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Pyroclastic Surge Deposits of Bezymyannyi Volcano

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The 1956 and 1984–1986 eruptions of Bezymyannyi were accompanied by the formation of ground and ash cloud surges. The mega- and microscopic structural and textural features of the resulting deposits are described, as well as their chemical and mineral compositions, particle-size distributions, and physical properties. The patterns of the different varieties of pyroclastic surge deposits specified are a possible index to their recognition and identification elsewhere.

Introduction. Pyroclastic surges are turbulent flows with a low solid phase–gas ratio [8], [11], [12]. Similar to pyroclastic flows, their driving forces are specific magma properties, autoexplosivity, high gas saturation, and high temperature. The speed of pyroclastic surge propagation has been reported to be as high as 100–150 km/h [6], [9], the range depending linearly on the size of the eruption, the composition, gas saturation, and temperature of the pyroclastic material, and some other factors. Pyroclastic surges propagate in a tornadic manner from the vent whatever the topography of the land surface. Instances where they overcame obstacles more than 600 m high have been reported [9]. At the same time, the materials carried by pyroclastic surges do not rise high above the ground because of the attraction by the Earth.

At the present time two main pyroclastic surge varieties are known – ground surge and ash cloud surge. Another variety, base surge, is known to take place during phreatic and phreatomagmatic eruptions; this phenomenon is beyond the context of this paper.

As described by Sparks and Walker [12], the ground surge forms as the marginal parts of the eruption column collapse prior to the formation of the pyroclastic flow resulting from the collapse of the central part of the column. Some volcanologists believe that these surges may also arise during the movement of pyroclastic flows: because of air inflow at the front and sides of the pyroclastic flow, its particles undergo separation and are deposit-

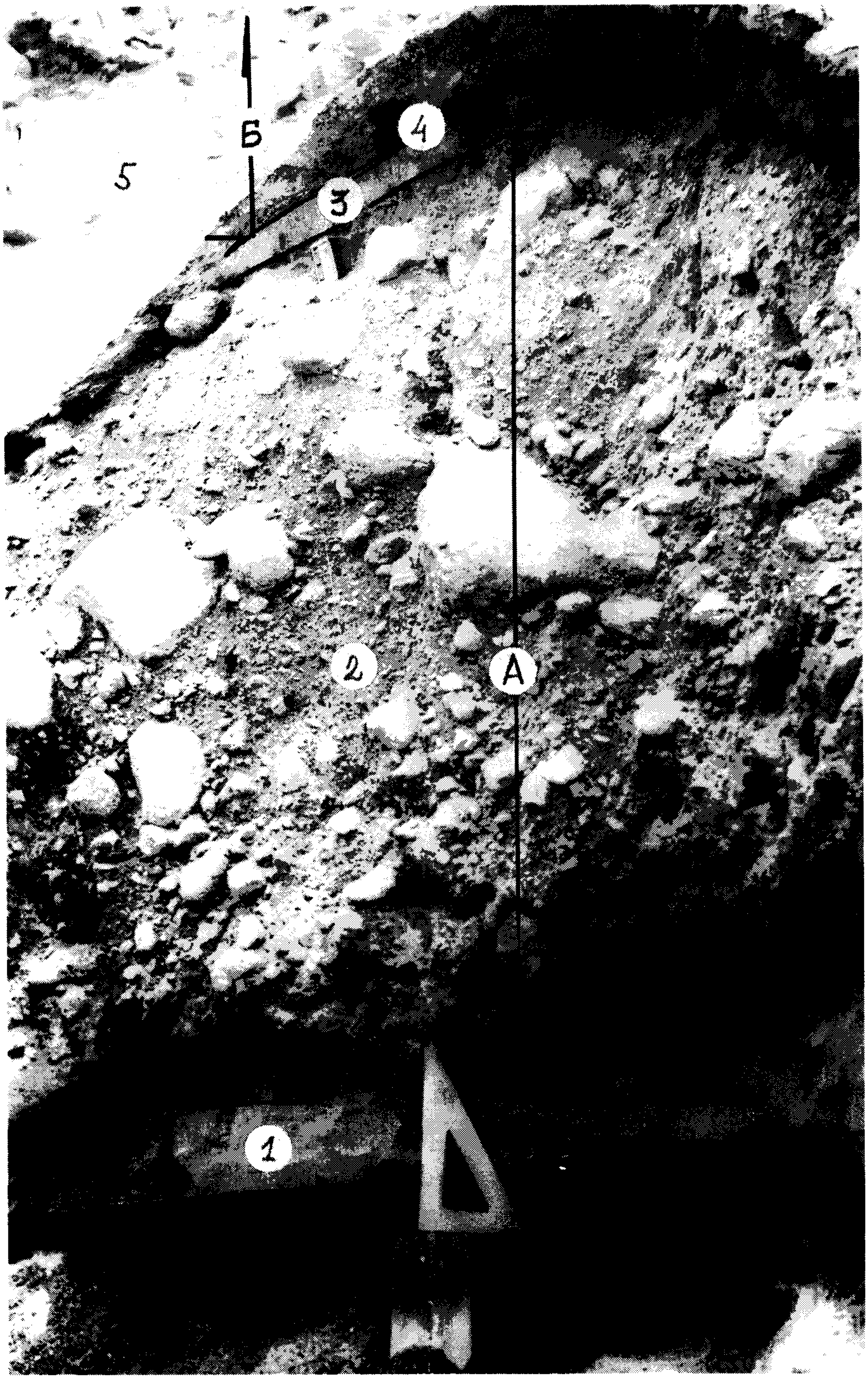

Figure 1 Section across the pyroclastic rocks deposited during the 1985 eruption of Bezymyannyi in the Tundrovyi Creek area 8 km from the volcano: 1 - pyroclastic ground surge deposited by pyroclastic flow A; 2 - ash and block pyroclastic flow A; 3 - ash-cloud surge material deposited by the first portions of pyroclastic flow B; 4 - ash-cloud surge deposit; 5 - vesicular juvenile andesite pyroclastic flow B. Photo by A. Malyshev.

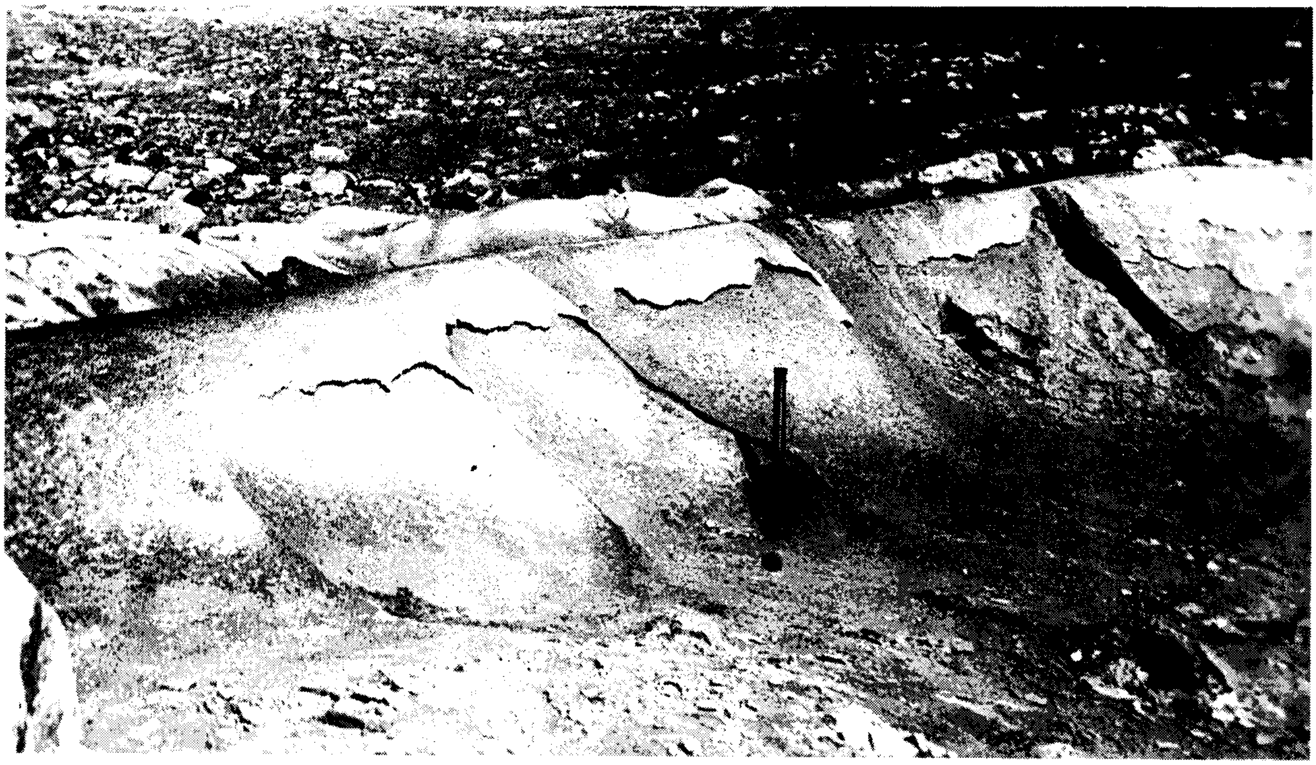

Figure 2 Dune relief produced by the deposition of ash-cloud surge material during the 1985 eruption of Bezymyannyi.

ed as a sand layer at the base of the flow [13], [14]. These two mechanisms explain the fact that the material of the ground surge underlies and borders the material of the pyroclastic flow.

The ash cloud surge (the term introduced by Fisher [9]) forms as a result of the convective gravitational differentiation (layering) of the pyroclastic mass during its movement down the volcanic slope [3], [4], [5], [9]. During the eruption of a pyroclastic flow ash clouds rise above it to a height of several kilometers. A turbulent, low-density, gas-saturated, high-temperature layer forms inside the ash cloud immediately above the pyroclastic flow. Because this layer propagates straight-forwardly at a very high speed, it may lose contact with the body of the flow and move independently of the latter. The material of this layer is deposited by action of gravity as an ash cloud surge deposit. The ash falling by gravity from the upper parts of the ash clouds traveling above the pyroclastic flow produces an ash cloud deposit. Ash cloud surge deposits usually cover the pyroclastic flow deposits as a mantle and can also be found beyond them. Sometimes they occur as dunes or peculiar thin flows deposited alongside or are spattered on the slopes of the valley along which the pyroclastic flow is traveling.

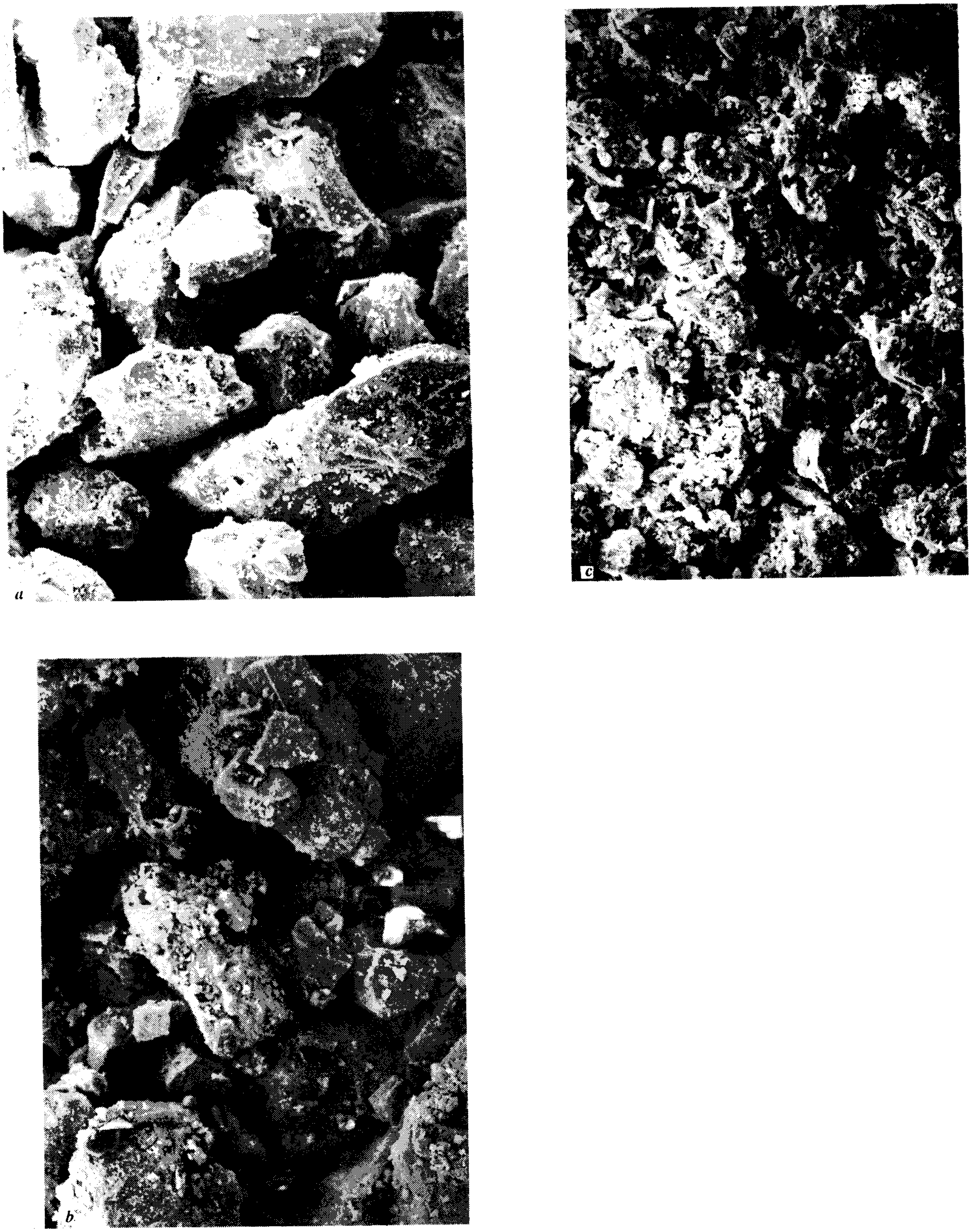

Figure 3 Photomicrographs of the undisturbed samples collected from the pyroclastic surge deposits of the 1985 eruption: *a* – ground surge deposit (Sample 1); *b, c* – ash-cloud surge deposits (Samples 2 and 3, respectively). Magnification 200×.

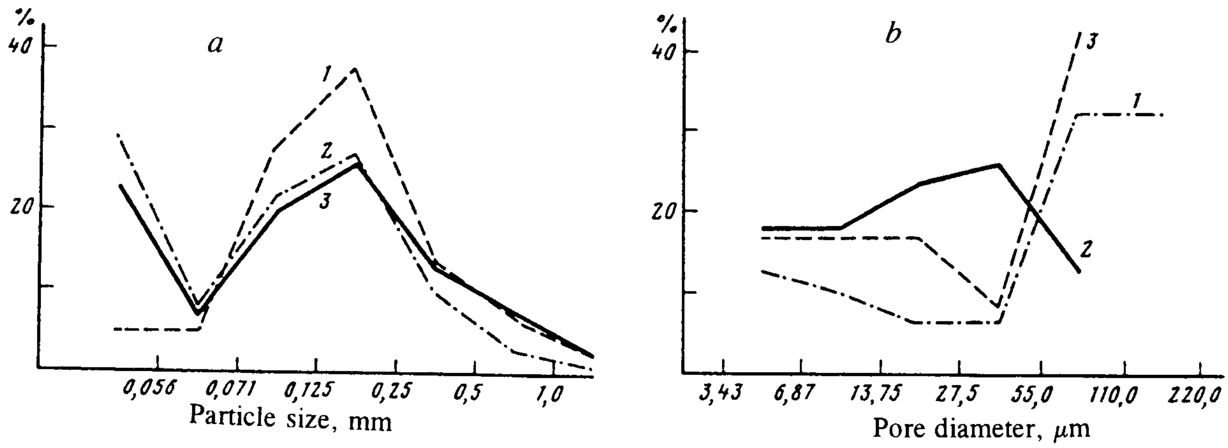

Figure 4 Curves of particle-size (*a*) and pore-diameter (*b*) distribution in undisturbed samples from pyroclastic surge deposits of the 1985 eruption: *1* - ground surge; *2, 3* - ash-cloud surge. The numbers of the curves correspond with the numbers of samples (Fig. 3).

Generally the material of pyroclastic surges is finer and better sorted than the material of pyroclastic flows. Its fragments may be as large as lapilli, their content varying between a few and several dozens of percent.

Pyroclastic surge deposits of Bezymyannyi. Both types of the pyroclastic surge deposits produced by the 1984–1986 eruptions of Bezymyannyi lay under or surrounded the pyroclastic flows as well-sorted layers or occurred on the surface of or alongside them as isolated dunes, dune ridges, or hillocks. Different types of pyroclastic surge deposits were identified more exactly during the study of the 1985 eruption products [1]; they were also located among the products of the 1986, 1984, and 1956 eruptions [2], [3], [7].

Chemical and mineral compositions. Our chemical study of the pyroclastic surge deposits of the eruptions discussed revealed that they were slightly more silicic than the lavas and pyroclastic flow deposits. The SiO_2 content averaged 56.72 wt % in the fragments from the lava and pyroclastic flows (33 analyses), 56.68 wt % in the pyroclastic flow material (16 analyses), and 57.18 wt % in the pyroclastic surge deposits (10 analyses) [4]. The same trend of the surge deposits being more silicic than the flow materials was reported from the 1980 eruption of Mount St. Helens [10].

Similar to the particles of the pyroclastic flow deposits, the particles of the surge material are fragments of mineral crystals, their aggregates, glass, and rocks. According to the analyses of V. Yu. Kiriyanov (Institute of Volcanic Geology and Geochemistry, Petropavlovsk-Kamchatskiy), the pyroclastic surge deposits of the 1985 eruption have the following mineral composition (vol %): glass - 16, plagioclase - 51, mafic minerals - 10, fragments - 13, and pyroxene - 10 [4].

Table 1 Pore space characteristics for undisturbed samples from pyroclastic surge deposits, 200×.

Parameter	*Sample number*		
	1	2	3
Porosity, %			
total	40.8	33.4	37.1
inside aggregates	-	-	16.8
between aggregates	-	-	20.3
Total pore area, μm^2	4828926.60	3953654.05	4387339.07
Total pore perimeter, μm	62994.66	136068.47	87089.20
Number of pores	60	226	104
% of connected pores	25	21.6	19.2
Average pore diameter, μm	24.06	14.03	-
inside aggregates	-	-	9.10
between aggregates	-	-	70.71
Average pore area, μm^2	454.74	154.62	-
inside aggregates	-	-	65.17
between aggregates	-	-	3927.39
Average pore perimeter, μm	96.85	56.43	-
inside aggregates	-	-	37.02
between aggregates	-	-	287.38
Pore shape ratio	0.60	0.61	0.59

Note. Sample 1 – ground surge deposit, Samples 2 and 3 – ash-cloud surge deposits.

The ash cloud surge deposits consist mainly of juvenile material; in addition to the latter, the ground surge deposits contain resurgent ejecta.

Mode of occurrence and fabric. The ground surge deposits are perfectly sorted medium- and coarse-grained sands containing small amounts of fragments ranging between 2 and 20–30 mm in size. They usually occur at the base of the pyroclastic flows and sometimes fringe them. The material deposited during the 1985 eruption had a maximum thickness of 10 cm, that of the 1956 eruption was as thick as 2–3 m [2].

The distinctive features of these deposits are a gently undulating bedding and a gradational contact between them and the pyroclastic flow deposits. The study of numerous samples collected from the ground surge deposits revealed that they contained not more than 10% of fragments larger than 2 mm across [5].

The ash cloud surge deposits, both thick-bedded and massive, are fine- and medium-grained sands with a significant amount of a fine-grained material. They usually occur as patches on the pyroclastic flow deposits and as splashes spattered on the sides of the valleys along which the pyroclastic flows traveled. They have also been found as dunes or dune ridges, small single flows, and fairly extensive mantles.

In some localities, ash cloud surge deposits have been found at the base of the pyroclastic flows. Figure 1 shows a section across a pyroclastic material that was deposit-

Table 2 Grain-size characteristics of the Bezymyannyi pyroclastic surge deposits.

Type of deposit	*Median, mm*	*Average particle size, mm*	*Sorting index*
	1984–1986 eruptions		
Ground surge (26)	0.17 0.12-0.21	0.22 0.13-027	0.16 0.07-0.23
Ash-cloud surge (9)	0.12 0.09-0.15	0.16 0.12-023	0.14 0.09-0.22
	1956 eruption		
Ground surge (2)	0.24 0.24-0.25	0.35 0.34-0.36	0.30 0.29-0.32
Ash-cloud surge (8)	0.12 (5) 0.22 (3)	0.13 (5) 0.32 (3)	0.12 (5) 0.37 (3)

Note. Top – average value; bottom – max–min range. The figures in the parentheses denote the number of samples.

ed during the 1985 eruption. The exposed rocks are (upward): (1) greenish, medium-grained sand lying on alluvium, having a maximum thickness of 10 cm and containing 3–4% of particles with a size ranging between 2 and 25 mm (ground surge deposit); (2) greenish ash and block pyroclastic flow deposit (A), up to 1.2 m thick, having a gradational contact with unit 1; (3) brownish, fine-grained sand, 7–10 cm thick, containing up to 20% of particles not exceeding the size of lapilli (ash cloud surge deposit); (4) brown, fine-grained ash 1 mm thick (airfall deposit from the clouds above the pyroclastic flow); (5) brownish juvenile vesicular andesite pyroclastic flow (B), 3–5 m thick. This sequence is covered by a 2-cm mantle of brown, uniform, fine-grained ash (ash cloud above a pyroclastic flow, provisional layer 6).

During the early study of the pyroclastic materials deposited by the 1985 eruption, it was supposed that layer (3) in Fig. 1 was a ground surge deposit related to pyroclastic flow B [1]. Later I carried out a more detailed study of the pyroclastics from this section and found layer (3) to be the material deposited from an ash cloud that traveled above the head of pyroclastic flow B. The sequence of the events seems to have been as follows: the first portions of pyroclastic flow B started to be erupted simultaneously with the formation of pyroclastic flow A at a distance of 8 km from the vent. The flow B material stopped at 3–5 km from the vent. Because of its high mobility, the flow B ash cloud material traveled farther and was deposited on the material of pyroclastic flow A. The absence of its own ash cloud material on the flow A deposit can be explained by a very short time that elapsed between the formation of the A flow deposit and that of an ash cloud surge. The interval between the deposition of the first and last portions of flow B at the top of the sequence (Fig. 1) was long enough for the ash cloud material of this flow

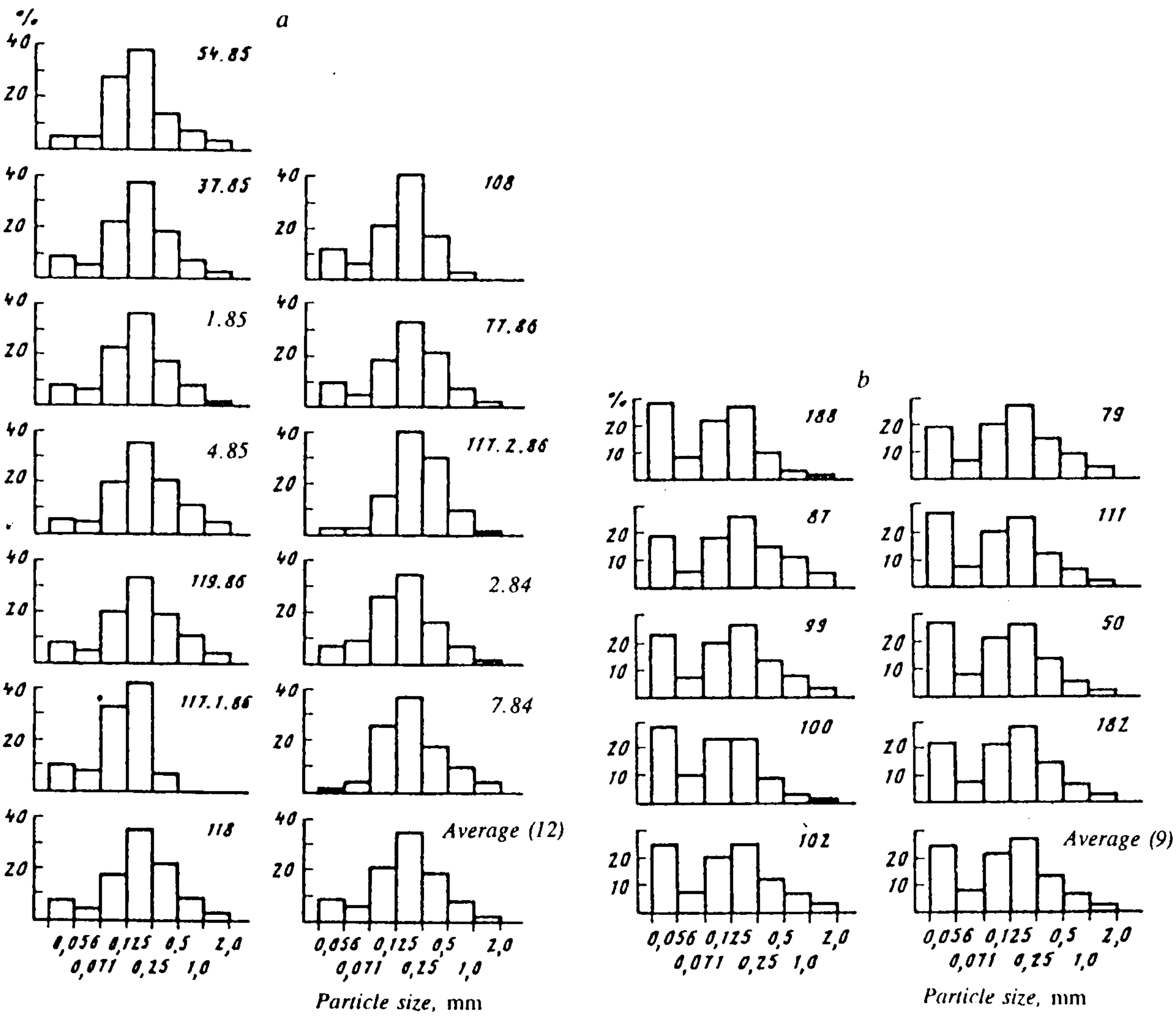

Figure 5 Histograms of particle-size distribution in samples from the pyroclastic surge deposits of the 1984–1986 eruptions: *a* – ground surge deposits, *b* – ash-cloud surge deposits. The figures on the right of the graphs are sample numbers.

(layer 4) to be deposited on top of the flow A ash cloud surge material. The closing eruptive phase deposited a thin ash mantle (ash cloud of the flow, layer 6) which covered all of the previously deposited materials.

A team of volcanologists (A. Malyshev, I. Kondrashov, and the author) discovered a unique formation in the deposits of the 1985 eruption at a distance of 5.5 km from the volcano – dune ridges made up of an ash cloud surge material (Fig. 2). Two lines of evidence documented the formation of the dunes during the 1985 eruption: (1) the dunes were not observed among the materials deposited by the 1984 eruption, and (2) the material of the dunes was fresh and still warm several weaks after the climactic phase of the 1985 eruption. A massif of dune ridges, up to 0.8 m high, up to 10 m wide, and 38 m long, was deposited on the side of a small rampart, facing the volcano, the dunes gently

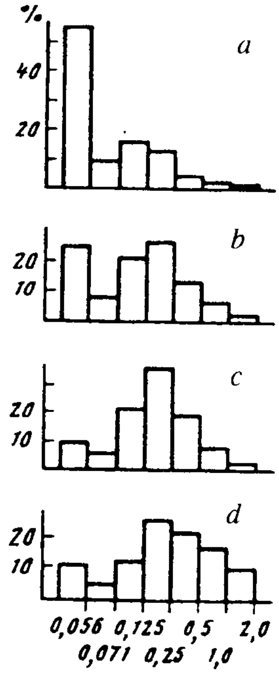

Figure 6 Particle-size distribution in the pyroclastic deposits of the 1984–1986 eruptions: *a* – airfall deposit from ash clouds above pyroclastic flows, *b* – ash-cloud surge deposit, *c* – ground surge deposit, *d* – pyroclastic flow.

dipping into a creek. The dunes have a concave form on the side opposite to the source of the material. The outer extent of the dune chain is limited by a block 2×1 m in size. A small (15-meter long) ash-sand flow consisting of the same material as the dunes is spread over the slope beyond the block. Similar dunes of a less distinct topographic expression were observed on the right-hand side of a canyon 3 km from the volcano after the June 1986 eruption [7].

The thickness of the ash cloud surge deposits was 1–2 m during the 1984–1986 eruptions and 3–5 m during the 1956 event [1], [2], [3], [4], [7].

The ash cloud surge deposits are usually covered by a thin mantle of ash deposited from the ash clouds that traveled above the pyroclastic flows. The thickness of the ash mantle ranges between a few millimeters, where the ash was deposited after some portions of the pyroclastic flows stopped, and a few to several tens of centimeters, where the ash was deposited after the end of a climactic eruptive phase.

The microstructure of the Bezymyannyi pyroclastics was studied using a scanning electron microscope at the Geological Department of the Lomonosov State University, Moscow.

The material of the pyroclastic surge deposits was found to consist of the same particles as the material of the pyroclastic flows. Along with the dominant angular particles, there are subrounded particles – aggregates of mineral crystals enclosed in peculiar glass jackets showing different erosion grades. The surface of the particles shows

Table 3 Physical and mechanical properties of the pyroclastic surge materials deposited during the 1984–1986 eruptions.

Parameter	*Deposits*		*Total*
	surge ground	*ash-cloud surge*	
Density, g/cm³	1.53(55) 1.30-1.64	1.41(10) 1.30-1.67	1.48(90) 1.30-1.67
Solid phase density, g/cm³	2.69(16) 2.56-2.75	2.70(6) 2.69-2.71	2.70(22) 2.56-2.75
Porosity factor	0.76(55) 0.56-0.92	0.92(10) 0.62-1.08	0.83(90) 0.56-1.08
Porosity, %	43(55) 36-52	49(10) 38-52	45(90) 36-52
Cohesion, MPa	0(7)	0.04(2) 0-0.08	0.01(9) 0-0.08
Angle of internal friction, deg.	42(7) 24-58	41(2) 30-52	42(9) 24-58
Modulus of total deformation, MPa	6.0(8) 2.5-15.6	5.3(3) 3.8-8.1	5.6(11) 2.5-15.6

Note. Top - average value; bottom - max–min range. The figures in the parentheses denote the number of samples.

indentations, cracks, shearing traces, striations, honeycomb structures, holes filled with minute particles, etc. Almost all of the particles are "contaminated" with fine fragments of plagioclase and glass.

To investigate the undisturbed structure of the pyroclastic surge deposits, we collected and paraffinized monolithic samples from two types of deposits: (1) the ground surge material from a reference section at the Tundrovyi Creek and (2) the dunes at 8 and 5.5 km from the volcano (Figs. 1 and 2, respectively). The fresh fractures of the samples were examined under the electron microscope; examples of the photomicrographs are presented in Fig. 3. Small magnifications were used to examine the general distribution patterns of structural elements; large magnifications, to investigate the fine details of the microstructure such as the size and form of the particles, pores, and the like. Magnification 200× was used to evaluate the size of the pore space.

Sample 1 was collected from layer 1 of the reference section of the pyroclastic material deposited during the 1985 eruption (Fig. 1), Sample 2 from layer 3 of the same section, Sample 3 from the dunes of Fig. 2: brownish medium- and fine-grained sand, 42 cm thick, containing 20–25% of fine andesite fragments. The photomicrographs of Samples 1, 2, and 3 are presented in Fig. 3 *a, b* and *c*, respectively.

The chemical compositions of the materials of all three samples are almost identical. The particle-size distribution of Sample 1 is different from those of Samples 2 and 3, which are very similar (Fig. 4, *a*).

The microstructure of the ground surge deposit is different from that of the ash cloud surge deposit. Although all three samples showed a skeleton structure, the skeleton pattern is more pronounced in the sample of the ground surge deposit (Fig. 3).

The particles are equant, sometimes elongated, monolithic, and generally comparable in size. Sample 2 showed abundant small grains which in some spots covered almost completely the large particles. The particle size ranges between fractions of a micron and 25×45, 85×95, 125×206, 130×380 μm, etc.

Various physical or physicochemical links exist between the particles: electrostatic coupling, ionic electrostatic coupling, molecular attraction, magnetic coupling, and capillary attraction. The particles of Sample 2 seem to be held together by mechanical linkage. The contacts between the particles are transient: they exist when the ash is dry (as evidenced by the microscopic study of the undisturbed samples) and vanish in the wet state.

The results of the quantitative evaluation of the pore space at magnification $200\times$ are presented in Fig. 4, *b* and Table 1.

The study of the microstructure of the undisturbed samples revealed that the ground surge deposits were more porous than the ash cloud surge deposits (40.8 and 33.4–37.1%, respectively), but had a smaller number of pores (60 and 104–226, respectively). This can be explained by the fact that the ash cloud surge material contained a greater amount of very fine particles (up to 35%), and also by the fact that the particles of this material coalesced to form aggregates, so that in addition to the general porosity, new types of pores appeared: the pores between the particles in aggregates and the pores between the aggregates.

Although the number of pores in the ground surge deposits was comparatively smaller, the average values of the diameters, areas, and perimeters of their pores were larger than those of the ash cloud surge deposits.

The comparison between the quantitative analysis of the pore space of the samples and their particle-size distributions revealed that the more dispersed material had a larger and the coarser material a smaller number of pores. The number of pores deceased, and the general porosity increased with the increasing size of the pores.

Particle-size distribution. The ground surge material deposited during the 1984–1986 eruptions can be classified as fine-grained sand (particles with a < 2-mm diameter). These deposits contain ≤ 10% of fragments larger than 2 mm. A remarkable feature of the material is a modal-diameter particle-size distribution – the great predominance of particles ranging between 0.125 and 0.25 mm across, up to 30–42% (Fig. 5, *a*). It is significant that the same particle size predominates in the material of the pyroclastic flows (Fig. 6) [5]. The median diameters range between 0.12 and 0.21 mm and average 0.17 mm, the average particle size being 0.13–0.27 and 0.22 mm, respectively (Table 2).

The material of the ash cloud surge deposits is dust sand with a 25–30% content of lapilli [5]. This material is characterized by a bimodal particle-size distribution – the dominant particles are < 0.056 and 0.071–0.25 mm across (Fig. 5, *b*) (the sizes similar to those of the pyroclastic flows) and also very fine particles, common for the material deposited from ash clouds that form above pyroclastic flows (Fig. 6) [5]. The median diameters vary from 0.09 to 0.15 mm and average 0.12 mm; the average particle sizes range between 0.12 and 0.23 mm (Table 2).

Based on the particle-size distribution, the pyroclastic surge deposits of the 1956 eruption can also be subdivided into the ground and ash-cloud surge materials. The dominant particle size of the ground surge material is identical with that of the pyroclastic flow deposits. The median diameter of the ground surge particles is 0.24 mm, the average particle size is 0.35 mm. The average median diameters of the ash-cloud surge particles range between 0.12 and 0.22 mm, the average particle sizes between 0.13 and 0.32 mm (Table 2).

Physical properties. The densities of the solid phases in the pyroclastic surges deposited during the 1984–1986 eruptions range between 2.56 and 2.75 g/cm^3: the average density of the ground surge material is 2.69 g/cm^3, that of the ash-cloud surge deposits is 2.70 g/cm^3 (Table 3).

The densities of the *in situ* pyroclastic surge deposits range between 1.30 and 1.67 g/cm^3: the average *in situ* density of the ground surge material is 1.53 g/cm^3, that of the ash-cloud surge deposits is 1.41 g/cm^3 (Table 3).

The porosity of the pyroclastic surge deposits ranges between 36 and 52%, averaging 43% for the ground surge and 49% for the ash-cloud surge material (Table 3).

Mechanical properties. The modulus of total deformation of the pyroclastic surge material ranges between 2.5 and 15.6 MPa: the average values are 6.0 MPa for the ground surge deposits and 5.3 MPa for the ash-cloud surge material (Table 3).

The strength of the ash-cloud surge material deposited during the 1984 eruption was measured using a Norwegian stabilimeter. The shear strength (or cohesion) was found to be 0.004 MPa, the angle of internal friction 30°. Generally, the cohesion of the ground surge material is equal to zero, that of the ash-cloud surge material is 0.04 MPa. The angle of internal friction ranges between 24 and 58°, averaging 42° for the ground surge and 41° for the ash-cloud surge material (Table 3).

The measurements of the physical and mechanical properties of the pyroclastic materials revealed that the densities of the solid phases from different deposits were almost identical, though showed different variation ranges. The packing density of the ground surge material is higher than that of the ash-cloud surge deposits because of a difference between the particle sizes of these materials, and also because the ground surge deposits are usually overlain by thick sequences of pyroclastic flows, whereas the ash-cloud surge deposits lie on the surface. The porosity of the ash-cloud surge material is somewhat higher than the porosity of the ground surge deposits because of its smaller particle size, aggregation, and lower packing density (Table 3). These deposits have comparable values of deformation characteristics except that the modulus of deformation of the ground surge material has a wider variation range. The deposits are also almost identical in terms of strength-related properties with the only difference that the angle of internal friction in the ground surge rocks showed a greater variation range as compared to that of the ash-cloud surge material.

Conclusions. The most important characteristics distinguishing the different types of the pyroclastic surge deposits at Bezymyannyi can be summarized as follows.

1. The deposits of the ground surge and the overlying pyroclastic flows do not have a distinct contact but grade into one another. The surface of the ash-cloud surge deposits is covered by a thin mantle of ash deposited from the ash clouds that traveled above the pyroclastic flows. The thickness of the ash mantle ranges between a few millimeters, where the ash was deposited after some portions of the pyroclastic flows stopped, and a few to several tens of centimeters, where the ash was deposited after the end of a climatic eruption phase.

2. The ground surge material has a single-mode particle-size distribution – the predominance of particles with diameters ranging between 0.125 and 0.25 mm (up to 30–42%). The amount of fragments larger than 2 mm is $\leq$ 10%. The dominant particle sizes are similar to those of the pyroclastic flows.

The ash-cloud surge material has a bimodal particle size distribution with the peaks of 0.125–0.25 and < 0.056-mm particles. The amount of the lapilli size particles is as large as 20–25%. The large particles are comparable in size with the particles from the pyroclastic flows.

3. The electron microscope study of the undisturbed samples of the pyroclastic surge deposits revealed that the ground surge deposits had a higher porosity compared to the ash-cloud surge material (40.8 and 33.4–37.1%, respectively), but a smaller number of pores (60 and 104–226, respectively). This can be explained by the fact that the ash-cloud surge material contains a larger amount of fine particles (up to 35%) and that the particles of this material form aggregates, so that in addition to the general porosity, new types of porosity appear: between the particles in the aggregates and between the aggregates.

The results of this study can be useful for a more exact identification of and distinction between various types of pyroclastic surge deposits and, hence, for a more exact prediction of volcanic hazards: eruptions at andesitic volcanoes during which ash-cloud surges take place are known to be most hazardous.

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