Atmospheric electrical effects during a strong explosive eruption of Bezymyanniy volcano (Kamchatka Peninsula, Russia) on December 20, 2017

P P Firstov¹,*, R R Akbashev¹, E I Malkin², N V Cherneva², G I Druzhin²
¹Kamchatka Branch of Federal Research Center, Geophysical Survey RAS, Petropavlovsk-Kamchatskiy, Piip Boulevard 9, Russia
²Institute of Cosmophysical Research and Radio Wave Propagation FEB RAS, Kamchatskiy kray, Elizovskiy raion, Paratunka, Mirnaya st., 7, Russia
*E-mail: firstov@emsd.ru

Abstract. A set of parameters of various geophysical methods is considered, which made it possible to quite clearly represent the mechanism of the explosive eruption of Bezymyanny volcano on January 20, 2017. The explosion began according to the «soft» scenario, which was reflected both in the seismic method and in the thunderstorm activity of the eruptive cloud (EC). The transition to Plinian activity was accompanied by the generation of an infrasonic signal and an increase in lightning discharges in the EC. The two-tiered EC was well traced in the potential gradient response in atmospheric electric field. The combination of various geophysical methods provides a detailed understanding of the mechanism of explosive eruptions and contributes to a better understanding of the physics of the explosive process on volcanoes.

1. Introduction
One of the most active volcanoes of the world is Bezymyanny volcano (55.98° N, 160.59° E, height 2869 m¹). It is located in the central part of the Klyuchevskaya group of volcanoes (KGV) on Kamchatka peninsula (figure 1a). The closest neighbor of Bezymyanny in the north is the extinct volcano Kamen (4670 m) next to which is the highest volcano of Europe and Asia, Klyuchevskoy volcano (4850 m). In the southern direction is the Ploskiy Tolbachik volcano, for which powerful lateral eruptions are typical (figure 1b). After the catastrophic eruption on March 30, 1956, the cone of Bezymyanny, formed in the new crater (1.5×2.8 km, depth 700 m), continuously extruded [7] up to the end of 2012. The process had active periods with separate explosive eruptions and relatively calm periods. Manifestations of the volcanic activity are various: cone and block extrusions; explosions of different intensity including directed blasts; eruptions of pyroclastic flows (PF) and extrusion of small viscous lava flows. For more than almost a 65-year period of investigation of Bezymyanniy volcano, the events, enumerated above, often occurred there [5,10].

Since the end of 2012 to December 2016, the volcano was relatively calm. That was, evidently, associated with lateral eruption of Tolbachik volcano in 2012-2013 and four terminal eruptions of Klyuchevskoy volcano during that period [10]. In December 2016 it became active again. Two explosive eruptions occurred on March 9 and June 16, 2017. The third, the most powerful eruption

¹ Hereinafter the height is from the sea level
took place on December 20, 2017 at 03:39\textsuperscript{2}. From 03:45 PF began to descent intensively. When they got into the deceleration area, they initiated secondary eruptive clouds. This process promoted multi-layer eruptive clouds (EC).

EC height was 15 km and the main area of the territory, over which it was spread, was ~78 000 km\textsuperscript{2} (figure 2a). Based on the satellite data, the PF deposits extension was 6 km and that of mud stream was up to 18 km. According to the model calculations of EC motion, the erupted tephra mass on the ground was estimated as ~ 3\times10\textsuperscript{7} t (~0.023 km\textsuperscript{3}) \textsuperscript{6}.

![Figure 1](image.png)

**Figure 1.** Location of Klyuchevskoy group of volcanos and observation sites in the far field zone of Kamchatka peninsula (1), location of RTSS (BZW, BZG, BZP) near Bezymyanny volcano (b) and four lightning strokes accompanying the eruption on December 20, 2017 based on WWLLN data.

2. **Instrumentation**

There are sites for volcano observations and radiotelemetric seismic stations (RTSS) of Kamchatka Branch of Federal Research Center, Geophysical Survey RAS in KGV region. They allow us to monitor the seismisity of the regions near the active volcanoes (figure 1). Infrasound channels, the sensors of which are microbarographs (ISMB-03M), are installed at KZY and KLY sites. They record wave disturbances in the atmosphere during explosive eruptions. Moreover, an infrasound station IS44 of the international infrasound monitoring system is installed at Nachik site (figure 1a). The station includes an antenna array composed of four microbarographs M-2000 (France) with the aperture of ~1.8 km. It allows us to record infrasound signals in the frequency range of 0.003–5 Hz and to determine the azimuth of a source \textsuperscript{9}. To record atmospheric electric potential gradient (PG) response in atmospheric electric field, occurring during EC passage over the observation sites, the electric field mills EF-4 was installed at KZY and KLY \textsuperscript{3}.

A direction finder of very low frequencies (VLF, 8-12 kHz) is operating at the Institute of Cosmophysical Research and Radio Wave Propagation (IKIR) FEB RAS. It records electromagnetic pulses (EMP) from lightning strokes. EMP are received by two mutually-perpendicular loop antennas to record the lightning component (\(H_{NS}, H_{EW}\)) and by a rod antenna to record the electric component (\(E_z\)). \textsuperscript{1}. The VLF direction finder, located at Karymshina site 390

\textsuperscript{2} Hereinafter the UTC time
3. Data and analysis

It follows from RTSS (BZW, BZP) records of the explosive earthquake, occurred during the eruption, that the eruption began at 3:39 on May 20, 2017. During the first ~5 minutes (I), seismic signal
intensity gradually increased. Then the signal level increased rapidly and during the following 4 minutes it exceeded the instrumentation dynamic range (II). Evidently, during this period a Plinian eruption with powerful ejection of ash-gas mixture into the atmosphere began. After that, signal amplitude decreased and remained quasi-constant for almost 5 minutes followed by a decrease up to the background in 10 minutes (III) (figure 4).

Turbulent column and EC were the sources of air infrasonic waves recorded at the infrasonic site IS44 and at KZY (figure 4a). A weak inversion ($c_{ef}=275$ m/s) is observed on the vertical profile of sound effective velocity ($c_{ef}$) on the path BZM- IS44 at the height of 11 km. It may be a reflecting boundary. Making an assumption that infrasonic waves propagate mainly along this boundary, figure 4a shows the times for separate wave group onsets from the moments of their occurrences. Infrasonic signal occurrence (figure 4a) coincides with the end of the region of ground vibration maximum velocity at BZW. It is likely to be associated with EC formation in the floating zone and PF descent. PF deposit area could be the source of heat-mass release. This source formed the second layer of EC at lower height.

Figure 4. Dynamics of geophysical fields parameters accompanying Bezymyanniy volcano eruption on December 20, 2017. a – wave disturbances recorded at the infrasonic site IS44, estimated time of signal occurrence is in brackets; b – ground vibration velocity record on the vertical component at BZW; c – PG response at KLY site during EC passage.

The beginning of time reading corresponds to: a - 04:03:51, b - 03:31:51, c - 03:17:15.

EC ash fall axis was located ~20 km from KZY. Fair weather conditions allowed us to record the response from its passage, lasting for about two hours, by the electrostatic fluxmeter. The response consisted of two bay-like signals of negative polarity with the amplitude $V_i = 60$ V and $V_f = 50$ V/m and duration of 20 and 90 minutes. EC propagation at different heights had different velocity under wind effect that was recorded in PG. Based on the atmosphere stratification, the first cloud layer propagated at the height of ~ 13 km, and the second one propagated at the height of 8 km. The volumetric charge for the both parts of EC was calculated from its trajectory and the recorded response in PG by the formula $Q = V \cdot (2 \pi \epsilon_0 R_{min}^2 / z)$, where $\epsilon_0$ is the dielectric constant, $R_{min}=25$ km is the minimum distance from the recorder to the horizontal projection of EC trajectory, $z=13$ km is the EC propagation height. EC charge was ~9 and ~7.5 C, respectively.

We consider EC lightning activity dynamics according to the data of the VLF direction finder when increased amount of EMPs (inset in figure 5a) was recorded for ~ 40 minutes from the direction to
Shiveluch volcano (23.6°). A weak increase of EMP number was recorded during the first 6 minutes (I) in minute intervals (N) with the total number of 9 pulses. This fact indicated the eruption beginning according to the «smooth» scenario that agreed with earthquake record (figure 4b). During that period EMPs had negative polarity of the first half period (figure 6a). All these pulses have a negative phase of the first half-wave, which indicates a predominantly vertical orientation of the emitting dipole with a positive pole at the bottom. The next 11 minutes (II+III) are characterized by N increase up to 54 pul/min followed by a decay during 15 minutes (IV) to N=12 pul/min. For the both periods, the average maximum amplitude (\( \overline{A}_{\text{max}} \)) was within 0.4 - 1.0 mV/m.

**Figure 5.** Lightning activity dynamics for EC developed as the result of Shiveluch volcano eruption on December 20, 2017 with 1-minute sampling rate: a – EMP number (N); b – average value of EMP maximum amplitudes (\( \overline{A}_{\text{max}} \)); c – average value of EMP electromagnetic energy flow per minute (\( \overline{E} \)).

The inset shows EMP density spectrogram from the azimuth of 0°-60°.

**Figure 6.** Examples of EMP: a – eruption beginning at 03:40:33.31735; b – after the development of the volcanic lightning at 04:00:25.05091 1 – EMP electric component (\( E_z \)), 2, 3 – magnetic components in two perpendicular planes (\( H_{EW}, H_{NS} \)).

Some increase of N and significant increase of \( \overline{A}_{\text{max}} \) and \( \overline{E} \) occurred in the section V (marked by pink in figure 5). During that period, EC interacted with meteorological clouds stretching along the Kamchatka coast. From 4:00, EMP had mainly positive onsets of the first quasiperiod (figure 6b) that indicated the prevalence of in-cloud strokes. The same was observed for other volcanoes [11]. Almost
all powerful EMP generated tweeks (resonance emission at the frequency of eigen resonance of the Earth-Ionosphere waveguide). An example of such a signal is shown in figure 6b.

4. Conclusion
Analysis of the parameter complex of different geophysical methods allowed us to understand quite clearly the mechanism of Bezymyanniy volcano explosive eruption occurred on December 20, 2017. The explosion began according to the «smooth» scenario, which reflected both in the seismic method in EC lightning activity. Transition to the Plinian activity was accompanied by infrasonic signal generation and EMP increase. Two layers of EC are clearly traced in AEF V’. Combination of different geophysical methods allows us to obtain a more detailed picture of the mechanism of explosive eruptions and to understand better the explosive process physics.

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References
[1] Druzhin G I, Pukhov V M, Sannikov D V and Malkin E I 2019 VLF direction finder to investigate natural radio radiations Bulletin KRASEC. Physical & Mathematical Sciences 2 95-104
[2] Eaton A R et al 2020 Did ice-charging generate volcanic lightning during the 2016–2017 eruption of Bogoslof volcano, Alaska? Bulletin of Volcanology 82(3) 24(2020)
[3] Efimov V A, Oreshkin D M, Firstov P P and Akbashev R R 2014 EF-4 electromagnetic fluxmeter for studies of geodynamic processes Seism. Instrum. 50(3) 230–7
[4] Firstov P P et al 2020 Registration of Atmospheric-Electric Effects from Volcanic Clouds on the Kamchatka Peninsula (Russia) Atmosphere 11 634
[5] Gorshkov G S and Bogoyavlenskaya G E 1965 Bezymyanniy volcano and the features of its latest eruption in 1995-1963 (Moscow: Nauka) p 170
[6] Girina O A 2013 Chronology of Bezmyanny Volcano activity, 1956-2010 J. Volcanol. Geother. Res. 263 22–41
[7] Girina O A, Loupian E A, Melnikov D V, Manevich A G, Sorokin A A, Kramareva L S, Uvarov I A and Kashnitskiy A V 2018 Bezymianny volcano eruption on December 20, 2018 Current problems in remote sensing of the Earth from Space 3 88–99
[8] Koulakov I et al 2021 Anatomy of the Bezymianny volcano merely before an explosive eruption on 20.12.2017 Scientific Reports 11(1)
[9] Makhmudov E R, Firstov P P and Budilov D I 2017 KamIn Information System for Monitoring Wave Perturbations in the Atmosphere on the Kamchatka Peninsula Seismic Instruments 53(1) 60–69
[10] Ozerov A Yu et al 2020 Eruptions in the Northern Group of Volcanoes, in Kamchatka, during the Early 21st Century J. of Volcanol. and Seismol. 14(1) 1–17
[11] Smith C, Said R, Eaton A V and Holzworth R H 2018 Volcanic lightning as a monitoring tool during the 2016-2017 eruption of Bogoslof Volcano, AK 25th International Lightning Detection Conf. (March 12-15 Florida)
[12] World Wide Lightning Location Network http://wwlln.com [Accessed 10.12.2020]
[13] NOAA/ESRL Radiosonde Database https://ruc.noaa.gov/raobs/intl [Accessed 19.09.2020]
[14] Seismic infrasound array for monitoring Arctic cryolitozone and continuous seismic monitoring of the Russian Federation, neighboring territories and the world https://ckp-rf.ru/usu/507436/ [Accessed 25.10.2020]