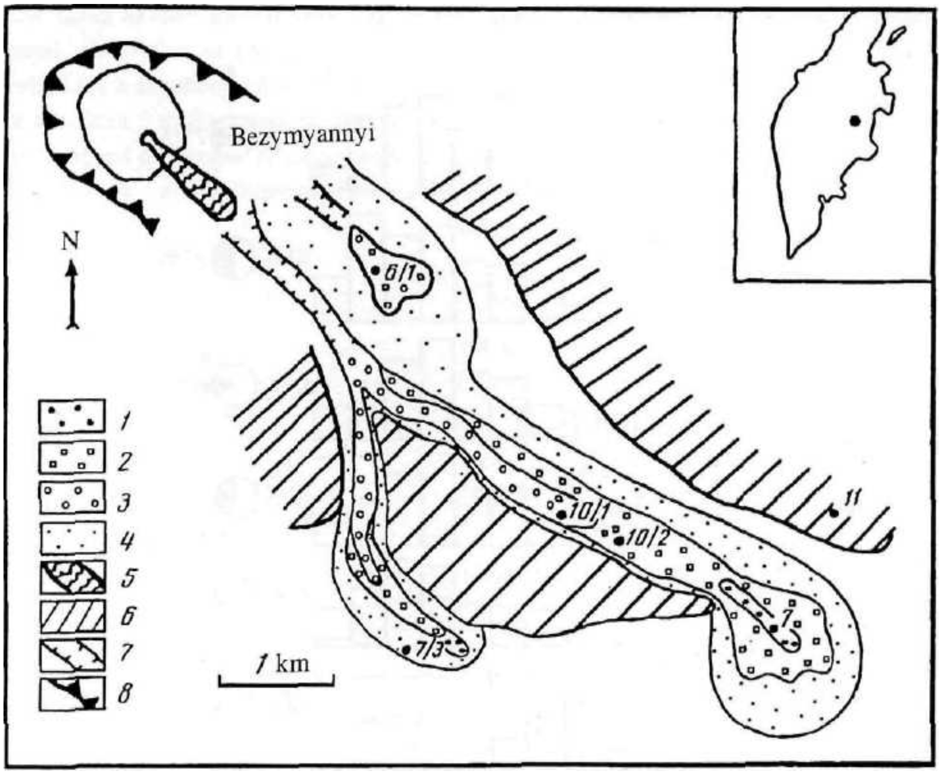

Figure 4 Distribution of erupted products in October 1993:*1-3* - pyroclastic flow deposits of the first, second, and third portions, respectively; *4* - undifferentiated ground surge deposits; 5 - lava flow of 1994; *6* - volcanic dome spurs (ridges); *7* - trenches worked by block-and-ash flows; *8* -crest of the 1956 crater. Solid circles and numbers denote sample sites.

Each portion of the material was deposited as a result of a certain explosive event. Fine ash layers that separate one portion from another suggest that they were deposited with intermissions of a few hours to a few days. The most prominent are three portions of pyroclastic material. Because they are best defined in the central tongue we will describe them below using its example.

The first portion is dominated by a juvenile material and has a common gray color. Counting under binocular microscope revealed that 79% of the particles of the size fraction 1-0.63 mm consisted of a juvenile material (Fig. 5). The particle-size histogram shown in Fig. 5 has only one maximum 1-2 phi (0.5-0.25 mm). The Inman sorting coefficient is 2-4.6 phi (Fig. 6). Large fragments from the surface of the flow are less than 1 m across and consist of juvenile andesite as well. The pyroclastic flows of the first portion had steep frontal and lateral sides and were very thick (max. 10 m). This material was deposited as a central narrow tongue 7 km long.

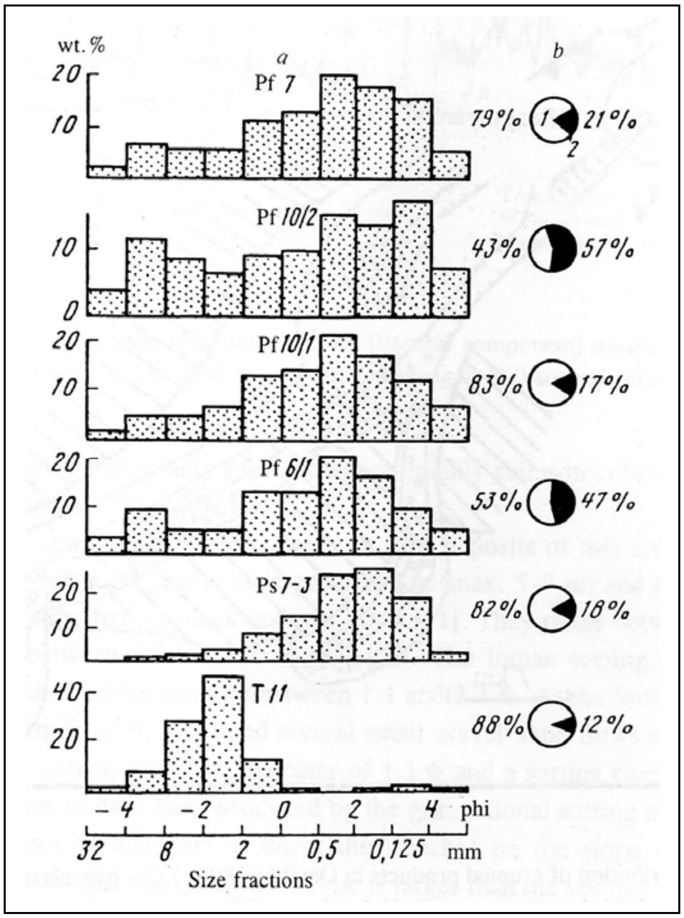

Figure 5 Histograms of particle-size distribution *(a)* and circular diagrams *(b)* for the percentage of juvenile (1) and resurgent (2) materials in the pyroclastic deposits of the 1993 eruption. Samples Pf 7, Pf 10/2, and Pf 10/1 are the pyroclastic flow deposits of portions 1, 2, and 3, respectively; Sample Pf 6/1 - undifferentiated portion 1 and 3 deposits of pyroclastic flows that moved along the old trench; Sample Ps 7/3 - ground surge deposits associated with portion 1 pyroclastic flows; T11 - coarse tephra ejected by explosion at the closing phase of the eruption. See Fig. 4 for the location of sample sites.

The second portion of pyroclastic flows contained a lower percentage of a juvenile material (43%) in the size fraction 1-0.63 mm. Because of a significant content of oxidized resurgent material (57%), the deposits have a characteristic crimson color. It is possible that the larger content of a resurgent material explains the polymodal particle-size distribution of this material and its poor sorting (sorting coefficient 3.2 phi) (Fig. 6). There are many large blocks (5-7 m) of relatively dense, often oxidized resurgent andesite on the surface of these flows. Some of them were found to consist of the poorly cemented material of the dome's debris mantle. This material had been plowed up and entrapped by the flows as they moved down the slope. In spite of the high content of a resurgent material, the flows of the second portion moved faster than those of the first: they travelled for a distance of 8 km filling all topographic depressions they encountered. They were less than 2 m thick and < 300 m wide. They had gently sloping frontal and lateral sides. A speed difference resulted in the fact that in the central tongue the deposits of the first portion rise above those of the second.

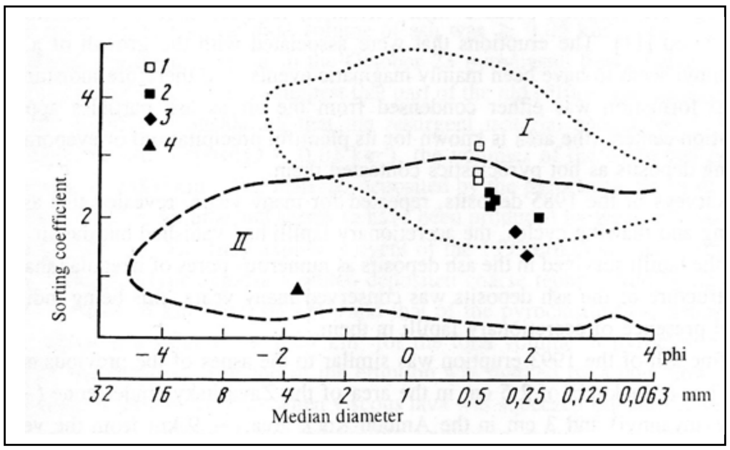

Figure 6 Relations between sorting coefficient and median diameter for the deposits of the 1993 eruption: 1 - block-and-ash flows of portion 1, 2 - block-and-ash flows of portions 2 and *3*, *3* - ground surges, *4* - coarse tephra. I - pyroclastic flow region, II - tephra area [12].

The material of the third-portion pyroclastic flows approximates the material of the first. The juvenile material accounts for > 80% of the size fraction 1-0.63 mm. The sorting coefficient is 2.2 phi. The maximum length of the flows is ~5 km.

The complex structure and high thickness variation of the flows precluded the exact evaluation of their volumes. The volumes of the first, second, and third portions were estimated roughly as 0.007, 0.01, and 0.003 km^3, respectively. Taking into account the content of the resurgent material, the total volume of the 1993 pyroclastic flows was ~ 0.013 km^3.

The pyroclastic surges of this eruption produced minor deposits. They occur as thin (< 10 cm) mantles of a relatively well sorted gravel-sand material (sorting coefficient 2.1

phi, median diameter 1.8 phi deposited only in the immediate vicinity of the pyroclastic flows. Based on their distribution, mode of occurrence, and particle size, they were classified as ash cloud surge deposits.

Tephra material is represented by two varieties: fine ash and lapilli. Fine ash is a typical material which is known to have accompanied the growth of the Novyi dome. This material fell out of ash clouds that rose above the pyroclastic flows during their movement and also was deposited from ash clouds produced by explosions on the dome. Ash interlayers produced by individual eruptions usually have a maximum thickness around the pyroclastic flow deposits and near the dome, its values ranging between 5 and 10 cm. They often contain accretionary lapilli — concentrically layered pellets of fine ash, sometimes as large as 10 cm across. Some ash layers, e.g. those of the 1985 eruption, consist wholly of accretionary lapilli. These lapilli are often interpreted as evidence of a phreatomagmatic eruption because their formation requires excessive moisture in the eruption cloud [11]. The eruptions that were associated with the growth of a dome at Bezymyannyi seem to have been mainly magmatic events, and therefore moisture needed for lapilli formation was either condensed from the air as ash particles appeared as condensation centers (the area is known for its plentiful precipitation) or evaporated from underlying deposits as hot pyroclastics contacted them.

The surveys of the 1985 deposits, repeated for many years, revealed that as a result of freezing and thawing cycles, the accretionary lapilli had vanished but the air secluded between the lapilli survived in the ash deposits as numerous pores of irregular shapes. The porous structure of the ash deposits was conserved many years, this being indicative of the initial presence of accretionary lapilli in them.

The fine ash of the 1993 eruption was similar to the ashes of the previous eruptions. This ash has a thickness of 2.5 cm in the area of the Zavaritsky cinder cone (~12 km from Bezymyannyi) and 3 cm in the Ambon Rock area (~ 9 km from the vent). The presence of small pores in the ash suggests that it contained accretionary lapilli at the time of its deposition. The maximum thickness of this ash is ~ 10 cm at the foot of the dome, where it contains accretionary lapilli, some of which are as large as 5 mm.

A distinctive feature of the 1993 eruption was the deposition of coarse tephra lapilli which covered all previous deposits of this eruption. At the time of our survey this layer was notably redeposited, its initial thickness remained unknown. The NE limit of its distribution was in the area of the Ambon Rock, where its material survived as isolated spots of gray coarse-grained sand on the surface of fine ash. In the area of the Nizhnii volcanologists' camp located 7 km from the volcano (Site 11 in Fig. 4) this material was represented by a gravel layer 1-2 cm thick (Figs 5 and 6). In the area of a triangulation station on the Northern Range (4 km from the volcano) there were single fragments, up to 4 cm across, of gray relatively dense juvenile andesite. The area of the eastern foot covered by lapilli was ~ 50 km^2. Microscopic examination of a coarse tephra specimen from Site 11 showed that 88% of the particles were of juvenile andesite similar to the material of the pyroclastic flows (Fig. 5). Distinctive features of the juvenile tephra material are the high degree of its crystallization and the high packing density of its particles. Most of the fragments (70%) have an angular block-shaped form. This suggests that the magma had almost solidified before it was involved in explosions.

Sequence of eruptive events. As mentioned above, two peaks of tremor activity were recorded during the 1993 eruption, when tremor was as high as 30 dB. This indicates a significant rate of pyroclastic discharge from the crater. These peaks can be correlated with two events when the first and second portions of pyroclastic flows were erupted: at 4-8 p.m. on October 21 and at midnight to 3 a.m. on October 23. The likely height of the eruption column on October 21 was ~ 13 km. In accordance with Fedotov's nomogram [8], the rate of ash discharge for an eruption column 10 km high must be 5 x 10^3 tonnes/s. The seismic data suggest that this event lasted ~3.5 hours. This means that the volume of the ejected ash was 0.04 km^3. Less ash was ejected on October 23. Using the lower estimates, the total volume of ash was > 0.05 km^3. The large content of an oxidized resurgent material in the October 23 pyroclastic flows and a significant change of the dome's morphology suggest that part of the old edifice was destroyed at that stage of the eruption. Considering that the resurgent material constituted 57% of the October 23 pyroclastic deposits (~ 0.01 km^3), the volumes of the destroyed portion of the dome was ~ 0.006 km^3. The material deposited by the pyroclastic flows of the third (last) event is small in volume and seems to have been produced by weak explosions after 3 a.m. of October 23. The final explosive event of the 1993 eruption was a rather large, obviously Vulcanian-type explosion which deposited coarse tephra. Adding up the total volume of the ejected ash (> 0.05 km^3) and that of the pyroclastic flow deposits (0.02 km^3), we arrive at a value of ~ 0.07 km^3 for the total volume of pyroclastic material produced by the eruption. The end of the eruption was marked by a lava flow.

There were at least two events when viscous lava was squeezed out and flowed during the two years that followed. No perceptible explosive activity was observed. The unusually large lengths of these lava flows indicate that the general trend of a declining lava viscosity, observed throughout of the dome's eruptive history, continued. By September 1995 the lava flows filled the basin produced on the SE slope by the 1993 collapse to the brim. The fact that we did not find any fresh pyroclastic flow during our field work indicates that there had been no perceptible explosive activity from November 1993 to October 1995. Very weak ash clouds that were observed from the Kozyrevsk Town seem to have been related to avalanches on the lava flows which is a usual phenomenon.

Conclusions. 1. A rather large explosive-effusive eruption took place at Bezymyannyi in late October-early November 1993. During the period that followed to September 1995 there were at least two events when viscous lava flows were squeezed out without any notable explosive activity.

2. Collapses of old portions of the dome became usual phenomena during explosive eruptions at Bezymyannyi. The fallen material mixes with the juvenile pyroclastics to form

block-and-ash pyroclastic flows which produce a strong erosive effect on the dome's slopes.

3. Outbreaks of violent and long-lasting volcanic tremor recorded during the explosive eruption of 1993, as well as the large lengths of the subsequent lava flows, seem to confirm a general trend of a slow lava viscosity decline which was observed throughout the history of a dome development at Bezymyannyi.

4. The events of 1993 confirmed the general tendency of the old portions of the dome to collapse during explosive eruptions, which emerged in 1984. The heterogeneous material of debris avalanches mixes with fresh pyroclastic flows, sometimes in a 1:1 proportion, which modifies its outer appearance and particle-size characteristics. The surfaces of these flows show a great number of andesite fragments varying widely in color, porosity, and structure, the andesites that once composed the dome and reflect the long history of its development. Some fragments are as large as 10 m across. Many of them have a relatively low porosity and crimson color, the features common for the material of volcanic domes. The material of the pyroclastic flows is somewhat reddish because of the oxidized resurgent fragments, and the histograms of their particle-size distribution become polymodal and approximate histograms for debris avalanches [2]. These flows have a strong erosive effect on the slope, possibly because of large blocks of dense material carried at the base. As a series of flows travel along the same route, they work out a trench in the underlying rocks. As a result, more resurgent material is added to the deposits of this type. The example of Bezymyannyi shows that block-and-ash flow deposits enriched in resurgent material are common for long-lived, intricately built domes composed of viscous silicic lavas.

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