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# The 15 March 2019 Bezymianny Volcano Explosive Eruption and Its Products

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**Abstract**—Bezymianny Volcano is one of the most active volcanoes in Kamchatka and in the world. This paper describes the preparation, behavior, products, dynamics, and the geological effect of the March 15, 2019 explosive eruption of the volcano, which was predicted 6.5 h before it began. The sequence of eruptive events was analyzed using data provided by video and satellite-based monitoring of the volcano; the quantitative characteristics for the distribution of pyroclastic deposits were obtained in the information system "Remote Monitoring of Activity of Volcanoes in Kamchatka and the Kurile Islands". The explosions lifted ash to heights of 15 km above sea level (up to 12 km above the volcano), the eruptive cloud was moving northeastward and east from the volcano, the main ashfall area was 210 400 km$^2$, including 15 000 km$^2$ on land. Apart from tephra, the eruption produced pyroclastic flows and pyroclastic surges covering an area of 30 km$^2$. The total volume of explosive products is estimated as 0.1–0.2 km$^3$. The eruptive rocks are calc-alkaline moderate-K basaltic andesites ($SiO_2$ = 54.84–56.29 wt %), they are the most mafic among all rocks of the current Bezymianny eruption cycle.

*Keywords:* Bezymianny Volcano, explosive eruption, KVERT, forecasting, video observations, satellite-based monitoring, VolSatView, Kamchatka

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## INTRODUCTION

Bezymianny Volcano, which is one of the more active volcanoes worldwide, is situated in the middle of the Klyuchevskoy Volcanic Group, Kamchatka (Fig. 1). Since the awakening of the volcano in 1955, it has produced 52 paroxysmal explosive eruptions, including the catastrophic event of March 30, 1956, after which the growth of a lava dome in its explosive crater went on almost without interruption until the end of 2012 (Girina, 2013; Ozerov et al., 2020). The volcano was in a relative repose during four years, from December 2012 to December 2016. This was due to a high effusive activity of the 2012–2013 Tolbachik Fissure Eruption named after the 50-year jubilee of the Institute of Volcanology and Seismology (IVS), Far East Branch, Russian Academy of Sciences (FEB RAS) and four eruptions of Klyuchevskoy Volcano in 2012–2013, 2013, 2015, and in 2016 (Girina, 2016; Girina et al., 2017d).

The period from December 2016 to mid-2018 saw viscous lava flows being squeezed out onto the southern and western slopes of the lava dome of the volcano; upon this background, three strong explosive eruptions occurred hurling ash to as high as 15 km above sea level (a.s.l.) (or 12 km above the crater): March 9, June 16, and December 20, 2017 (Girina et al., 2017a–c, 2018a).

No explosive eruptions were recorded in 2018, but the lava dome remained in an active state as could be inferred from a thermal anomaly that was almost invariably observed on satellite images of the area. The anomaly had a higher temperature from March 24 through November 5, 2018 owing to the growth and existence of a new, small lava dome detected in the crater during a helicopter flight on July 9, 2018 (http://geoportal.kscnet.ru/volcanoes/imgs/2373.jpg). A next explosive eruption occurred at 16:10 UTC (Universal Time Coordinated) on January 20, 2019: the eruption cloud rose to heights of 7–9 km above the crater (up to 10–12 km a.s.l.) and was moving northwestward from the volcano. The ashfall area was approximately 200 000 km$^2$, VEI (Volcanic Explosivity Index) was 2 (Girina et al., 2018c, 2019b).

**Fig. 1.** The state of Bezymianny Volcano on April 13, 2019, in the foreground are tephra deposits discharged by the explosive eruption of March 15, 2019. Photographed by Yu. Demyanchuk on the east side of the volcano.

The volcano has been visually monitored since 1958 by observers at the seismic station in the village of Kozyrevsk. To this was added the Apakhonchich station from October 1960 to June 27, 1989, until this was replaced with a telemetered station. Bezymianny has been monitored using video cameras since August 20, 2003 (Girina et al., 2018b). Satellite-based monitoring has been carried out by scientists with the KVERT (Kamchatkan Volcanic Eruption Response Team, IVS FEB RAS) since 2002 (Girina et al., 2018b; Gordeev and Girina, 2014). The data on the distribution of pyroclastic deposits (flows, surges, and tephra) on the volcano's slopes, as well as observations of the movement and size of the eruption cloud discharged by Bezymianny in March 2019 were obtained using the information system (IS) "Remote Monitoring of Activity of Volcanoes in Kamchatka and the Kurile Islands (VolSatView)" (Girina et al., 2018b, 2019a; Gordeev et al., 2016). The VolSatView IS operation uses the distributed computer resources at the *Planeta* Far East Research Center, the Center of Collective Use (CCU) *IKI-Monitoring* (Institute of Space Research, RAS), and CCU *Data Center FEB RAS* (Computing Center, FEB RAS), which make use of technologies for storage and processing of satellite information, including those developed for project 15-29-07953 of the Russian Foundation for Basic Research (Loupian et al., 2014, 2015).

## THE PREPARATION, FORECAST, AND PROGRESS OF THE MARCH 15, 2019 EXPLOSIVE ERUPTION ON BEZYMIANNY VOLCANO

The explosive eruption of January 20, 2019 was followed by the discharge of lava flows onto the western and northwestern slopes of the Novy Dome on Bezymianny: the difference in temperature between the thermal anomaly and the background was always higher than usual (Fig. 2). Since February 23, the anomaly temperature began to increase, an incandescence being observed during nighttime in video records around the crater in addition to collapse of hot avalanches onto the eastern slopes of the lava dome, indicating the supply of fresh juvenile material into the crater and the start of the extrusive phase of this eruption, which usually precedes the explosive phase on Bezymianny (Girina, 2013).

Based on a gradual buildup of activity on the volcano, a warning for aviation was issued by KVERT staff on February 26, 2019 (Volcano Observatory Notice for Aviation, VONA) where the Aviation Color Code (ACC) for volcanic hazard was changed from yellow to orange (http://www.kscnet.ru/ivs/kvert/van/?n=2019-43). It was pointed out in the forecast that an explosive eruption with ash lifting up to 10–15 km a.s.l. (7–12 km above the crater) was possible within a few days.

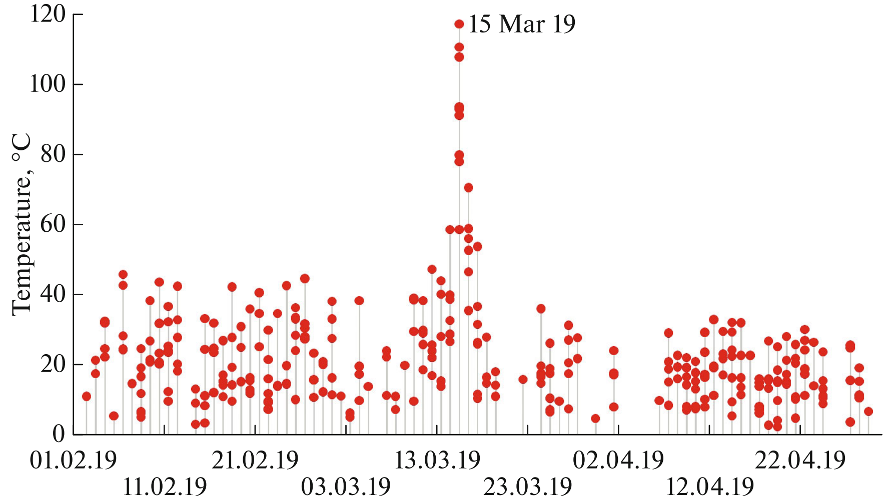



**Fig. 2.** The variation in the temperature difference between the thermal anomaly and the background in the area of Bezymianny volcano in February to April 2019, as inferred from satellite information of medium resolution in the VolSatView IS.

Since March 5, hot avalanches became more numerous, and the thermal anomaly began to steadily increase in temperature since March 10 (see Fig. 2). On March 12, the forecast of the development of the eruption was made more specific in the VONA: an explosive eruption hurling ash to heights of 10–15 km a.s.l. (7–12 km above the crater) can occur during the following week (http://www.kscnet.ru/ivs/kvert/van/?n=2019-60).

The hot avalanches descending along the northeastern and eastern slopes of the dome were becoming more frequent and their volume was increasing (Fig. 3). From 00:30 to 03:00 UTC on March 15, ash was noted in the gas–steam plume, which was extending for 100 km northeast of the volcano. The temperature of the thermal anomaly in the volcano area began to increase rapidly from 07:30 UTC March 15 (see Fig. 2). From 08:15 UTC, a vertical gas–steam column began to form above the volcano with occasional admixtures of ash from major hot avalanches. The VONA KVERT ACC for volcanic hazard was changed from orange to red at 11:00 UTC March 15; the forecast pointed out that an explosive eruption with ash lifting up to 10–15 km a.s.l. (7–12 km above the crater) was possible during this night (http://www.kscnet.ru/ivs/kvert/van/?n=2019-63).

The paroxysmal explosive eruption of Bezymianny hurling ash to heights of 15 km a.s.l. (12 km above the crater) began at 17:30 UTC March 15, the relevant VONA message was issued by the KVERT at 17:37 UTC March 15 (http://www.kscnet.ru/ivs/kvert/van/?n=2019-64). The KVERT forecast was confirmed 6.5 hours after publication.

According to video data, explosions in the crater of Bezymianny lava dome and large hot avalanches which collapsed on the eastern slopes began to be recorded from 17:10 UTC March 15. At 17:22 UTC, very bright flashes were observed in the night darkness, several powerful explosions occurred discharging hot avalanches and pyroclastic flows onto all slopes of the volcano. An eruption column rose above the volcano, reaching 10–12 km a.s.l. (7–9 km above the volcano) by 17:27 UTC. A series of the largest, probably directed, explosions occurred during the time 17:29–17:45 UTC, producing an eruption cloud rising to 15 km a.s.l. and traveling northeastward from the volcano at speeds of 60–80 km/h (Girina et al., 2020) (Fig. 4). According to satellite data from the VolSatView IS, the temperature difference between the thermal anomaly and the background reached 117°C at the instant of the main explosion (17:40 UTC) (see Fig. 2). The azimuth of propagation for the ash cloud changed from 54° to 80° during a single hour (between 17:30 and 18:30 UTC) (Girina et al., 2020), later on the ash plume moving eastward from the volcano (Fig. 5a).

According to video and satellite observations, it was until about 00:10 UTC March 16 that the occurrences included continuous discharge of ash from the volcano, the formation of pyroclastic flows and ash plume; that is to say, the explosive phase lasted about 7.5 h to be followed by powerful gas-steam activity during several days.

According to seismic data by the Kamchatka Branch (KB) of Geophysical Survey (GS) of the Federal Research Center (FRC) RAS, the paroxysmal phase lasted 4 h, and the volcanic tremor had a magnitude of 0.12 μm (www.emsd.ru/~ssl/monitoring/).

According to satellite data from the VolSatView IS, the southern edge of the ash plume reached the northern part of Bering Island (Komandorskie Islands) by about 22:30 UTC March 15, the plume completely covered the island by 02:00 UTC March 16, and the ashfall continued approximately until 04:00 UTC


**Fig. 3.** Traces of continuous hot avalanches descending onto the eastern and northeastern slopes of the Novy dome of Bezymianny volcano on March 10, 2019. Video data by the KB GS RAS from the eastern slope of the volcano.

March 16. According to visual observations by E. Mamaev from out Bering Island, a copious ashfall began on the northernmost cape of the island (Cape Yushin) at 23:30 UTC March 15. Judging from E. Mamaev's photographs, ash was deposited in different locations over the Island 0.3 to 1.0 cm thick during the ashfall duration (3–4 h) (see Fig. 5b).

Data from Himawari-8 satellite at the VolSatView IS, the Bezymianny eruption cloud grew in area from 1200 to 107072 $km^2$ from 17:30 March 15 to 03:00 March 16. The ashfalls due to the eruption cloud had a total area of 210400 $km^2$ by 03:00 UTC March 16 (Girina et al., 2020). When the eruption came to an end, a bright thermal anomaly (see Fig. 2) continued to be recorded in the crater area during several months, and the summit was seen to be incandescence during dark hours of the day, probably reflecting the discharge of a new lava flow onto the northwestern slope of the dome.

## THE PRODUCTS OF THE MARCH 15, 2019 EXPLOSIVE ERUPTION OF BEZYMIANNY

### *Tephra*

When the F.Yu. Levinson-Lessing Kamchatka Volcanological Station (IVS FEB RAS) staff sampled tephra with snow at distances of 10–12 km from the volcano during April 9–13, 2019, they noticed the presence of acute-angled clasts of porous lava of Bezymianny reaching 7–9 cm across.

Analysis of the tephra samples performed at IVS FEB RAS showed that ash weight was 280 $g/m^2$ nearer to the ashfall edge (sampling site 8 at 16 km from the volcano) and 1.1 $kg/m^2$ near the Apakhonchich station (15.5 km from the volcano). The tephra samples contained lapilli up to 3 cm across, and the tephra weight was 3.6 to 4.4 $kg/m^2$ nearer to the ashfall axis (sampling sites 4–6, 17.6–23 km from the volcano). The dominant fractions in the tephra deposits at the ashfall

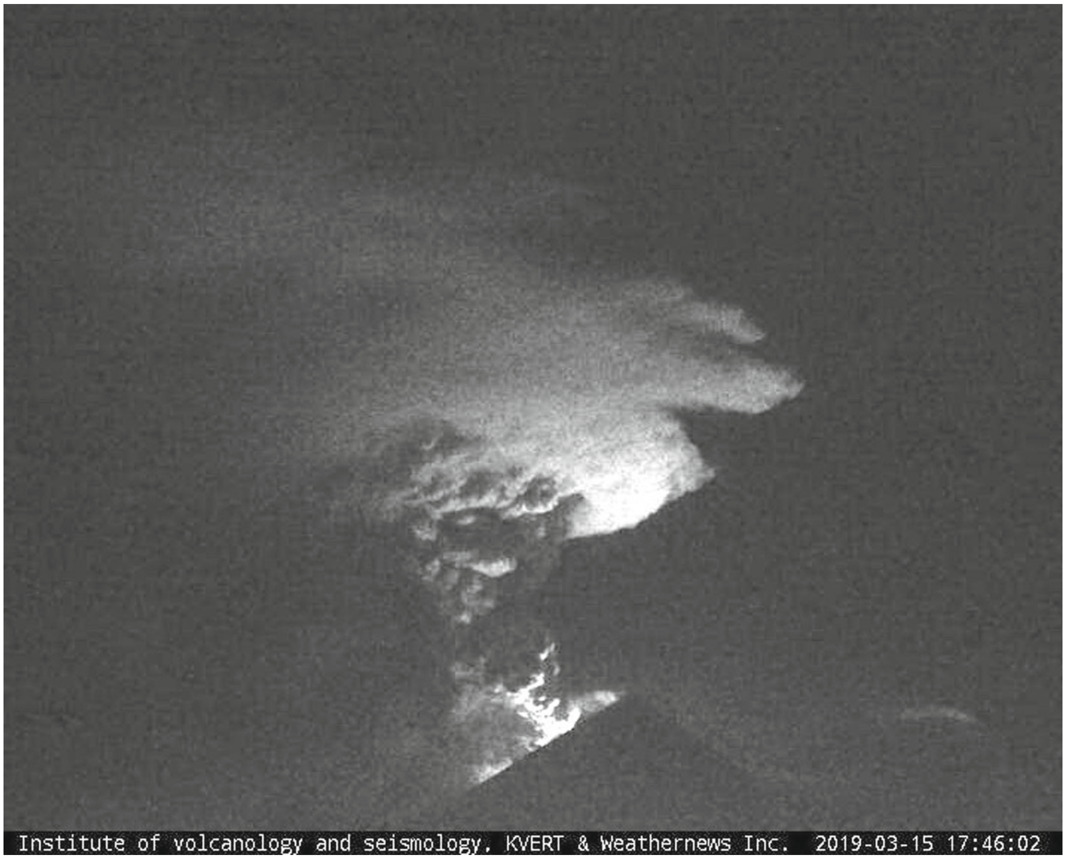



**Fig. 4.** The eruption column and eruption cloud of Bezymianny during the explosive eruption of March 15, 2019, in the foreground is the cone of Klyuchevskoy Volcano. View from the Kamchatkan Volcanological Station north of the volcano. Video data by KVERT (IVS FEB RAS) and by Weathernews Inc.

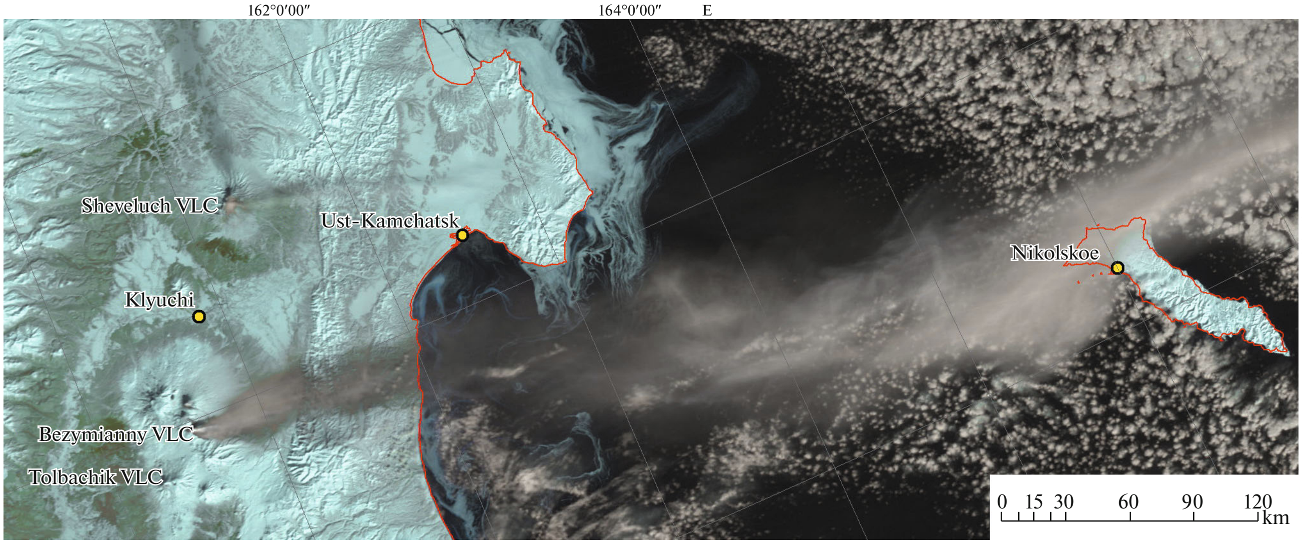
edge were 0.5–1.0 mm, and 2–4 mm nearer to the ashfall axis; that is to say, the tephra material was large-grained and coarse-grained (Fig. 6). The large-grained tephra fractions are dominated by greenish highly porous particles, but also contain angular light and dark grey clasts, with the latter being saturated with plagioclase. The tephra particles in the other fractions (except for fine ones) are rounded and are mostly lava clasts of fresh appearance from light whitish to black in color; as well, there are some minerals and their growths (plagioclase, pyroxenes, and titanomagnetite) and occasional resurgent particles (rock clasts, dark crimson in color). The particles in the finer fractions mostly consist of volcanic glass (up to 80%), plagioclase, pyroxenes, and titanomagnetite.

The tephra sampled at distances of 15.5–23 km from the volcano has a chemical composition that differs from the lavas and matrices of the pyroclastic flows and surges in having slightly lower concentrations of FeO, MgO, and $K_2O$ and higher concentrations of $Al_2O_3$, CaO, and $Na_2O$ (Table 1). The aqueous extracts from six tephra samples have pH varying between 5.85 and 6.5, with the ranges of component concentrations (in mg-equ, %) being as follows: $HCO_3^-$ between 14.23 and 47.05 (27.95 on average), $Cl^-$ between 17.76 and 26.12 (22.68), $SO_4^{2-}$ between 22.05 and 60.19 (40.79), $F^-$ between 5.26 and 12.25 (8.39), $Na^+$ between 11.26 and 26.96 (20.9), $Ca^{2+}$ between 65.99 and 84.71 (73.01), and $Mg^{2+}$ between 4.03 and 8.64 (6.08) (the aqueous extracts from ash were analyzed at the Analytical Center of IVS FEB RAS). Higher concentrations of sulfuric gases in eruption clouds are typical of Bezymianny (Basharina, 1966; Dubik and Menyailov, 1969], while haloids are less abundant in such clouds.

### *Deposits of Pyroclastic Flows and Surges*

According to satellite data acquired on March 16, 2019, pyroclastics were observed on the southeastern, eastern, and northeastern slopes of the volcano (Fig. 7). Data from the VolSatView IS showed that the deposits of pyroclastic flows were 3.5–4 km long on the western slope, approximately 8 km in the Vostochnaya Valley, and 7 km in a canyon near the Lokhmaty extrusion on the southeastern slope. The deposits of pyroclastic flows and pyroclastic surges in the area of the volcano were approximately 30 km$^2$ in area. Taking the

(a)




(b)

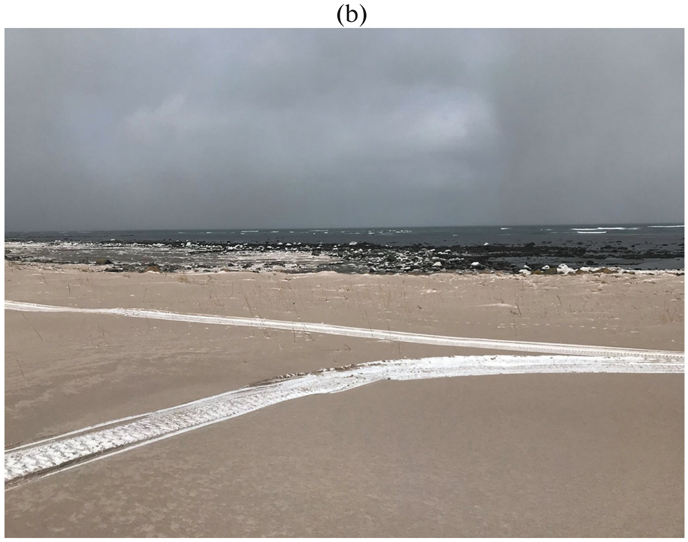


**Fig. 5.** The ash plume from Bezymianny volcano during the explosive eruption of March 15, 2019, and ash deposits on Bering Island: a ash plume on the Terra MODIS satellite image at 00:01 March 16, 2019, the data were supplied by the *Planeta* Far East Research Center; b ash on snow in Cape Yushin in northern Bering Island on Match 15, 2019. Photographed by E. Mamaev.

pyroclastic flow deposits to be 1.5 to 20 m thick and the pyroclastic surges to be up to 2 m thick, the deposits of pyroclastic flows and surges can be estimated as being 0.1–0.2 km$^3$.

Field surveys of pyroclastic deposits of the eruption were carried out in early July 2019.

**Pyroclastic flow deposits** were found in all valleys and small narrow gullies on all slopes of Bezymianny. As an example, the canyon situated at the northeastern base of the Lokhmaty extrusion had a V-shaped profile in its middle prior to the eruption, and was deeper than 20 m. The explosive eruption filled the lower half in this part of the canyon with pyroclastic flow deposits, producing a trough-shaped profile. At the exit from the canyon, the heaps of lava blocks in the pyroclastic flow were 2–3 m above its sides. Pyroclastic flow material came in portions, with individual portions clearly visible in the relief reaching a thickness of 10 m.

The pyroclastic flow was heavily dominated by porous blocks of lava up to 3–4 m across, greenish–grey–brown on the outside and dark grey to black inside. The flow also contained dense rock varieties grey to black in color and up to 1.5 m across (Fig. 8a). The surface of the porous blocks was found to have traces of "soft" deformation (as if crumpled) produced by impact due to other blocks. All blocks were rounded and broken by numerous cracks. Probably, lava blocks have been very hot, plastic, and saturated with gas during the eruption. As the blocks were moving in a flow, they were crumpled as they were hitting

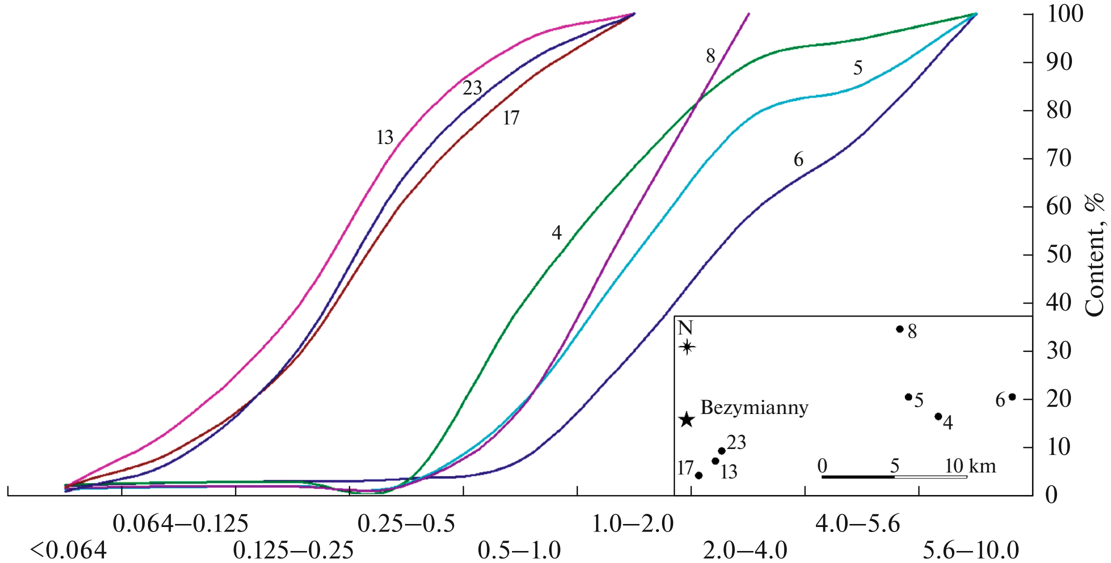



**Fig. 6.** The cumulative curves of grain-size distribution for samples of pyroclastic deposits due to the Bezymianny explosive eruption of March 15, 2019.

Tephra: nearer to the ashfall axis (4–6), nearer to ashfall edge (8); matrices of pyroclastic flow deposits (17) and pyroclastic surge deposits (13 and 23). The inset shows the sites where pyroclastic material was sampled relative to the volcano.

**Table 1.** The chemical composition of the rocks erupted due to the explosive eruption of March 15, 2019 on Bezymianny Volcano

| ## | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Sample # | 7761-1 | 7761-2 | GB-4 | GB-6 | GB-7 | GB-13 | GB-17 | GB-22 | GB-23 |
| $SiO_2$ | 56.11 | 55.58 | 55.15 | 55.13 | 56.48 | 55.28 | 55.65 | 54.95 | 54.72 |
| $TiO_2$ | 0.81 | 0.78 | 0.62 | 0.70 | 0.59 | 0.76 | 0.74 | 0.77 | 0.76 |
| $Al_2O_3$ | 18.38 | 18.44 | 20.51 | 19.88 | 19.84 | 18.32 | 18.82 | 18.26 | 18.42 |
| FeO | 8.43 | 8.16 | 6.97 | 7.71 | 6.61 | 8.61 | 8.50 | 8.59 | 8.78 |
| MnO | 0.15 | 0.15 | 0.13 | 0.14 | 0.12 | 0.16 | 0.16 | 0.16 | 0.16 |
| MgO | 4.35 | 4.24 | 3.63 | 3.91 | 3.68 | 4.75 | 4.71 | 4.50 | 4.78 |
| CaO | 8.15 | 8.27 | 8.99 | 8.77 | 8.40 | 8.28 | 8.43 | 8.10 | 8.36 |
| $Na_2O$ | 3.27 | 3.23 | 3.35 | 3.29 | 3.60 | 3.16 | 3.13 | 3.14 | 3.08 |
| $K_2O$ | 1.06 | 1.04 | 0.86 | 0.87 | 0.90 | 0.92 | 0.89 | 0.94 | 0.88 |
| $P_2O_5$ | 0.15 | 0.14 | 0.11 | 0.12 | 0.11 | 0.13 | 0.12 | 0.13 | 0.12 |
| L.O.I. | –0.09 | –0.06 | 0.08 | –0.06 | 0.06 | –0.07 | 0.11 | 0.04 | –0.02 |
| Total | 100.84 | 100.04 | 100.49 | 100.54 | 100.49 | 100.38 | 101.34 | 99.66 | 100.12 |
| V | 232 | 215 | 174 | 201 | 160 | 221 | 210 | 222 | 217 |
| Cr | 25 | 22 | 26 | 39 | 40 | 32 | 36 | 27 | 29 |
| Co | 24 | 27 | 19 | 22 | 19 | 24 | 23 | 26 | 26 |
| Ni | 20 | 20 | 18 | 18 | 21 | 22 | 22 | 20 | 21 |
| Cu | 51 | 53 | 45 | 50 | 42 | 37 | 39 | 39 | 37 |
| Zn | 81 | 80 | 66 | 73 | 62 | 78 | 78 | 81 | 84 |
| Y | 24 | 23 | 18 | 19 | 18 | 19 | 18 | 23 | 20 |
| Zr | 95 | 102 | 73 | 79 | 73 | 85 | 81 | 85 | 79 |

The concentrations of major oxides are in wt %, those of trace elements are in g/t. Samples 1 and 2 are fragments of juvenile lavas from pyroclastic flow deposits; 3–5 tephra sampled around the Apakhonchich station (IVS FEB RAS) and near the ashfall axis; 6, 9 and 7, 8 are matrices in deposits of pyroclastic surges and pyroclastic flows, respectively, in the canyon near the Lokhmaty extrusive dome (6, 7) and in the Vostochnaya Valley (8, 9). The concentrations of major elements and several trace elements in rocks were determined at the Center of Collective Use for isotope geochemical studies, Vinogradov Institute of Geochemistry, Siberian Branch RAS, Irkutsk.

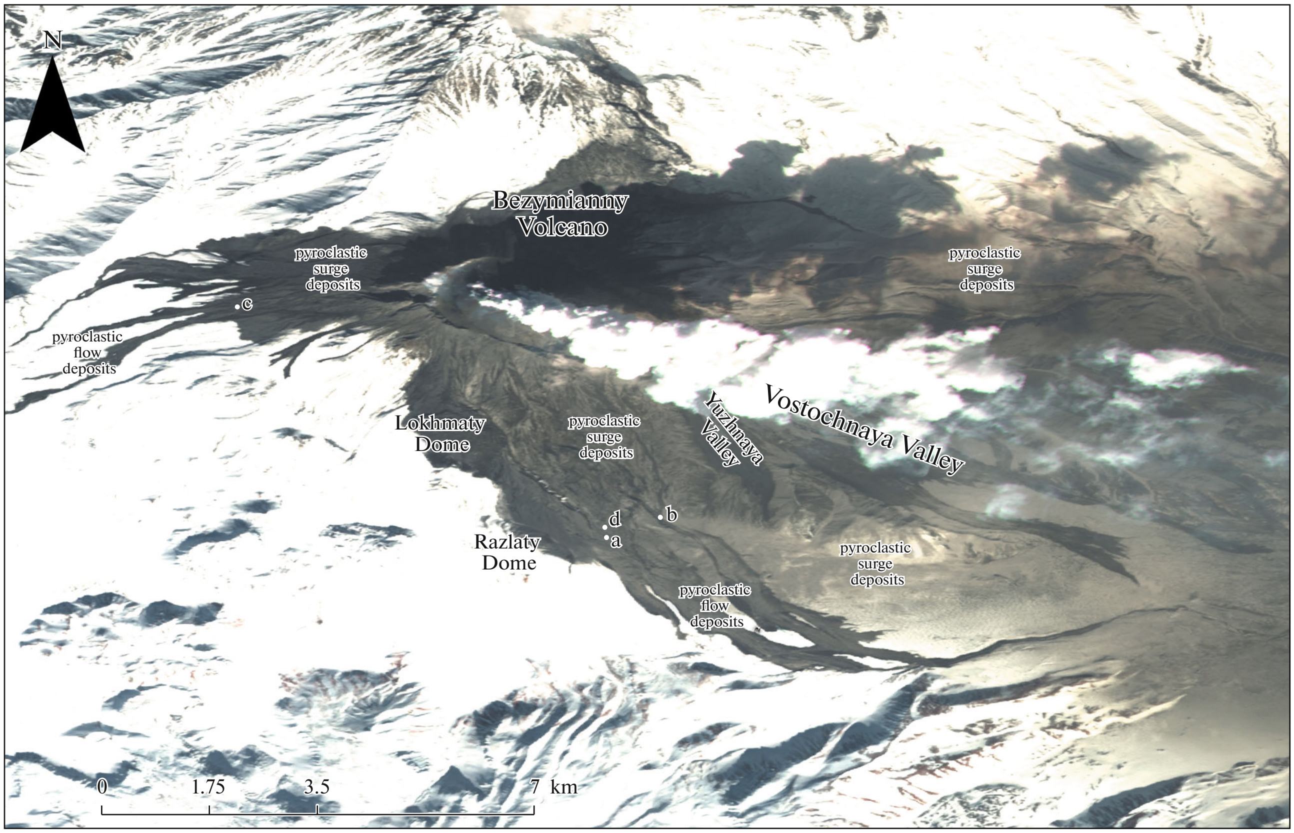



**Fig. 7.** The deposits of pyroclastic flows and surges on the Bezymianny slopes after the explosive eruption of March 15, 2019. The data from the Sentinel-2B satellite image at 00:30 UTC March 16, 2019 in the VolSatView IS. Points (a–d) are in correspondence with the images (see Fig. 8).

obstacles (canyon walls, other blocks, etc.), and were broken by cracks due to rapid degassing, the evidence being furnished by the presence of foamed rock inside the cracks. The undisturbed structure of the flow deposits matrix had densities varying in the range 1.40–1.49 g/cm$^3$ in July 2019 (1.44 g/cm$^3$ being the average based on three samples). The flow deposits matrix was greenish medium-grained sand dominated by particles 0.25–0.5 mm across (see Fig. 6).

There were few pyroclastic flow deposits in a deep valley adjacent to the canyon; they were no more than 3 m thick, they were uniformly distributed over the valley, and washed out in places after snowmelt (see Fig. 8b). The rock blocks and the flow matrix had characteristics that were like those in the canyon deposits.

The bulk of pyroclastic deposits of the March 15 eruption were in the Vostochnaya Valley, overlying the valley nearly as far as its middle and farther descending in two narrow tongues along the northern and southern valley sides as far as the outlet from the valley (see Fig. 7). Some few flow deposits were observed in the Yuzhnaya Valley. The pyroclastic deposits in the upper reaches of the Vostochnaya Valley had larger blocks of plastic lava (up to 4–5 m across) and denser varieties (up to 3 m across). That these deposits are much thicker is indicated by a higher brightness temperature (–12°C) compared with the flow deposits (–23°C) in other valleys; these data were obtained from satellite-based observations for March 19, 2019 (Girina et al., 2020).

Thin (up to 3 m) pyroclastic flows lay in narrow shallow gullies on the western slopes of the volcano, mostly consisting of fragments of plastic lava of medium size (up to 30–50 cm, although larger lava blocks were encountered, 1.5 m across) immersed in a greenish medium-grained sandy mass (see Fig. 8c).

**Deposits of pyroclastic surges** were observed on all slopes of the volcano, but their distribution was not uniform. Because the origin of pyroclastic surges is directly related to the generation of pyroclastic flows (Girina, 1998), their volumes were dependent on those of the flows. The thinnest pyroclastic surge deposits were observed on the western slope: that slope is as it were overstrewn with greenish sand whose thickness was 4–5 cm at places on snow patches; in addition, there were disordered occasional porous greenish, rounded volcanic bombs and acute–angled clasts of foamed lava on the sand; these were the same as those in the flow, but smaller (up to 10 cm). The pyroclastic surge deposits were the thickest (up to 2 m)

(a)

(b)

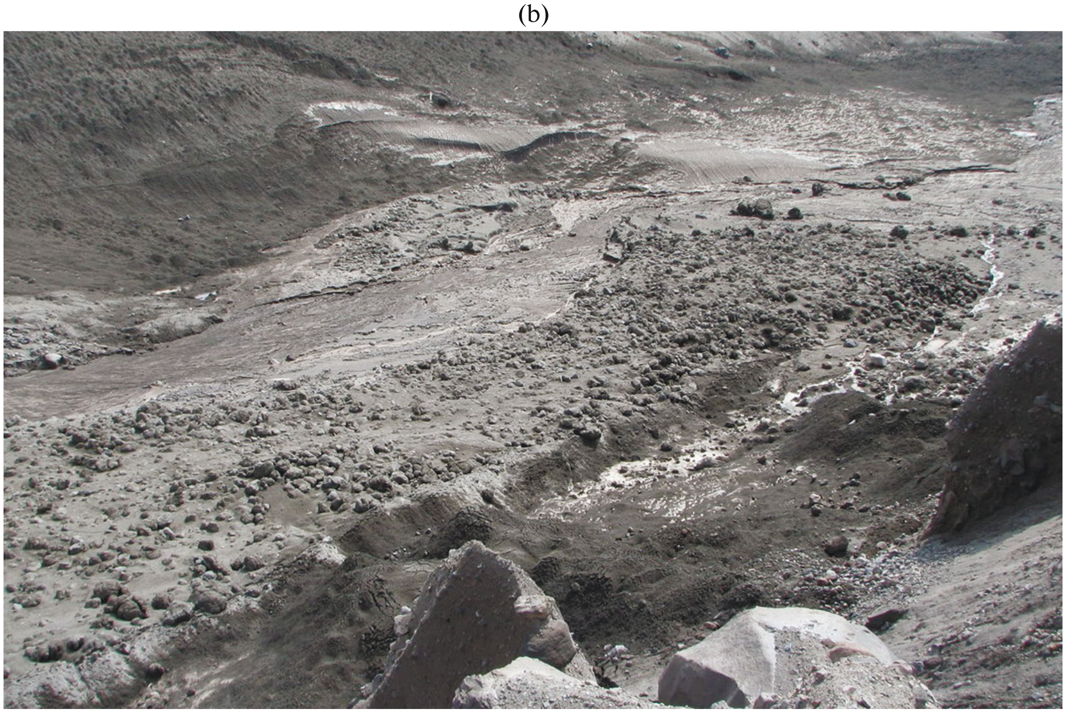


**Fig. 8.** The pyroclastic deposits discharged by the March 15, 2019 explosive eruption of Bezymianny

The deposits of pyroclastic flows: (a) at the outlet from the canyon near the Lokhmaty extrusion (the spade is 35 cm long), (b) in a valley adjacent to the canyon, (c) in a narrow shallow gully on the western slope of the volcano (backpack height is 70 cm), (d) dune relief of pyroclastic surge deposits left of the canyon near the Lokhmaty extrusion, nearby are pyroclastic flow deposits at the outlet from the canyon. For a description of the deposits see text. Photographed by O. Girina (a–c) and V. Davydova (d).

(c)

(d)

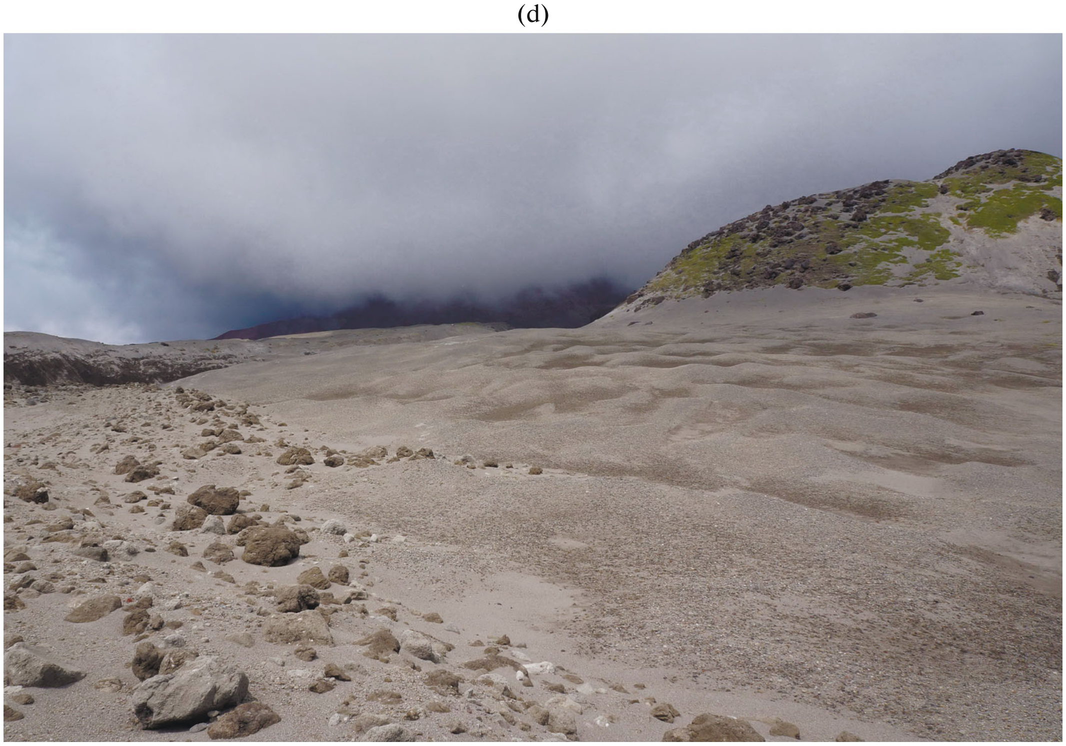


**Fig. 8.** (Contd.)

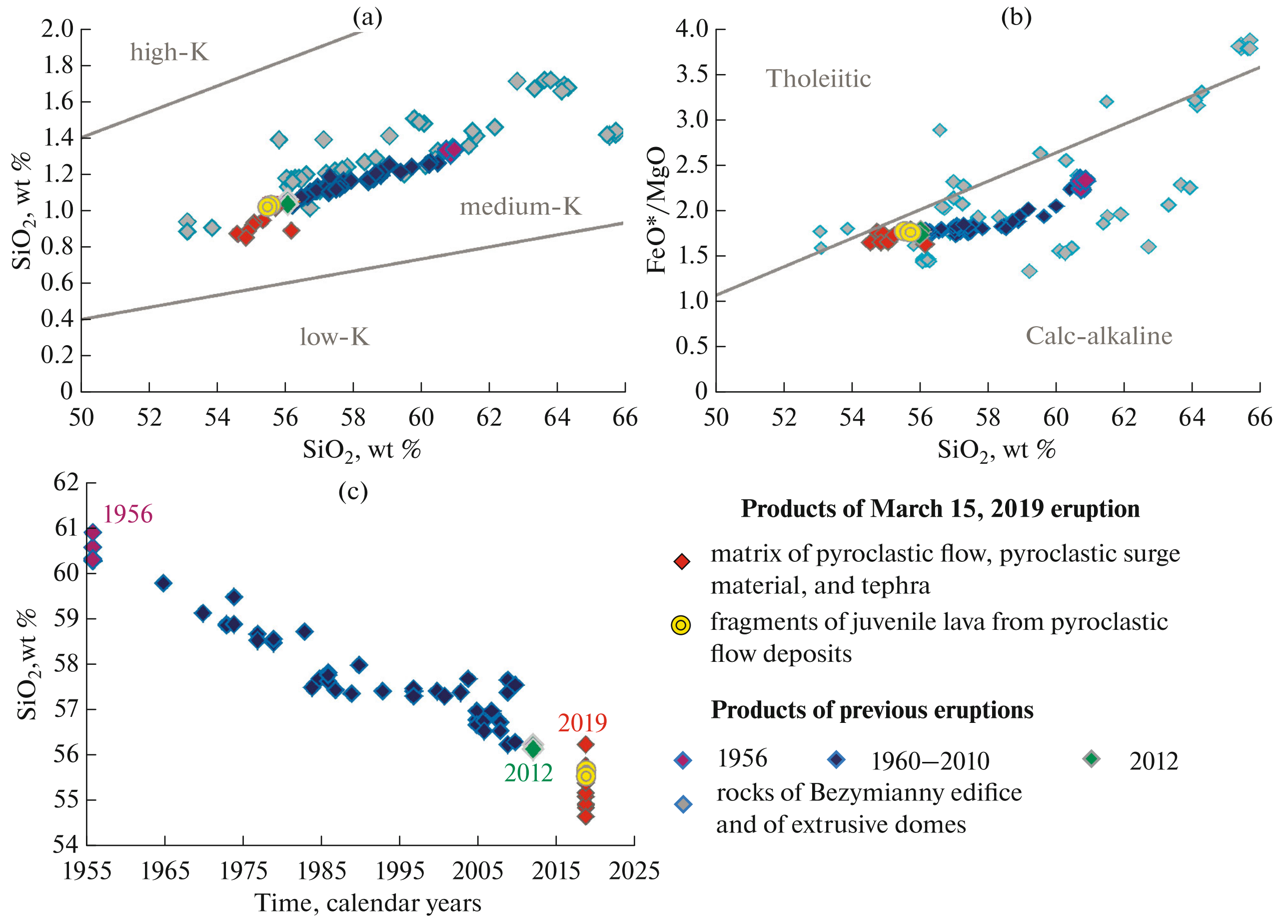



**Fig. 9.** The compositions of the rocks discharged during the recent eruption cycle of Bezymianny Volcano, including those of March 15, 2019, and earlier phases of activity

The compositions of the 1956–2010 products are after (Girina and Gorbach, 2006; Ozerov et al., 1997; Turner et al., 2013); those for 2012 are after (Davydova et al., 2017); the older products are after (Bogoyavlenskaya et al., 1991; Braitseva et al., 1990; Almeev et al., 2013).

in the northern part of the upper reaches of the Vostochnaya Valley.

The zone where the pyroclastic surge deposits are found is clearly seen on a Sentinel-2B image (see Fig. 7), and confirmed by field surveys: the deposits were confined to the northern slope of the Razlaty extrusion on the volcano's southern and southeastern slopes and occupied the entire field of pyroclastic deposits as far as the the volcano's northern slopes and the spurs of the adjacent Kamen volcano. In a narrow shallow gully near Razlaty, the surge deposits lay on a snow patch; they were well-sorted greenish sands as thick as 10–15 cm. There were a few rounded fragments of plastic lava up to 30–40 cm across on the surface of these deposits. The pyroclastic surge deposits covered with a cloak the southeastern and eastern slopes of the volcano and had the same general appearance and grain size as the sand near the Razlaty extrusion. Left of the canyon near the Lokhmaty dome and in the upper reaches of the Vostochnaya Valley, the pyroclastic surge deposits formed a hilly dune relief (see Fig. 8d) which is typical of such deposits (Girina, 1997, 1998). The density of undisturbed deposits of pyroclastic surges varied in the range 1.35–1.44 g/cm$^3$ (1.42 g/cm$^3$ is the average value based on four samples). The matrix of the pyroclastic surge deposits was medium-grained greenish sand dominated by particles 0.25–0.5 mm across (see Fig. 6). Judging from the well-pronounced unimodal distribution of the sand particles, these deposits are the formation of ground surges (Girina, 1998).

### *The Chemical and Mineralogical Compositions of the Products Due to the March 15, 2019 Explosive Eruption of Bezymianny*

The erupted rocks are calc-alkaline moderate-K basaltic andesites ($SiO_2$ = 54.84–56.29 wt %, $K_2O$ = 0.86–1.05 wt %, MgO = 3.62–4.78 wt %, FeO*/MgO = 1.61–1.83 on dry basis; the figures were converted to total oxides 100%) (Fig. 9). Fragments of juvenile lava in the pyroclastic flow deposits and the matrix of pyro-

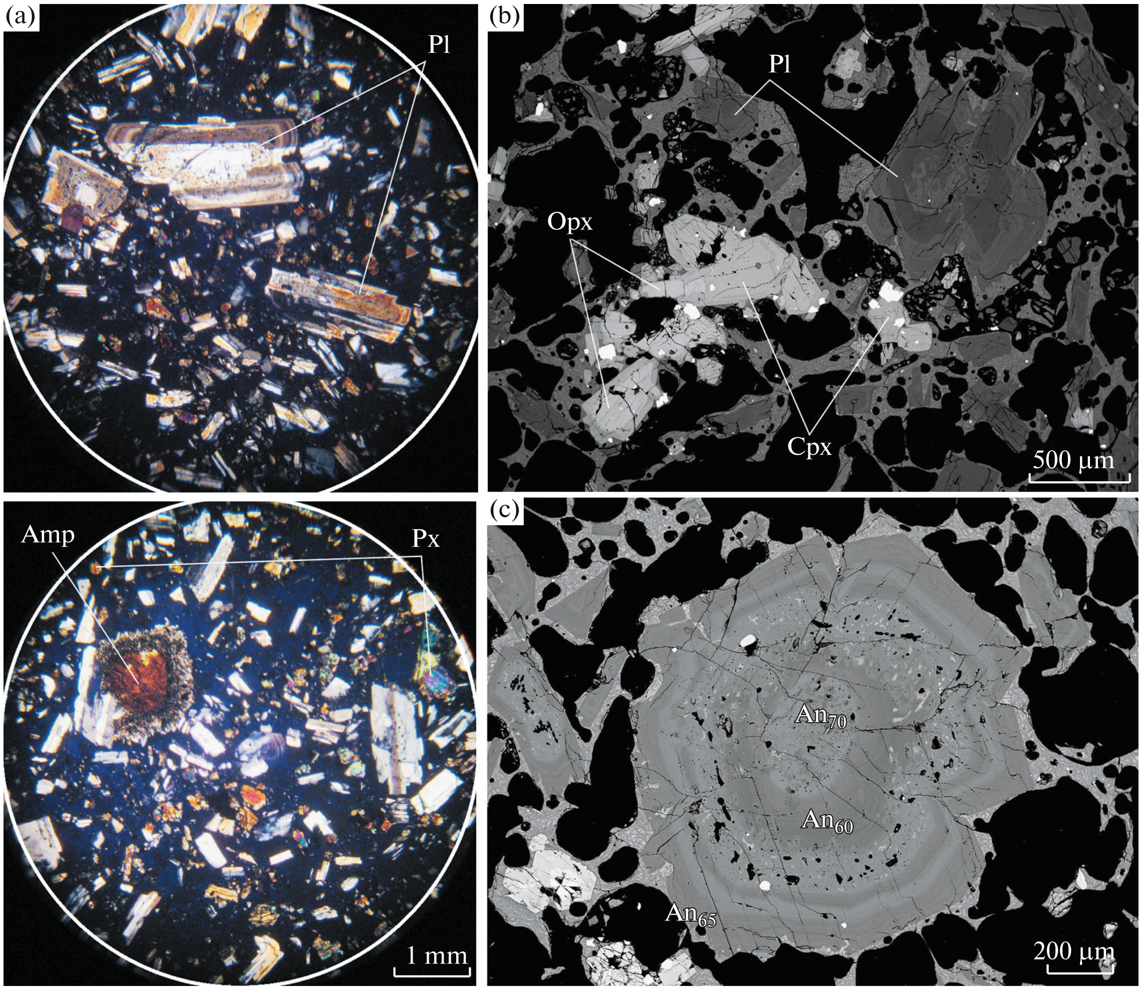



**Fig. 10.** A general view of a fragment sampled in basaltic andesite lava from pyroclastic flow deposits: (a) in crossed nikols, (b) in reflected electrons, (c) a typical zonal plagioclase phenocryst in reflected electrons. Notation: Pl plagioclase, An the concentration of anorthite endmember in plagioclase, Px pyroxene, Cpx clinopyroxene, Opx orthopyroxene, Amp amphibole.

clastic flows and surges have similar compositions, and contain 55.01–55.64 wt % of silica (see Table 1).

The fragments of juvenile lava are very porous (50–70% of total polished section area), porphyritic (from 10–15 to 30–35 vol % of phenocrysts), and their groundmass is fine-crystallized (Fig. 10a). The phenocrysts are dominated by plagioclase (up to 80–90%); also present are orthopyroxene, clinopyroxene, and titanomagnetite microphenocrysts. Apatite and amphibole relicts are found in lesser amounts. Minerals and glasses were analyzed for composition at the Laboratory of Local Materials Analysis Methods, Chair of Petrology, Faculty of Geology, Moscow State University using a JSM-6480 LV scanning electron microscope with an Oxford XMaxN detector for local microanalysis.

The **plagioclase** in phenocrysts is present in three generations identifiable by crystal size. The larger plagioclases reach 3–4 mm and make ~10% of the total amount of phenocrysts. The plagioclase of the dominant generation occurs in tabular crystals as long as 1 mm (occasionally 2 mm) with a complicated zoning. The larger crystals typically exhibit a rhythmic zoning involving two or three rhythms on an average (a zone of higher basicity, which is frequently resorbed and/or complicated by mottled zoning, giving way to one of higher acidity having oscillating zoning and numerous thin zones with traces of dissolution) (see Figs. 10b, 10c). In cores that have mottled zoning, the plagioclase that is the most enriched in anorthite endmember corresponds to ~$An_{70}$, while resorbed zones in the middle of the crystals have up to ~$An_{76}$ and zones with oscillating zoning have $An_{60-65}$. The larger microlites (up to 100 μm) also exhibit rhythmic zoning, frequently with traces of dissolution (from $An_{72}$ in zones of moderate basicity to $An_{59}$ in the rim which has a higher acidity). The smaller microlites are homogeneous, sheath-shaped, and/or skeleton crystals that are little amenable to quantitative analysis because of size; they correspond to edge parts of the larger crystals considered in terms of brightness of image in reflected electrons.

**Pyroxenes** (orthopyroxene and clinopyroxene) are present in phenocrysts (prismatic and long prismatic crystals, commonly no longer than 0.8 mm) and large microlites (see Fig. 10b). All pyroxenes have practically homogeneous cores (Mg# 65–66 for orthopyroxene and 71–72 for clinopyroxene) surrounded by a rim of higher magnesium (Mg# 74–76 for orthopyroxene and 75–79 for clinopyroxene), and which frequently involve a rhythmic zoning of their own. One frequently encounters growths of two pyroxenes and clinopyroxene overgrowing on orthopyroxene.

The ore mineral is **titanomagnetite**, occasionally with some traces of exsolution. Titanomagnetite forms microphenocrysts and microlites.

**Apatite** occurs as an accessory mineral.

Occasional **amphibole** relicts corresponding to the tschermakite–pargasite series are surrounded by a thick two-member 2Px-Pl-Mag rim or else are completely replaced with a bipyroxene –plagioclase–titanomagnetite aggregate.

**The groundmass of the rocks** is fine-crystallized and consists of numerous skeletal microlites of plagioclase with occasional microlites of pyroxene and apatite in-between. The interstitial glass has a dacite/dacitic andesite composition.

## DISCUSSION

### *The Dynamics of the March 15, 2019 Explosive Eruption on Bezymianny*

As has been said above, the preparation of this eruption continued 21 days. The rate of hot avalanches had been steadily increasing during 17 h before the paroxysmal event, with ash being noticed in the gas–steam plume emitted by the volcano. Ten hours before the eruption, the temperature of the thermal anomaly on the volcano sharply increased, probably because fresh high-temperature portions of juvenile material began to extrude in the crater. An impressive gas–steam column had been observed above the volcano during 9 to 10 h before the explosive phase, indicating the supply of lava with high concentrations of volatiles.

The explosive phase started at 17:10 UTC on March 15 as explosions of moderate vigor, discharging the material of hot avalanches and pyroclastic flows onto the eastern slopes of the volcano. Starting 17:22 UTC, powerful explosions brought down hot avalanches and pyroclastic flows onto all slopes of the volcano. A sequence of vigorous directed blasts drove the eruption cloud northeastward from the volcano at a speed of 60–80 km/h at 17:29–17:45 UTC, though the wind blew from the west. That those were directed blasts is also borne out by a thick mass of deposits on the Bezymianny northeastern slope (see Fig. 1), as well as by the fact that the tephra material was coarse-grained and acute–angled at distances of 10–12 km from the volcano. It was probably at that time that partially degassed (foamed) solidified lava that filled the crater during the extrusive phase was being destroyed and discharged.

The paroxysmal phase of the explosive eruption lasted approximately 7.5 h accompanied by continuous discharge of ash from the volcano, the formation of pyroclastic flows and of the ash plume going on until approximately 00:10 UTC March 16. When portions of degassed lava had been destroyed by the blasts, the crater began to discharge a high–temperature material that went to form the bulk of lava blocks in the pyroclastic flows. These blasts were probably directed as well, since most pyroclastic deposits are concentrated on the volcano's eastern and southeastern slopes. The matrix of pyroclastic flows and the matrix of pyroclastic surges was the same substance that appeared during blasts and discharges of gas-rich juvenile material from the crater, as well as during autoexplosivity phenomena as plastic blocks of lava were moving in pyroclastic flows down the Bezymianny slopes. The high gas saturation of the pyroclastic deposits and the steepness of open slopes of the volcano with sparse snow cover produced the result that individual plastic lava blocks of varying size experienced saltation and were thus carried far from the crater, to distances of 8–10 km, to be deposited on all slopes of the volcano, similarly to the pyroclastic surge deposits. The pyroclastic flow deposits were mostly concentrated in deep valleys on the volcano's slopes. Apart from areal propagation, the pyroclastic surge deposits occasionally assumed the shape of sand flows. Such a flow was formed, e.g., in narrow shallow gullies near the northern slope of the Razlaty extrusion, which served as an obstacle to the movement of pyroclastic surges.

### *The Geological Effect of the March 15, 2019 Explosive Eruption of Bezymianny*

The eruption has altered the appearance of the volcano's slopes. As an example, the profile of the canyon near the northeastern base of the Lokhmaty extrusion became trough-shaped instead of V-shaped as before, its mouth part was completely overlain by pyroclastic flow deposits; the lows on the volcano's northern and eastern slopes are filled with deposits of pyroclastic flows and pyroclastic surges; large deposits of fresh pyroclastic material were formed in the upper reaches of the Vostochnaya Valley.

According to satellite data, the pyroclastic flow deposits were about 8 km long in the Vostochnaya Valley, 7 km on the southeastern slope in the canyon near the Lokhmaty extrusion, and 3.5–4 km on the western slope. The deposits of pyroclastic flows and pyroclastic surges covered an area of about 30 km$^2$, with the volume being estimated as 0.1–0.2 km$^3$.

The ashfalls associated with the propagation of the eruption cloud had an approximate area of 211 000 km$^2$ by 03:00 UTC March 16 as inferred from satellite data, while the volume of the tephra can be roughly evaluated as 0.01–0.02 km$^3$ based on its thickness around the volcano and on Bering Island.

Based on calculations of tephra discharge in relation to the height of the eruption column as described in (Carazzo et al., 2008; Dacre et al., 2011; Kaminski et al., 2011; Mastin et al., 2009; Wilson, and Walker, 1987), using the height of the eruption column as 12 km above the crater, the tephra discharge rate at Bezymianny was estimated as 270000 to 6700000 kg/s on March 15, 2019. Knowing that the most powerful phase of the eruption lasted 960 s (from 17:29 to 17:45 UTC on March 15), the amount of tephra discharged during that time was estimated as 2.6 to 6.4 million tons. Using the average tephra density 1.5 g/cm$^3$ (Girina, 1998), the tephra volume is 0.0017 to 0.004 km$^3$. Considering that tephra had been continuously discharged until 00:10 UTC on March 16, the VEI of this eruption was estimated as 3.

### *The Eruption of March 15, 2019 Compared with the Other Explosive Eruptions of Bezymianny*

The explosive eruption studied here is one of the largest in the recent history of Bezymianny Volcano, judging by the area and volume of the deposits of pyroclastic flows and surges. As an example, the largest eruption that occurred during the period 1965 to 2010 took place in 1985 (the pyroclastic flow deposits covered an area of 12.25 km$^2$, the volume of all products was 0.05 km$^3$); during this period, the volcano erupted approximately 0.41 km$^3$ of products (Girina, 2013). The eruption of March 15, 2019 discharged pyroclastic flow and surge materials over an area of about 30 km$^2$, with the volume being evaluated as 0.1–0.2 km$^3$.

The events and products similar to this eruption were observed on Bezymianny volcano only once, in January 2005 (Girina and Gorbach, 2006). Then, as now, the pyroclastic flows in the Vostochnaya and Yuzhnaya valleys were largely composed of blocks of plastic lava. The deposits of pyroclastic surges formed a dune relief in the Vostochnaya Valley; they lay in brook valleys and on open spaces on the southern and southeastern slopes of the volcano as sand flows up to 0.5 m thick. The deposits of pyroclastic flows and surges had a large volume, about 0.05 km$^3$. The tephra deposits were coarse-grained; as an example, they were dominated by particles 0.5–2.0 mm across at a distance of 65 km from the volcano. In addition, it was noticed that the lava flow discharged onto the western slope of the Bezymianny dome after the January 2005 eruption had a lower viscosity compared with the flows due to the previous eruptions (Girina and Gorbach, 2006).

### *The Chemical Composition of the Erupted Rocks*

The basaltic andesites discharged by the explosive eruption of March 15, 2019 have the highest basicity among all the rocks produced during the recent eruption cycle of Bezymianny (see Fig. 9). Compared with the juvenile rocks discharged by the catastrophic eruption of March 30, 1956, the concentration of $SiO_2$ in the lavas discharged by the later eruption dropped by ~6 wt %. There were several periods showing more rapid decreases in silica concentration when seen upon the general background of an antidrome trend in compositional variation from 1956 to 2019 (see Fig. 9). As an example, the concentration of $SiO_2$ decreased from 61 to 57.5–58 wt % from 1956 to the early 1980s. During the sane period, the hornblende mineral association of 1956–1969 gave way to the hornblende pyroxene association, and afterwards, in 1979–1981, to the two–pyroxene association (Kadik et al., 1986); this had persisted in existence for 20 years (until the beginning of 2000) (Turner et al., 2013).

The well-pronounced tendency toward the progressive decrease in $SiO_2$ below 57 wt % in the rocks discharged by successive eruptions was observed since 2005 (see Fig. 9). The decrease in $SiO_2$ and the growth in MgO were noted, not only in the bulk composition of the rocks, but also in the compositions of interstitial glasses and melt inclusions in the minerals of basaltic andesites (Shcherbakov et al., 2011).

Geological and tephrochronologic studies (Bogoyavlenskaya et al., 1991; Braitseva et al., 1990) showed that hornblende and hornblende pyroxene andesites repeatedly gave way to two–pyroxene andesites and basaltic andesites during the eruption history of Bezymianny. Paroxysmal events like the catastrophic eruption of 1956 were followed by comparatively long (100–400 years) eruption cycles that mostly discharged two-pyroxene andesites and basaltic andesites. The current state of the volcano seems to be at the middle of such a cycle.

## CONCLUSIONS

The explosive eruption of Bezymianny on March 15, 2019 was the largest in the 1965–2019 sequence of paroxysmal eruptions related to the growth of the volcano's lava dome.

The explosive eruption of March 15, 2019 had been predicted by the KVERT scientists 6.5 h before its start.

The explosions hurled ash to 15 km above sea level (up to 12 km above the volcano). The explosive phase lasted 7.5 h.

The total area of ashfalls associated with the eruptive cloud was about 210400 km$^2$ by 03:00 UTC on March 16. Of this area, 15000 km$^2$ were on land. The tephra volume varied between 0.0017 and 0.004 km$^3$.

The area of pyroclastic flow and pyroclastic surge deposits was about 30 $km^2$, their volume being estimated as 0.1–0.2 $km^3$.

The products of this explosive eruption are calc-alkaline moderate-K basaltic andesites. They are the most mafic among all the rocks discharged during the recent eruption cycle of Bezymianny.

The total volume of the products discharged by the explosive Bezymianny eruption of March 15, 2019 is estimated as 0.1–0.2 $km^3$, VEI is 3.

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