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A Characteristic Electrostatic Structure of Eruptive Plumes Emitted by Large Explosive Eruptions of Shiveluch and Bezymianny Volcanoes, Kamchatka

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Abstract—This paper presents an analysis of recorded variations (anomalies) in the potential gradient of electrical field in the atmosphere caused by the propagation of eruption plumes discharged by eruptions of Shiveluch and Bezymianny volcanoes in Kamchatka. The anomalies were recorded at various distances from eruption centers and under different conditions of atmospheric stratification. These conditions have enabled us to show that the eruption plumes of Shiveluch and Bezymianny possessed a 3D electrostatic structure that is consistent with a known phenomenological model derived on the basis of surveys conducted on various volcanoes worldwide. According to this model, the top of an eruption plume contains a positive volumetric electrostatic charge, while the respective charges are negative in the middle, and positive in the lower part of the plume.

Keywords: explosion plume, electrification of eruption plumes, potential gradient of atmospheric electric field, volumetric electrostatic charge

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INTRODUCTION

Explosive volcanic eruptions discharge an eruption column which can rise to the tropopause heights, with especially strong eruptions hurling their discharges above the tropopause boundary to reach the stratosphere (Meng, 2022; Gorshkov, 1965). Wind stratification of the atmosphere favors the formation of ash plumes that can travel for hundreds of kilometers (Girina, 2017). The eruption plume contains volcanic gases, aerosol, and ash. The volcanic ejecta are electrified by physical processes such as triboelectrification, fracture emission, and the interaction between the ejecta and meteorological clouds. The eruption plume acquires 3D electrostatic structures whose charges can achieve values of breakdown in air (Rulenko, 1994; Mather and Harrison, 2006; Behnke, 2013). It is because of this phenomenon that the evolution of an eruption plume is generally accompanied by volcanic lightnings and discharges (Thomas et al., 2007; Arason et al., 2011; Behnke et al., 2013; Shevtsov et al., 2016; Cimarelli et al., 2016; Aizawa et al., 2016; Firstov et al., 2019b, 2020b; Van Eaton et al., 2020; Mendez et. al., 2021).

One of the main mechanisms which charges ash particles is fracture emission. The charging process in this mechanism acts by magma fragmentation during the initial explosion; as well, the same charging process can occur by injection of an ash–gas jet into the atmosphere, when ash particles are destroyed on collision (James et al., 2000; Mueller et al., 2017). The prevailing opinion of researchers is that it is this charging mechanism which is responsible for multiple crater discharges generating continual radio frequency (CRF) observed as a relatively high frequency of ultrashort frequency radiation (between a few thousands and more than a ten of thousands of pulses per second) (Thomas et al., 2007; Behnke et al., 2013, 2018; Behnke and Bruning, 2015; Smith et al., 2018; Mendez et al., 2021).

During the injection of the ash–gas jet, the main mechanism for electrification of ejecta becomes triboelectrification, or contact electrification (Rulenko et al., 1986; Aplin et al., 2014, 2016; Mendez et al., 2021).

When an eruption column reaches the maximum height, and an eruption plume is formed by wind stratification, the electrification processes in the plume are

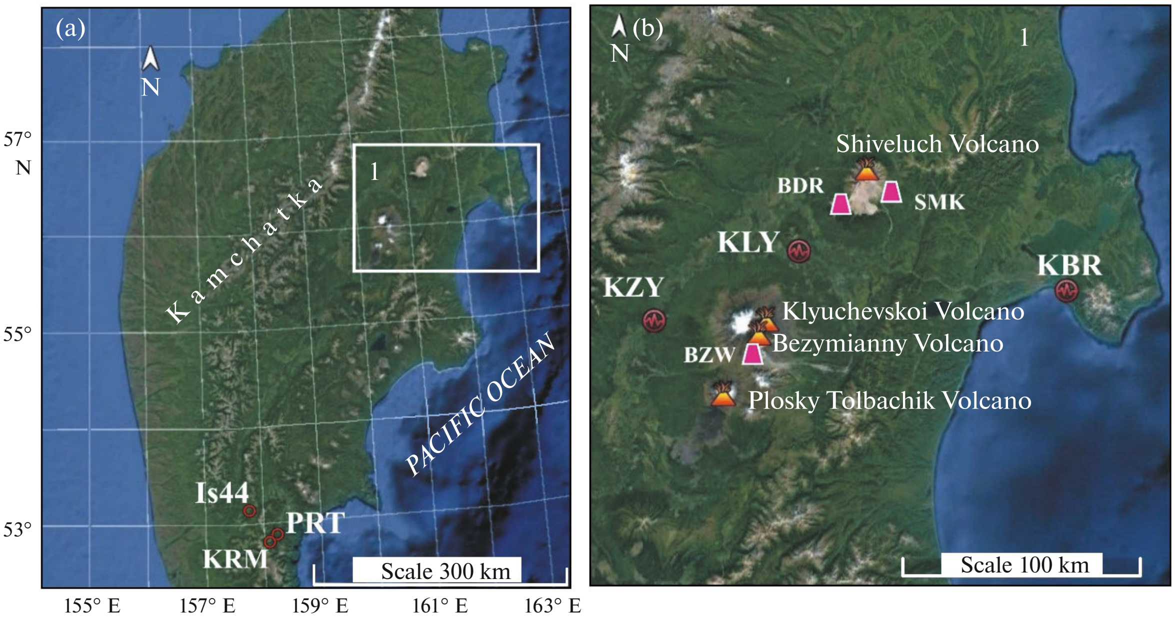

Fig. 1. A schematic map showing the sites for observation of *V' AEF* in Kamchatka. (a) A general view, (b) an enlarged fragment of the map in the area of the Northern Volcanic Cluster. KLY village of Klyuchi, KZY Kozyrevsk, KBR Krutoberegovo, IS44 infrasound station, PRT and KRM are observatories operated by the IPSRRWP FEB RAS.

similar to the formation of volumetric electrostatic charges in meteorological clouds where the important stage is the formation of hailstones. In this process, ash particles become condensation nuclei which make hailstones on contact with supercooled water (Arason et al., 2011; Van Eaton et al., 2020).

INSTRUMENTATION AND OBSERVATIONAL PROCEDURES

The central part of the Kamchatka Peninsula contains the Northern Volcanic Cluster, which includes four active volcanoes: Shiveluch, Klyuchevskoi (the highest, 4750 m, and the most productive volcano in Eurasia), Bezymianny, and Plosky Tolbachik (Fig. 1). The seismic stations (operated by the Kamchatka Branch of the Federal Research Center “Unified Geophysical Survey” of the Russian Academy of Sciences, abbreviated as KB FRC UGS RAS) near the Northern Cluster at the Klyuchi (KLY) and Kozyrevsk (KZY) stations are measuring the potential gradient of atmospheric electric field (*V'* AEF) using an EF-4 electrostatic fluxmeter with upper boundary frequency 5 Hz and rms error of 5 mV (Efimov et al., 2013). Data recorded at these stations enable us to study the electrostatic structure of eruption plumes, in addition to the traditional tasks in atmospheric electricity (the study of unitary variation, mechanisms of the global electric circuit, etc.). A detailed description of the current network of observing stations that measure *V'* AEF using an instrumental and software complex can be found in (Akbashev et al., 2021).

A VLF direction finder ($f \approx 0.5-60$ kHz) has been designed at the Institute of Physical Space Research and Radio Wave Propagation (IPSRRWP), FEB RAS to record impulsive electromagnetic radiation (IEMR) due to storm discharges. The appropriate instrumentation-software complex for the recording of IEMR is described in (Druzhin et al., 2019). In addition to the VLF direction finder installed at the Karymshina station (KRM) (see Fig. 1), the IPSRRWP FEB RAS is recording IEMR due to volcanic lightnings at the Paratunka Observatory (see Fig. 1) to within a time uncertainty of a few microseconds using a segment of the World Wide Lightning Location Network (WWLLN) (Dowden et al., 2002), which provides excellent results for monitoring the propagation of eruption plumes in the case of an optimal arrangement of recording stations. The main source of information for this study was provided by data recorded at the network of potential gradient measurement for atmospheric electric field and by the VLF direction finder of the IPSRRWP FEB RAS.

Data selection in records of *V'* AEF due to eruption plumes was based on integration of data from the geophysical control carried out at the IPSRRWP FEB RAS, viz., seismic, infrared sonic, and video monitoring. The analysis also incorporated satellite-based observations of volcanic activity in Kamchatka and data from balloon sounding incorporating weather observations and recording of storms. This integrated data analysis has enabled us to reconstruct the kinematic parameters of eruption plume propagation at

Table 1. The parameters of V' *AEF* responses recorded from eruption clouds discharged by Shiveluch Volcano

Event	Date	t_0	KZY			KLY			
			polarity	V', kV/m	Δt, min	polarity	V', kV/m	Δt, min	δ, g/m^2
Sh-1	16 Nov 2014	10:17:55	+	0.17	85	Station out of operation			
Sh-2	16 Dec 2016	22:31:32	Cloud passed far from station			–	–0.125	51	20
Sh-3	14 Jun 2017	16:26:37	+	2	360	–/+	–5.9/+4.8	40/34	~300
Sh-4	30 Dec 2018	00:34:46	Station out of operation			–	–0.59	90	80

Sh is an abbreviation of Shiveluch

the times when V' AEF responses were recorded (Firstov et al., 2017, 2019a, 2020a; Akbashev et al., 2018).

THE RESPONSE OF POTENTIAL GRADIENT OF ATMOSPHERIC ELECTRIC FIELD TO ERUPTION PLUMES DUE TO EXPLOSIVE ERUPTIONS OF SHEVELUCH VOLCANO

Shiveluch is the northernmost active volcano in Kamchatka (56°47′ N, 157°56′ E) whose extrusive dome stands 2500 m above sea level (a.s.l.). During the most recent decades its activity was due to slow extrusion of magma and formation of a dome. Violent explosive eruptions occur when pressure and temperature reach the critical values. Some of the eruptions discharged eruption plumes reaching the tropopause height (~10 km a.s.l.), with ash falling in the villages of Klyuchi and Kozyrevsk. The 2013–2018 observations at KZY and KLY have recorded four responses in V' AEF variations (Table 1) due to the movement of eruption plumes discharged by explosive eruptions of Shiveluch. An analysis of these events can be found in (Firstov et al., 2017, 2019a, 2020a).

Consider the events Sh-1 and Sh-3 in more detail (see Table 1).

The eruption of November 16, 2014

All explosive eruptions at Shiveluch were accompanied by seismic signals recorded at the network of radiotelemetry seismic stations (RTSS) operated by the KB FRC USS RAS. According to these data (http://www.emsd.ru/~ssl/monitoring/main.htm), the November 15, 2014 eruption produced an eruption column rising to12 km a.s.l., this estimate being based on the intensity of the seismic signal (Bliznetsov, 2015). The seismic records made at BDR (Baidarnaya seismic station) show a signal with maximum velocity of ground motion at all three seismometers (N–S, W–E, Z) exceeding 40 μm/s during 13 min. Figure 2a shows a fragment of the recorded explosive earthquake on the vertical component of ground motion velocity. The onset time of the seismic signal can be treated as the time when the explosive eruption started to within one second $t_0 \approx$ 10:17:55. Some idea of the configuration of the eruption plume can be gathered from a space image (Landsat 8) acquired 22 minutes after the eruption began (see Fig. 2b). The head of the eruption plume is approximately a circle with diameter ~30 km, and is surcharged with ash (dark tint). Data from balloon sounding of the atmosphere (the weather station at Klyuchi is operated by the Kamchatka Agency on Hydrometeorology and Environmental Monitoring) (http://www.esrl.noaa.gov/raobs/intl/intl2000.wmo.) acquired at 12 h 00 min November 16, 2014 were used to make temperature and wind stratification profiles up to 25 km height. The temperature stratification (temperature profile) at heights of 9–10 and 12 km involves two inversions (see Fig. 2c), with wind speed at these heights being 11 m/s and 17 m/s (see Fig. 2d) blowing north and northeast at azimuths of 50° and 80°, respectively (see Fig. 2e). The height of the lower temperature inversion is the tropopause height that is characteristic for Kamchatka during fall and winter times.

The evolution of the eruption plume can also be followed based on lightning discharges that occurred during its generation and movement. The WWLLN network has recorded seven discharges whose times and coordinates are listed in Table 2. The interval 25–40 s since the start of the eruption saw three discharges recorded near the eruption center which seem to have accompanied the rise and formation of the eruption column. The three discharges to follow occurred nearly simultaneously in 8.5 min, the hypothesis being that they occurred at the front of the eruption plume as driven by the wind as it came into contact with a cooler cloud structure. The last discharge was recorded after the lapse of 17 min at a distance of 20.5 km from the crater.

The background value of V' AEF was relatively quiet at KZY before the eruption, being greater than 0.06 kV/m (Fig. 3). At 10 h 45 min one could see the first weak variations in V' AEF, and in nearly two hours after the eruption distinct onsets appeared of two anomalies in the V' AEF record (12 h 04 min and 13 h 10 min) whose total duration was about 90 min at the time when the maximum value of V' AEF reached 0.17 kV/m. One can clearly see oscillations of higher frequency with amplitude ~0.01 kV/m before well-pronounced positive anomalies in V' AEF during 78 min. The anomalies themselves are complicated

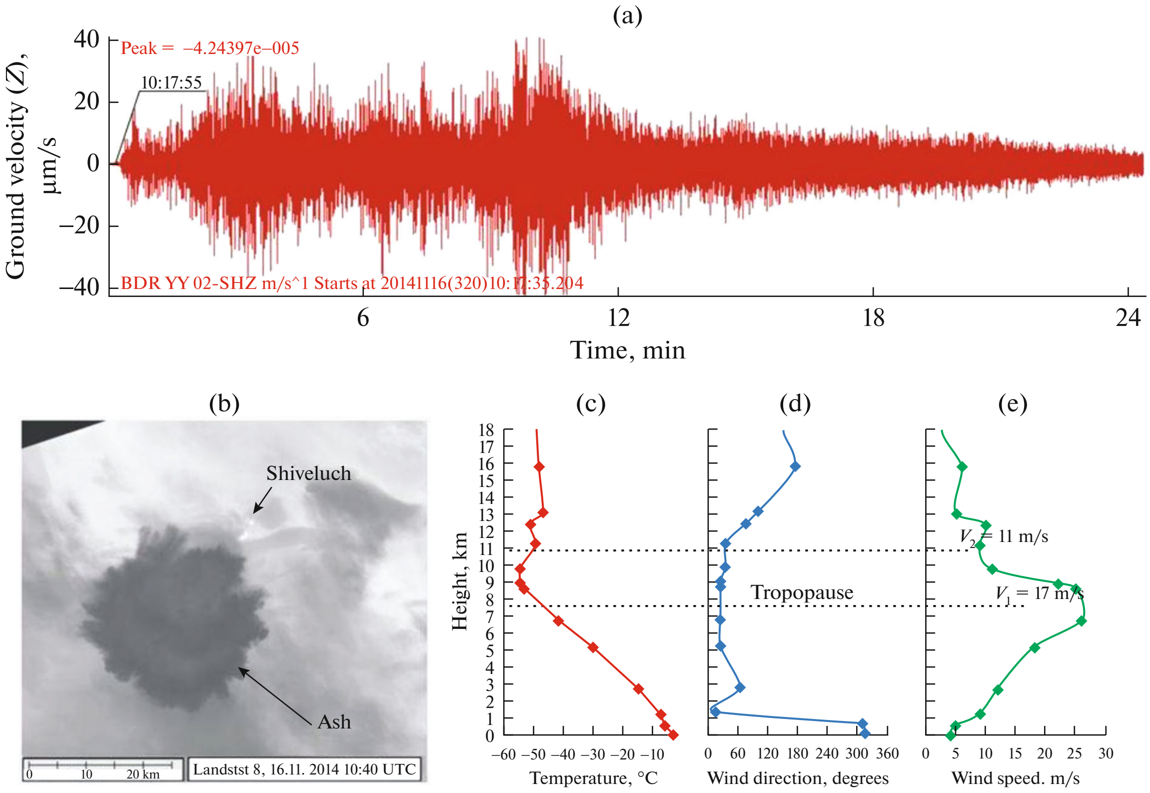

Fig. 2. Data supplied by monitoring the explosive eruption and the propagation of the eruption plume. (a) Vertical component of ground velocity due to the seismic signal at BDR which accompanied the November 16, 2014 explosive eruption of Shiveluch; (b) satellite image (Landsat 8) of the eruption plume discharged by the explosive eruption of Shiveluch, the image was taken at 10:40 on November 16, 2014; (c) data recorded at the Klyuchi weather station at 12:00 on November 16, 2014: temperature stratification; (d) wind direction; (e) wind speed.

with "high-frequency" oscillations. This signal structure provides evidence of a complex distribution of volumetric electrostatic charge density in the eruption plume, with the dominant charge being positive in the electrostatic structure of the eruption plume at at the time of recording.

We used the time difference between t_0 and the onset times of both anomalies in V' AEF to estimate the velocity of movement for the eruption plume, these being 17.7 and 10.9 m/s, respectively. The fact that the velocities of travel for aeroelectric structures are equal to wind speeds at certain heights shows that

Table 2. The chronology of the evolution of an eruption cloud due to the November 16, 2014 explosion on Shiveluch Volcano

No.	Event	Time	φ, N	λ, E	*R*, km	*v*, m/s
1	Seismic onset at BDR	10:17:55.3				
2	Discharges due to volcanic lightnings	10:19:16.1	56.58	161.31	2.7	
3		10:19:26.7	56.67	161.38	4.5	
4		10:19:33.8	56.82	161.31	8.9	
5		10:26:22.6	56.56	161.23	10.9	
6		10:26:22.6	56.60	161.17	10.8	
7		10:26:22.6	56.64	161.13	11.9	
8		10:36:10.2	56.53	161.31	20.5	18.7
9	Satellite image-1	10:40				
10	Response in V' AEF variations as recorded at KZY station	12:04	1st front		113.0	17.7
11		13:10	2nd front		113.0	10.9

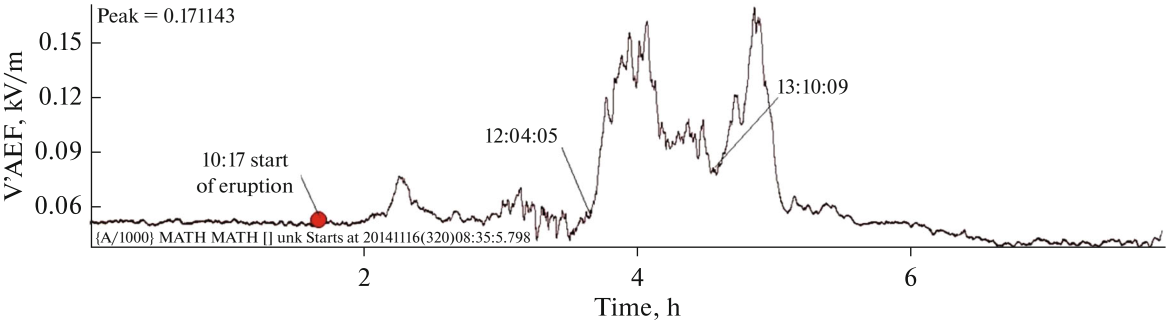

Fig. 3. Fragments of a record of electric potential gradient at KZY as the eruption plume discharged by the November 16, 2014 eruption of Shiveluch was propagating.

the eruption plume due to the November 16, 2014 eruption of Shiveluch could reside at two heights, 8–10 and 12 km.

An integrated data analysis was applied to this case to obtain kinematic parameters for the propagation of the eruption plume. These data have enabled us to estimate the electrostatic charges for both parts of the eruption plume using the relation $Q = V'(2\pi\varepsilon_0 R^3_{\min}/z)$ (Cherneva, 2007) where ε_0 is the dielectric constant, $R_{\min} = 25$ km is the shortest distance from the recorder to the horizontal projection of the eruption plume, and $z = 10$ (12) km is the height at which the eruption plume was moving. The charge of the eruption plume was estimated as 17.7 and 23.8°C, respectively.

The June 14, 2017 eruption

During this explosive eruption as reported by the KB FRC UGS RAS (http://www.emsd.ru/~ssl/monitoring/main.htm), the eruption column as estimated from the intensity of the seismic signal (Bliznetsov and Senyukov, 2015) was ~12 km. The explosive earthquake that accompanied the eruption lasted about 10 min at SMK. The instrumentation had capabilities limited by the available dynamic range, so that we could not record the peak amplitude of ground velocity, but it can still be asserted that the amplitude exceeded $A_{\max} > 40$ μm/s. Figure 4a shows a fragment of recorded ground velocity at the vertical component.

The eruption was accompanied by a shock air wave that was converted to an infrasound wave with increasing distance, and was recorded by all microbarographic instruments installed in Kamchatka (Fig. 5). The delay time of the acoustic signal relative to the seismic signal as recorded at SMK, which can be treated as the start of the eruption, was 2.19 min for KLY and 5.28 min for KZY. As to IS44, we identified two arrivals of individual groups of infrasound waves related to the propagation of sound rays in the stratospheric and tropospheric waveguides.

Satellite images (HIMAWARI-8, data from Regional and Mesoscale Meteorology Branch NOAA/NESDIS, http://rammb.cira.colostate.edu/) show that a nearly circular eruption plume was formed during 34 min after the eruption. Its diameter was ~70 km at a height of 9 km (see Fig. 5b). Later on, according to the current wind stratification, the eruption plume started moving to the village of Klyuchi at a velocity of 12 m/s (see Figs. 5b, 5c, 5d). The formation of the eruption plume during the first few minutes after the start of the explosive eruption was recorded at KLY by a video camera which was part of the geophysical complex for monitoring the activity of Shiveluch Volcano (see Fig. 5e).

After the lapse of nearly one hour the eruption plume reached Klyuchi where it deposited 100 g/m^2 ash, and then continued moving toward Klyuchevskoi Volcano (see Figs. 5f, 5g). At 21:33 it reached Kozyrevsk where there was a small fallout of fine-particle ash.

Based on the data of the VLF direction finder, the formation of the eruption plume was accompanied by IEMR as shown by the azimuth of recorded IEMR (Fig. 6a), with the dynamics of the rate of counts for IEMR in the minutes range (see Fig. 6b). The duration of the volcanic storm was determined to be 13 min (Malkin et al., 2023), the maximum rate of counts was 75 pulses per minute, the azimuth of the recorded IEMR was toward Shiveluch 25.6° [±] 10°.

A favorable combination of a fair weather and wind direction during the eruption of June 14, 2017 has enabled the response of V' AEF to be recorded during the propagation of the eruption plume above the villages of Klyuchi and Kozyrevsk.

The value of V' AEF started to decrease at KLY since 17:40, reaching –6 kV/m to be replaced with a sharp increase in V' AEF up to +5 kV/m (see Fig. 6c). An analysis of satellite monitoring data, video observations, and observed V' AEF showed that a negative disturbance in V' AEF was recorded as the eruption plume was approaching KLY, which reflected the total electrostatic field induced at KLY owing to its electrostatic structure, thus providing evidence of a dominant

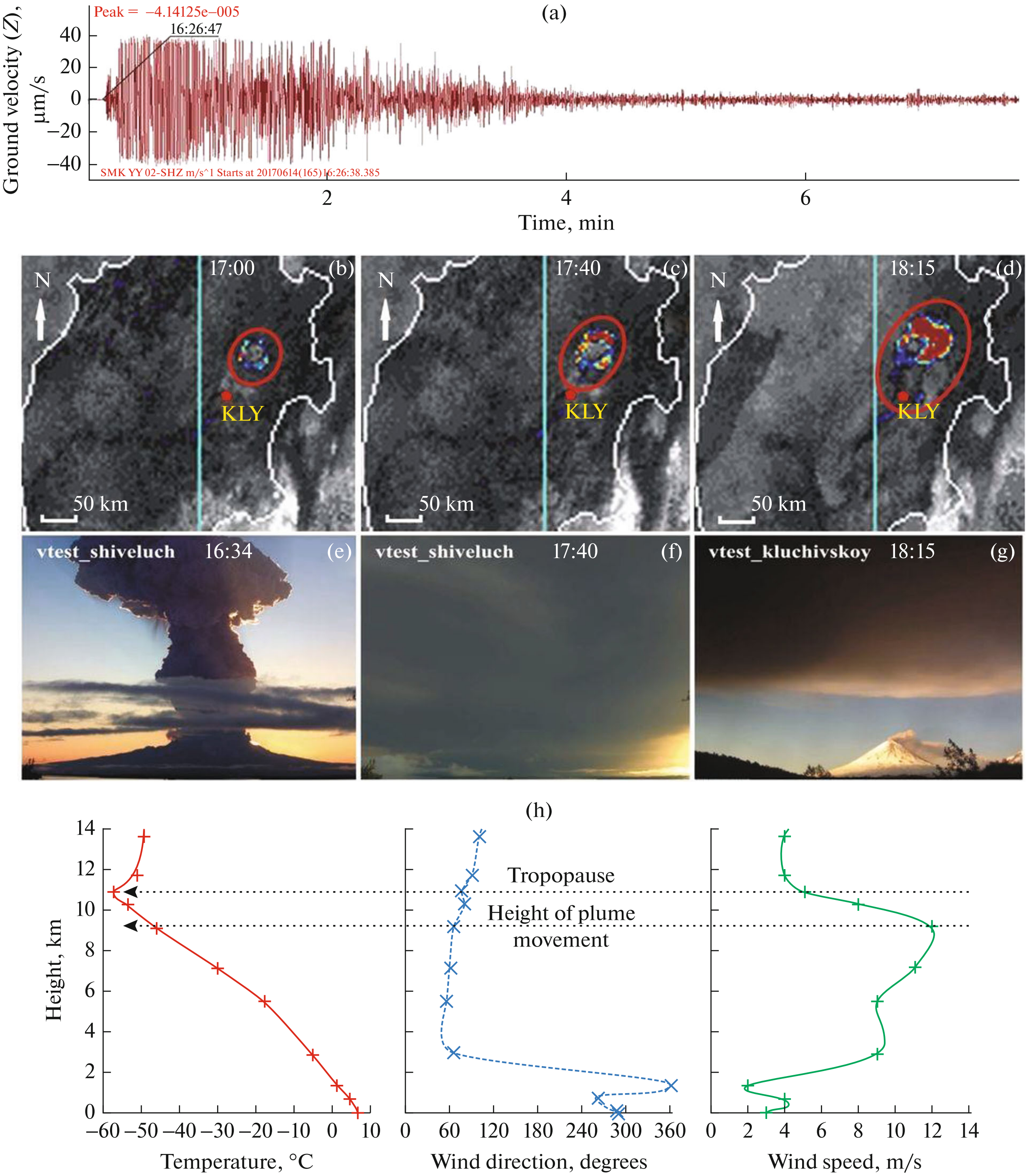

Fig. 4. Data supplied by monitoring the explosive eruption and the propagating eruption plume. (a) Vertical component of ground velocity due to the seismic signal as recorded at SMK, which accompanied the June 14, 2017 explosive eruption of Shiveluch; (b, c, d) propagating eruption plume discharged by the June 14, 2017 eruption of Shiveluch: at 16:26 based on HIMAWARI-8 satellite images (http://rammb.cira.colostate.edu); (e, f, g) evolution of the eruption plume as recorded by a video camera installed at KLY; (h) temperature and wind stratification based on balloon sounding of the atmosphere at KLY.

negative charge in it. As the eruption plume was passing above KLY depositing larger ash particles, a positive disturbance in V' AEF was recorded, providing evidence of a volumetric positive charge that was localized in the lower part of the eruption plume.

Based on known parameters characterizing the propagation of both parts of the eruption plume ($R = 0$ km, $h_1 = 5.7$ km, $h_2 = 4.1$ km), we estimated their volumetric electrostatic charges, these being −26 C for the upper region and 15 C for the lower.

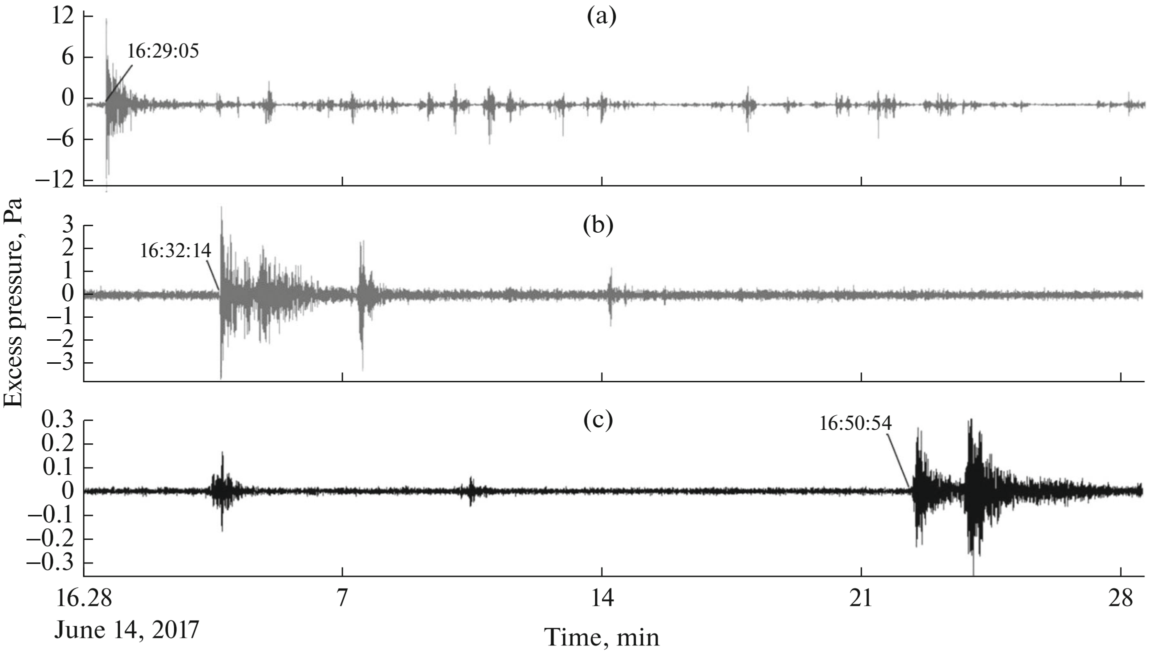

Fig. 5. The record of the air wave that accompanied the June 14, 2017 eruption as recorded at acoustic stations ((a) KLY; (b) KZY; (c) IS44).

The eruption plume reached Kozyrevsk after nearly 5 h, where some fine ash was deposited. A fluxmeter installed at KZY recorded response 9 (see Fig. 6d) of positive polarity lasting over 6 h and having the maximum signal amplitude equal to 2 kV/m. The response had a strongly elongated structure along the direction of movement with a dominant positive charge. The rugged character of the V' AEF signal provides evidence that the ash plume had a strongly inhomogeneous electrostatic structure with different charge densities in it.

THE RESPONSE OF THE POTENTIAL GRADIENT IN THE ATMOSPHERIC ELECTRIC FIELD TO ERUPTION PLUMES OF EXPLOSIVE ERUPTIONS ON BEZYMIANNY VOLCANO

Bezymianny (55.98° N, 160.59° E, height 2869 m a.s.l.) is one of the most active volcanoes in the world. It stands in the middle of the Klyuchevskoi Volcanic Cluster, Kamchatka (see Fig. 1).

Two responses in V' AEF variations have been recorded at KLY during the period 2013–2022 (Table 3). The responses were due to the eruption plumes produced by powerful explosive eruptions of Bezymianny (Firstov, 2021b).

The Bezymianny eruption of December 20, 2017

During this explosive eruption as reported by the KB FRC UGS RAS (http://www.emsd.ru/~ssl/monitoring/main.htm), the height of the eruption plume as estimated from the intensity of the associated seismic signal (Bliznetsov and Senyukov, 2015) was ~15 km.

It follows from BZW records of an explosion earthquake occurring during the eruption that it started at 3:39:24 on December 20, 2017. During the first ~5 min the intensity of the seismic signal was gradually increasing to be followed by a sharp increase in signal level, exceeding the dynamic range of the instrument during the subsequent 4 min $A_{\max} > 40$ μm/s. It seems that a Plinian eruption began to occur during that period accompanied by a powerful discharge of ash—

Table 3. The parameters of V' *AEF*, responses recorded from eruption clouds discharged by Bezymianny Volcano

Event	Date	t_0	KLY					
			polarity	V', kV/m		Δt, min		δ, g/m^2
B-1	20 May 2017	3:39:24	–	–0.09	–0.08	20	90	No ashfall
B-2	15 Mar 2022	12:51:19	+	1.3		75		No ashfall

B is an abbreviation of Bezymianny.

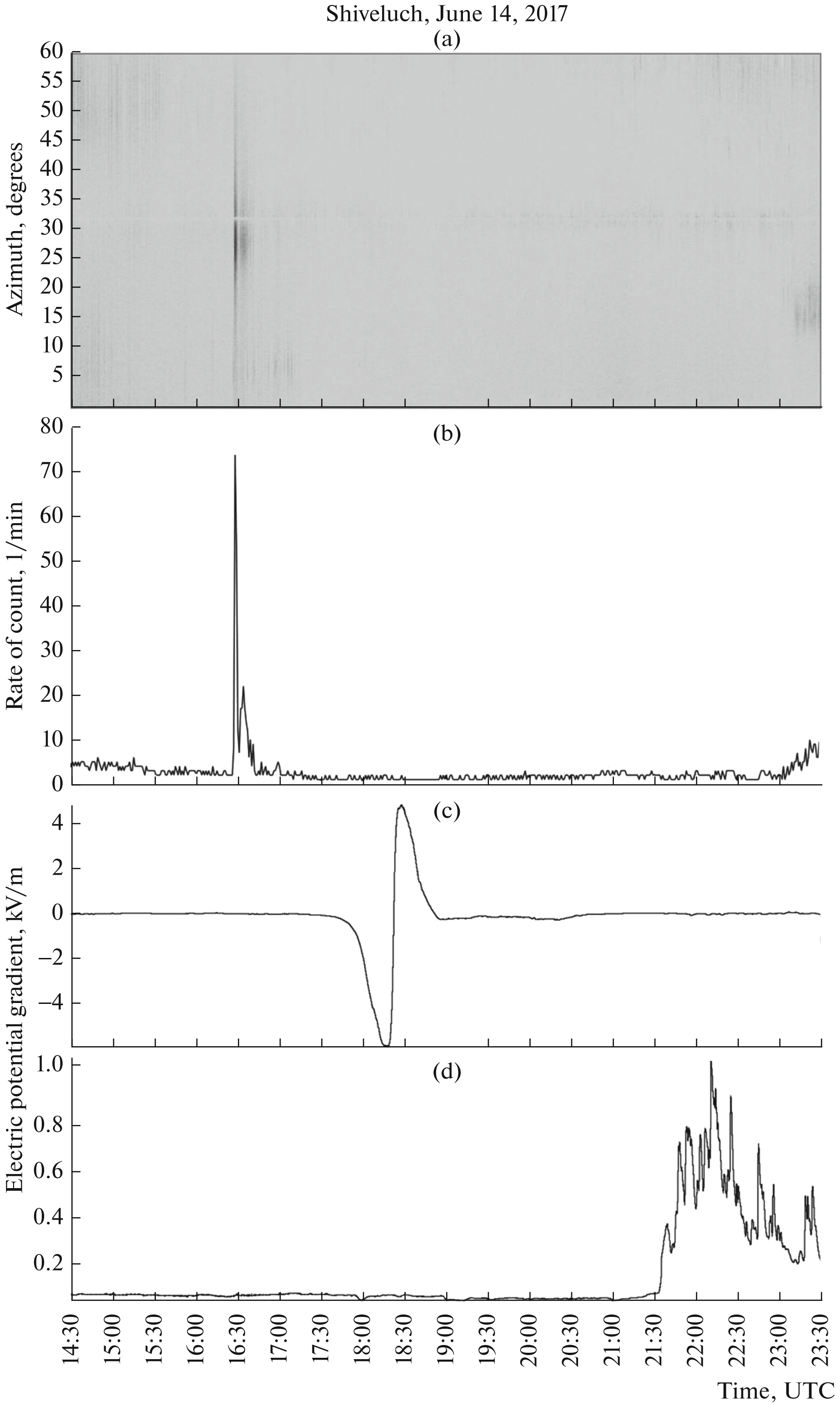

Fig. 6. Recorded electromagnetic disturbances that accompanied the Shiveluch eruption of June 14, 2017. (a) Arrival azimuth of IEMR; (b) rate of counts for IEMR in one-minute intervals; (c) fragments of a record of atmospheric electrical potential gradient at KLY; (d) fragments of a record of atmospheric electrical potential gradient at KZY.

gas mixture into the atmosphere (Fig. 7a). The signal amplitude then decreased, and was nearly constant during ~5 min to be followed by subsequent decay down to the background level in 10 min.

According to the data of balloon sounding (see Figs. 7d, 7e, 7f) carried out at the Klyuchi weather station of the Kamchatka Hydrologic and Meteorological Survey at 00:00 December 20, 2017, the wind direction at heights of 6–16 km was constant (~220°) with considerable variations in its speed between 10 and 30 m/s. The direction of movement and speed of the eruption plume are clearly seen in Himawari-8 satellite images (http://dvrcpod.planeta.smislab.ru/animation/1513757110.gif). According to Girina et al. (2018), the area of plume propagation was ~78 000 km^2 (see Fig. 7c). The tephra due to this eruption deposited on land was ~3×10^7 t according to modeling calculations (volume ~0.023 km^3); the deposits of pyroclastic flows were 6 km long, those of mudflows were within 18 km. As pyroclastic flows came into a braking zone, the result was to produce secondary eruption plumes. The process favored a multilevel character of the eruption plume.

Based on data supplied by the VLF direction finder, the formation of the eruption plume was accompanied by IEMR as can be inferred from the azimuth of the recorded IEMR (Fig. 8a). Figure 8b shows the dynamics of the rate of counts for IEMR in the interval of one minute. The duration of the volcanic storm was determined to be 45 min (Malkin et al., 2023), with the maximum rate of counts being 195 pulses per minute and the azimuth of recorded IEMR pointing toward Bezymianny Volcano, 32.5° [±] 10°.

The ashfall axis was at a distance of ~20 km from KLY (see Fig. 7c), no ash fell at the observation site. There was fair weather, which permitted the response in V' AEF variations to be recorded using an electrostatic fluxmeter. The response was due to an eruption plume whose total duration was about two hours. The response consisted of two bay-like signals of negative polarity whose amplitudes were 0.06 and 0.05 kV/m and the durations were 20 and 90 min (see Fig. 8c). The eruption plume was traveling at different speeds at different heights owing to wind action, which has been recorded in the V' AEF field. According to atmospheric stratification, the first level of plumes was traveling at a height of ~13 km and speed ~20 m/s, while the second was at 8 km and its speed of propagation was ~10–12 m/s. The parameters of propagation such as these correspond with the time when responses in V' AEF variations began to occur.

The eruption plume due to this event was not traveling above the recording site, and no ash fell at KLY. For this reason the recorded response with a negative disturbance reflects the total electrostatic field induced at KLY by the entire electrostatic structure of the eruption plume, which provides evidence of a dominant negative charge in the plume at the time the response was recorded.

Based on known parameters involved in the propagation of both parts of the plume (R = 20 km, h_1 = 13 km, h_2 = 8 km), we estimated their total electrostatic charges as –9 and –7.5°C, respectively.

The March 15, 2022 eruption of Bezymianny Volcano

This eruption started at 12:51:19 as can be inferred from data at the BZW station where an explosive earthquake has been recorded (Fig. 9a). The maximum height of the eruption plume was estimated as ~11 km a.s.l.

In that case the upper part of the eruption plume mostly propagated northward (180°–210°), being driven by wind stratification at heights of 10–11 km at a speed of 5–8 m/s (see Figs. 9f, 9g), while its lower part was propagating at heights of 6–10 km north-northwest (150°) at a speed of 9–12 m/s. According to data supplied by the Japan Meteorological Agency (http://ds.data.jma.go.jp/svd/vaac/data/vaac_list.html), satellite images (Himawari-8) clearly show the evolution of the upper and lower parts of the plume and their propagation in accordance with wind stratification (see Figs. 9b, 9c, 9d, 9f, 9g). It thus appears that the upper part of the eruption plume was propagating above KLY at the tropopause height and above it (see Figs. 9c, 9d).

Owing to an inhomogeneous stratification of the atmosphere at the eruption time, the eruption plume was elongated, its observed azimuthal angle size was 22.5° relative to the Karymshina station (KRM) (see Fig. 1) where an VLF IEMR direction finder was installed (Firstov et al., 2020b; Malkin et al., 2021). An analysis of the data supplied by the VLF direction finder has confirmed the presence of a storm source in the azimuthal angles between 8.2° and 27° (Fig. 10a). The highest rate of counts was 36 pulses per minute (see Fig. 10b), with the total number of recorded pulses being 1138. The arrival azimuth of impulsive radiation (see Fig. 10a) for all pulses during the first phase of the storm was 23.6° ± 0.4°, which was the same as the azimuthal direction toward the volcano itself. The highest intensity of discharges was observed after the lapse of 17 minutes since the start of the eruption with azimuth ~17°. An analysis of initial phases of the recorded pulses revealed that the direction of positive lightnings in the dynamics of storm evolution was steadily moving with decreasing azimuth (the last positive pulse had azimuth 8.2°), while negative lightnings were recorded in all azimuthal angles mentioned above. The arrival azimuths of positive pulses provide evidence of the fact that the upper part of the eruption plume propagating northward was passing above KLY (see Fig. 1), which too provides evidence of a positive volumetric charge in this part of the eruption plume.

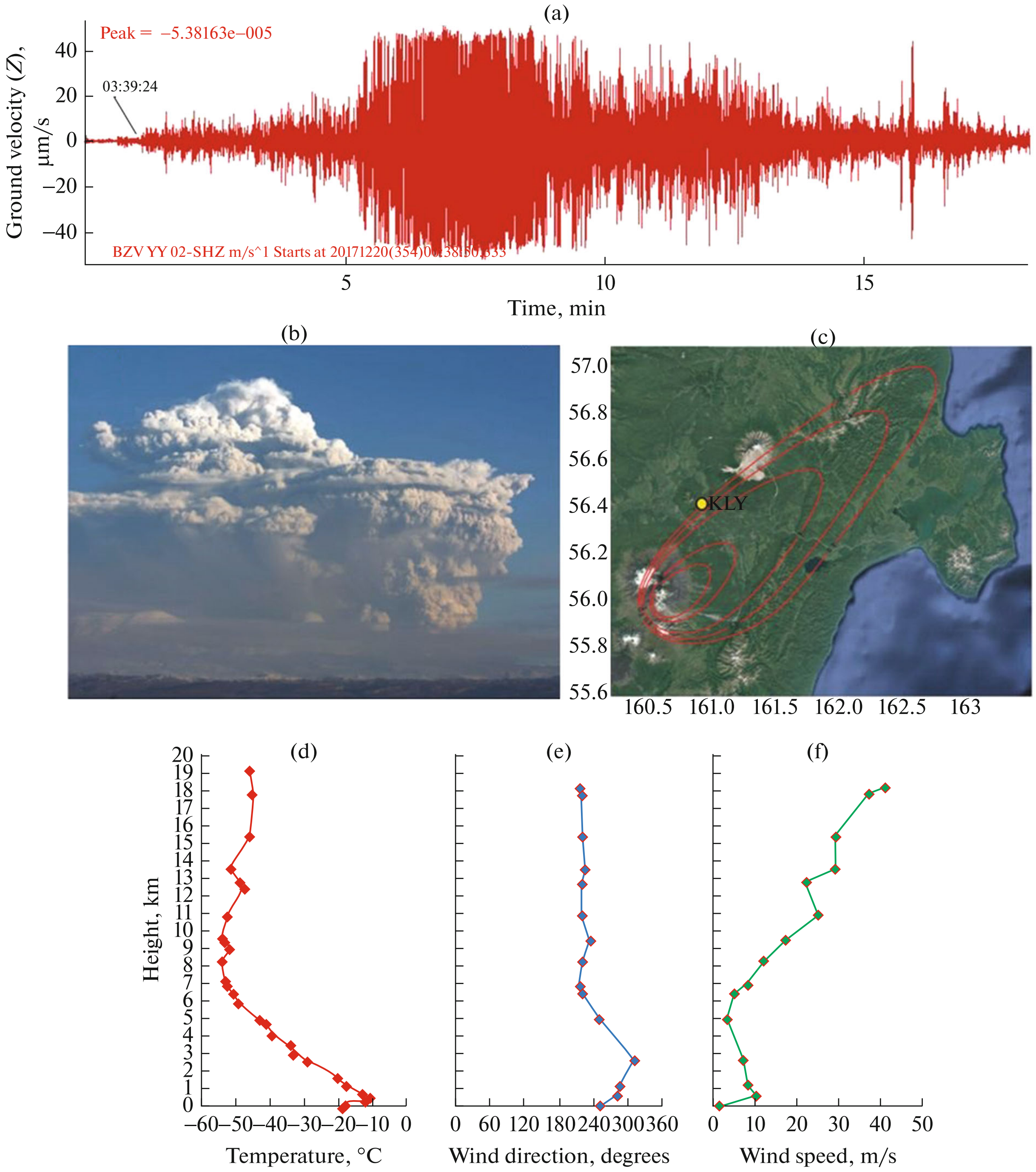

Fig. 7. Data from monitoring the explosive eruption and the propagation of the eruption plume. (a) Vertical component of ground velocity due to the seismic signal recorded at BZW accompanying the explosive Bezymianny eruption of December 20, 2017; (b) a photograph of the eruption plume taken at KZY at 03:59; (c) calculated isopachs for pyroclastic deposits due to the December 20, 2017 eruption, after (Girina et al., 2018); (d, e, f) temperature and wind stratification of the atmosphere as inferred from data supplied by the balloon sounding at KLY 00:00 on December 20, 2017.

A response with a positive disturbance was recorded in *V*′ AEF variations during the time interval between 13:30 and 14:30 (see Fig. 10c), which reflects the total electrostatic field induced at KLY from the upper part of the eruption plume, which too provides evidence of a dominant positive charge in the plume at the time the response was recorded.

An integrated data analysis has reconstructed the kinematic parameters for the propagation of the eruption plume. Using the minimum distance from the

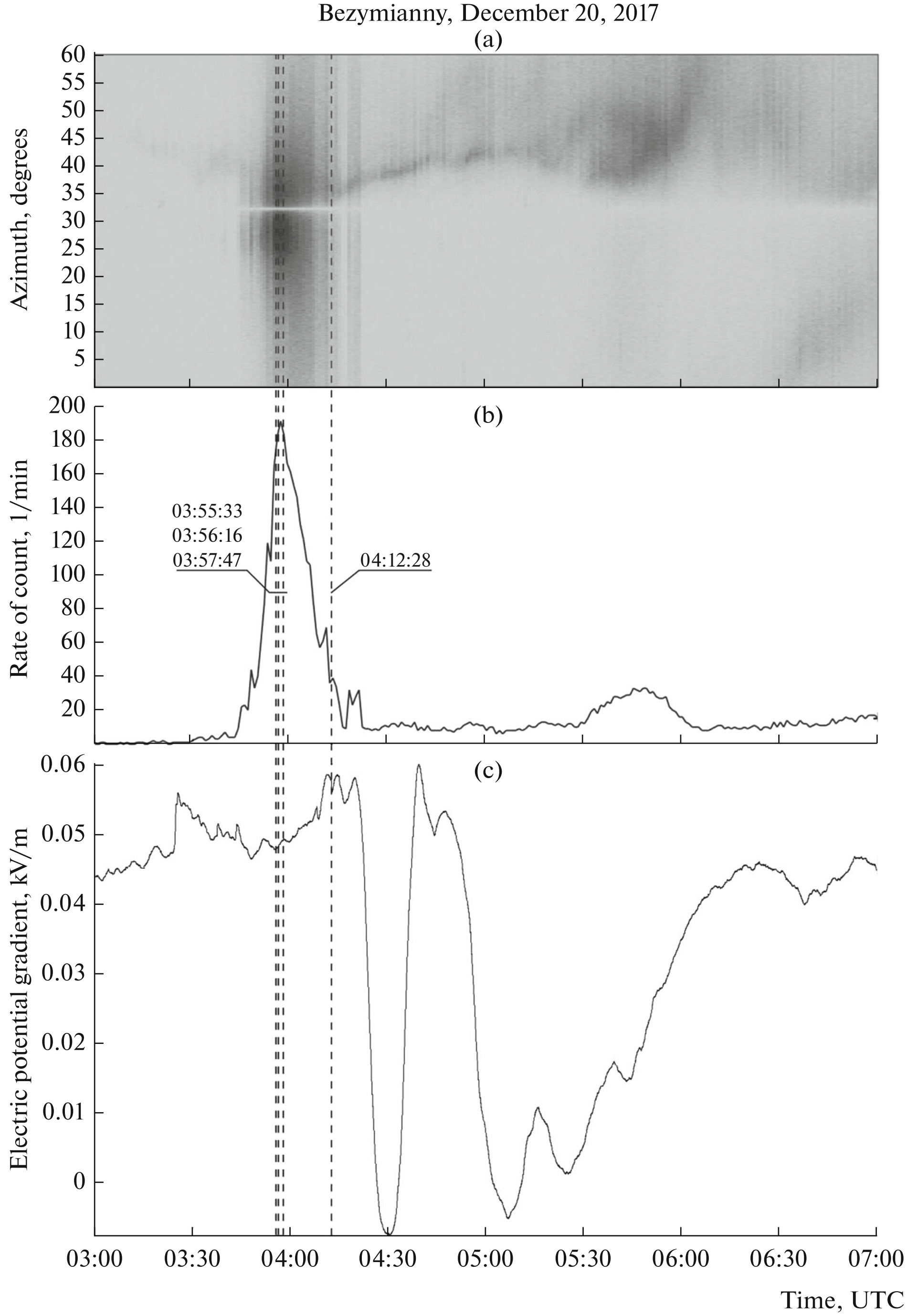

Fig. 8. Recorded electromagnetic disturbances that accompanied the Bezymianny eruption of December 20, 2017. (a) Arrival azimuth of IEMR; (b) rate of counts of IERM in one-minute intervals; (c) fragments of a record of atmospheric electric potential gradient at KLY. The dashed line shows the time of lightning discharges as recorded by the WWLLN network.

recorder to the horizontal projection of the path of the eruption plume $R_{\min} = 0$ km and the height at which it was propagating ($h = 11$ km), we estimated the charge of the eruption plume as +12.2°C.

RESULTS AND DISCUSSION

We used the results of in situ observations of the potential gradient in the atmospheric electric field (V' AEF) on Sakurajima Volcano, Japan during its 1991 eruption (Lane and Gilbert, 1992) and the 1995 eruption of the same volcano (Miura et al., 2002), as well as observations during the Great Tolbachik Fissure Eruption (GTFE) in July–October 1975 (Kamchatka, Russia) (Rulenko and Tokarev, 1979). We proposed phenomenological models of how volumetric charges are separated during the formation of an erup-

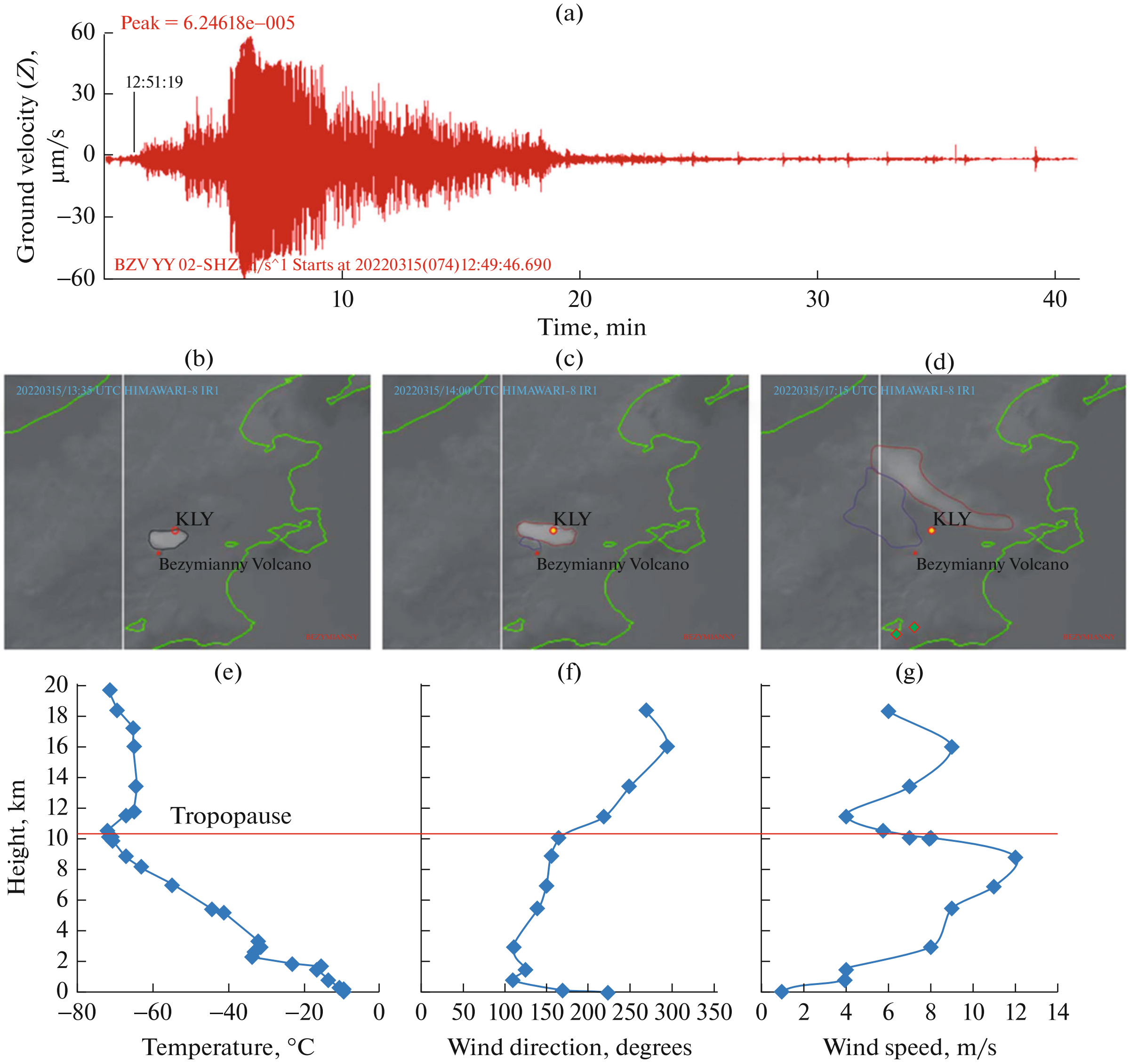

Fig. 9. Data obtained by monitoring the explosive eruption and the propagating eruption plume. (a) Vertical component of ground velocity due to the seismic signal as recorded at BZW which accompanied the explosive Bezymianny eruption of March 15, 2022; (b, c, d) phases in the propagation of the eruption plume as inferred from HIMAWARI-8 satellite images (http://rammb.cira.colostate.edu): the evolution of the eruption plume at 13:00 (b), 14:00 (c), and 17:00 (d); (e) data from height sounding at the village of Klyuchi at 12:00 on March 15, 2022: temperature stratification of the atmosphere; (f, g) wind stratification in the atmosphere.

tion column and during the propagation of the eruption plume (Fig. 11).

In these works, the charge distribution in an eruption plume was explained by eolian differentiation and sedimentation of ejecta in the gravity field. Such a charge distribution due to wind stratification in the atmosphere and under the force of gravity is in agreement with one known phenomenological feature of triboelectrification, namely, size-dependent bipolar charging (SDBC), with negative charges being characteristic for smaller particles and positive ones for larger particles (Lacks and Levandovsky, 2007; Alois et al., 2017; Mendez et al., 2021).

An analysis of data coming from geophysical monitoring of volcanic activity, satellite monitoring, data from balloon sounding of the atmosphere, and data from the recording of storms (IPSRRWP FEB RAS) has enabled us to reconstruct the kinematic parameters for the propagation of the upper and lower parts of the eruption plume in the atmosphere due to the eruptions of Shiveluch and Bezymianny volcanoes. This has enabled us to establish a connection between the recorded response and the volumetric electrostatic charges in the eruption plume. It has been shown based on these data that volumetric electrostatic charges in the eruption plume for explosions occurring

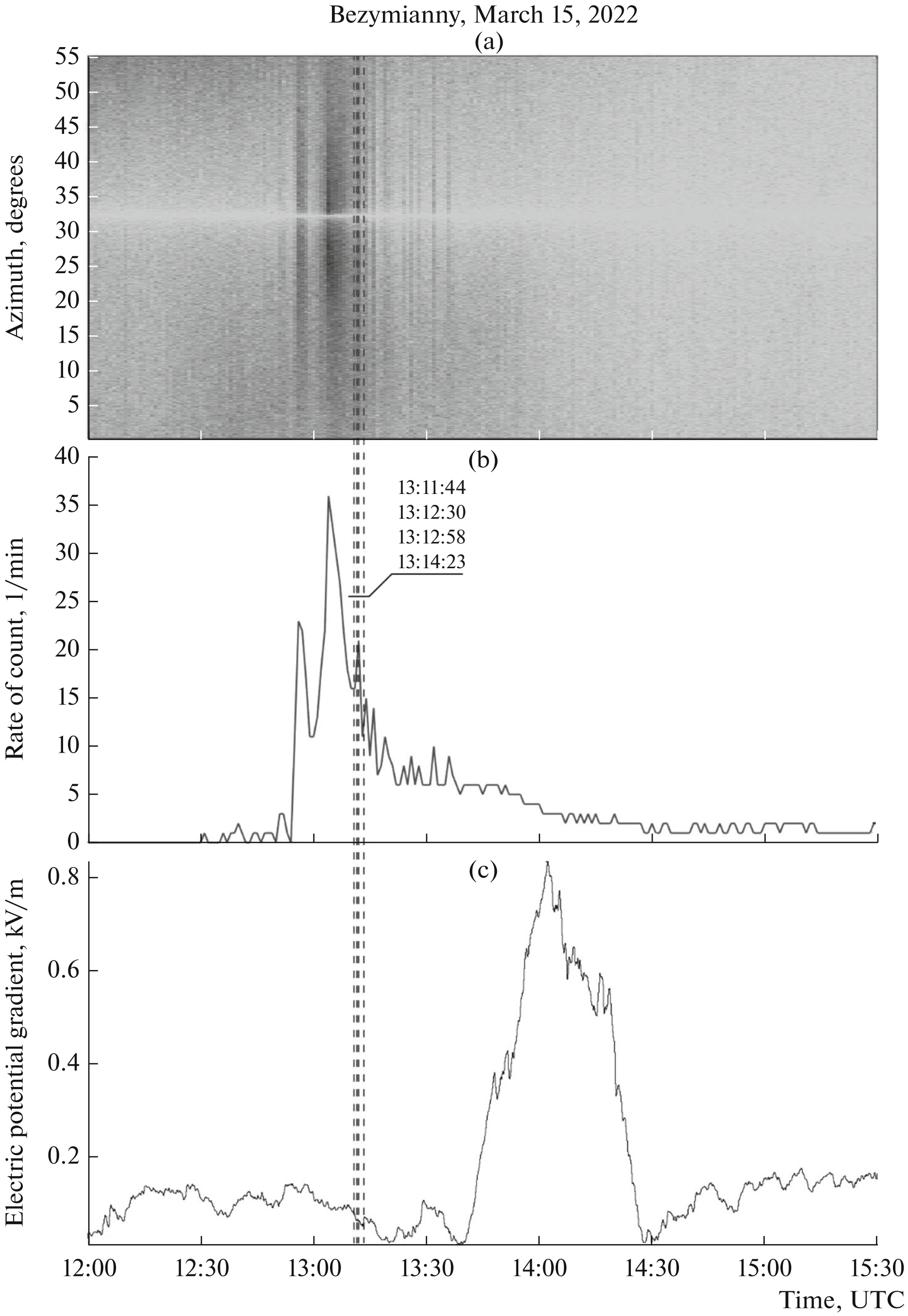

Fig. 10. Recorded electromagnetic disturbances that accompanied the Bezymianny eruption of March 15, 2022. (a) Arrival azimuth of IEMR; (b) rate of counts for IEMR in one-minute intervals; (c) fragments of a record of atmospheric electric potential gradient at KLY. The dashed line shows the time of lightning discharges as recorded by the WWLLN network.

at Shiveluch and Bezymianny volcanoes were formed following a known model, namely, positive/negative/positive (“P/N/P”) (Rulenko, 1994; Miura, 2002). According to this model, the dominant charge in the eruption plume is negative, it is transported by fine ash, and is localized in the lower part of the plume. A positive electrostatic charge is formed in the lower and upper regions. In the lower region the charge is transported with the coarsest ash and in the upper with aerosol and gas.

The dominant negative charge in the eruption plumes discharged by Shiveluch and Bezymianny can be supported by two events which were considered in this paper: (1) July 14, 2017 for Shiveluch and (2) May 20, 2017 for Bezymianny. As an example, in the former case, as the eruption plume was moving toward the

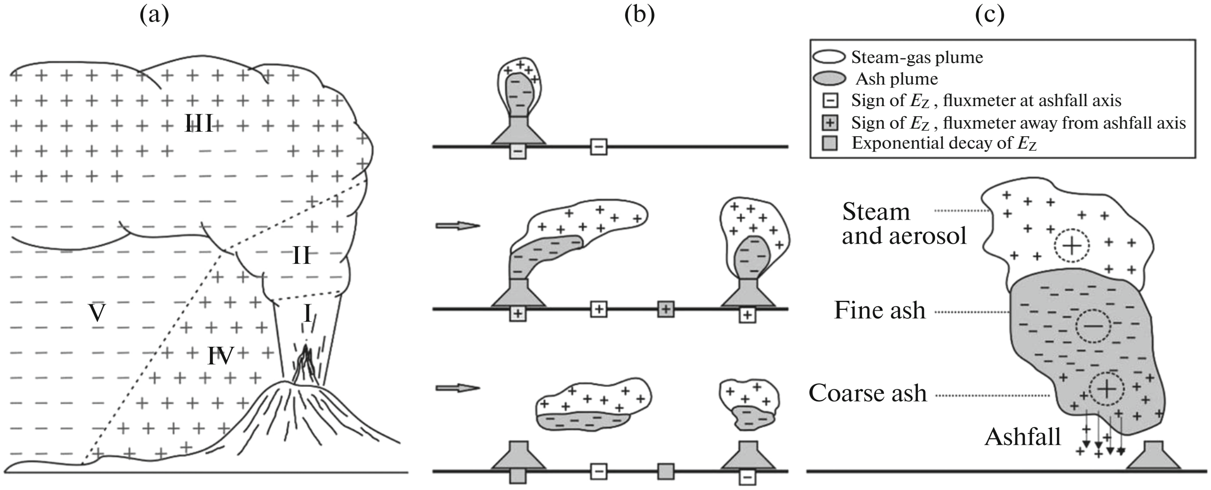

Fig. 11. Phenomenological schemes for separation of charges in an eruption plume: in the near zone around the volcanic crater (Rulenko, 1994) (a); schemes for charge separation during the formation of a volcanic plume when driven by wind, according to (Lane and Gilbert, 1992) (b); charge separation in eruption plumes based on in situ observations at Sakurajima Volcano after (Miura et al., 2002) (c). (I) charge separation under gravity at the initial segment with a light wind; (II) plume formation in the self-similar segment under the action of wind; (III) plume in the buoyant zone; (IV) area where the coarser fraction was deposited; (V) area of tephra deposition. The models have been adapted by these authors.

KLY observation site, the induced total electrostatic field due to the entire plume was characterized by negative polarity in the *V'* AEF variations (see Fig. 6c), while a positive disturbance was only recorded at the time when the eruption plume was passing above the observation site during ashfall. This provides evidence that a positive volumetric electrostatic charge was formed in the lower region. In the latter case the atmospheric stratification was such as to make the eruption plume move in a single direction and far from the observation site (see Fig. 7c), and a *V'* AEF signal was recorded with a negative disturbance (see Fig. 8c).

The resulting positive volumetric electrostatic charge in the upper regions of the eruption plumes discharged by Shiveluch and Bezymianny can be confirmed by three events considered in this paper: the first two events for Shiveluch (November 16, 2014 and July 14, 2017), and the third for Bezymianny (March 15, 2022). As an example, *V' AEF* signals with positive disturbances were recorded at KZY, which is 110 km from the eruption center (relative to Shiveluch Volcano). The rugged character of the *V'* AEF signal (see Figs. 3, 6d) provides evidence that the ash plume has a strongly inhomogeneous electrostatic structure with different charge densities in the plume. It seems that, owing to eolian and gravity sedimentation at distances longer than 100 km from the eruption center, the ash plume mostly consists of aerosols and gases, which were localized in the upper region of the plume at the time when the plume was formed. The presence of a positive volumetric electrostatic charge in the upper region of the eruption plume can also be inferred from a positive disturbance in the variations of *V'* AEF gradient (see Fig. 10c) recorded at KLY (~40 km from the eruption center) as the March 15, 2022) eruption plume was traveling. In that case the stratification conditions were such as to make the lower and middle regions of the eruption plume travel northwestward, while the upper region was moving north. As a result, only the upper region of the eruption plume was traveling above KLY.

CONCLUSIONS

An integrated analysis of data supplied by the geophysical monitoring of volcanic activity, satellite monitoring, data from the balloon sounding of the atmosphere, and data of storm recording (IPSRRWP FEB RAS) has enabled us to reconstruct the kinematic parameters for the propagation of the upper and lower regions of the eruption plume in the atmosphere discharged by eruptions of Shiveluch and Bezymianny. The reconstructed conditions for the propagation of eruption plumes due to the eruptions under study here were compared with measurements of potential gradient of the atmospheric electric field, thus enabling us to identify the associated volumetric electrostatic charges in the eruption plume. It has been shown that the volumetric electrostatic charges were formed in the eruption plumes excited by explosions at Shiveluch and Bezymianny following a well-known model, namely, positive/negative/positive ("P/N/P") (Rulenko, 1994; Miura, 2002). The upper region has a positive charge, the middle a negative, while the lower region has a positive charge.

The configuration of the volumetric charge in accordance with the P/N/P model was in all probability formed in the near zone around the volcanic crater owing to sedimentation of ejecta under the force of gravity. However, to confirm this inference we need additional experimental surveys in the near zone around volcanic craters. It should be noted that the above model for the formation of unipolar charges in an eruption plume is consistent with the known phenomenological feature of triboelectrification, namely, size-dependent bipolar charging of particles (SDBC), with negative charge being characteristic for smaller particles and positive for larger ones (Mendez et al., 2021).

ABBREVIATIONS AND NOTATION

BDR	Baidarnaya station
CRF	continual radio frequency
FEB	Far East Branch
FRC	Federal Research Center
IEMR	impulsive electromagnetic radiation
IPSRRWP	Institute of Physical Space Research and Radio Wave Propagation
KB	Kamchatka Branch
KLY	Klyuchi station
KZY	Kozyrevsk station
RAS	Russian Academy of Sciences
RTSS	radiotelemetry seismic stations
UGS	Unified Geophysical Survey
WWLLN	World Wide Lightning Location Network

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

Aizawa, K., Cimarelli, C., Alatorre-Ibarguengoitia, M.A., et al., Physical properties of volcanic lightning: constraints from magnetotelluric and video observations at Sakurajima volcano, Japan, *Earth Planet. Sci. Lett.,* 2016, vol. 444, pp. 45–55. https://doi.org/10.1016/j.epsl.2016.03.024

Akbashev, R.R., Firstov, P.P., and Cherneva, N.V., Recording of atmospheric electrical potential gradient in the central part of Kamchatka peninsula, *E3S Web Conf.,* 2018, vol. 62, pp. 1–8. https://doi.org/10.1051/e3sconf/20186202013

Akbashev, R.R., Firstov, P.P., Budilov, D.I., and Zavodevkin, I.A., Monitoring the potential gradient of the electric field in the atmosphere on the Kamchatka Peninsula and on the Paramushir Island (Kuril Islands), *Materials II International Scientific Conference CAMS-Tech-II 2021 on Advances in Materials, Systems and Technologies(Camstech-II-6016),* 2021, 2467(1): 080013. https://doi.org/10.1063/5.0092738

Alois, S., Merrison, J., Iversen, J.J., and Sesterhenn, J., Contact electrification in aerosolized monodispersed silica microspheres quantified using laser based velocimetry, *J. Aerosol Sci.*, 2017, vol. 106, pp. 1–10. https://doi.org/10.1016/j.jaerosci.2016.12.003

Aplin, K.L., Bennett, A.J., Harrison, R.G., and Houghton, I.M.P., Electrostatics and in situ Sampling of Volcanic Plumes, in Chapter 6 in *Volcanic Ash: Hazard Observation and Monitoring*, Amsterdam: Elsevier, 2016, pp. 99–113. ISBN: 978–0–081004050

Aplin, K.L., Houghton, I.M.P., and Nicoll, K.A., Electrical charging of ash in Icelandic volcanic plumes, in *XV International Conference on Atmospheric Electricity*, 15–20 June 2014, Norman, Oklahoma, U.S.A, 2014.

Arason, P., Bennett, A.J., and Burgin, L.E., Charge mechanism of volcanic lightning revealed during the 2010 eruption of Eyjafjallajökull, *J. Geophys. Res.,* 2011, vol. 116, no. B9. B00C03. https://doi.org/10.1029/2011JB008651

Behnke, S. and Bruning, E., Changes to the turbulent kinematics of a volcanic plume inferred from lightning data: Plume turbulence and lightning, *Geophys. Res. Lett.,* 2015, vol. 42, no. 10, pp. 4232–4239. https://doi.org/10.1002/2015GL064199

Behnke, S.A., Thomas, R.J., McNutt, S.R., et al., Observations of volcanic lightning during the 2009 eruption of Redoubt Volcano, *J. Volcanol. Geotherm. Res.,* 2013, vol. 259, pp. 214–234.

Behnke, S., Edens, H., Thomas, R., et al., Investigating the origin of continual radio frequency impulses during explosive volcanic eruptions, *J. Geophys. Res.: Atmospheres,* 2018, vol. 123, no. 8, pp. 4157–4174. https://doi.org/10.1002/2017JD027990

Bliznetsov, V.E. and Senyukov, S.L., The ADAP program for automatic identification of ash emissions and for calculating their heights from seismological data, *Seismicheskie Pribory,* 2015, vol. 51, no. 1, pp. 46–59.

Cherneva, N.V., Ponomarev, E.A., Firstov, P.P., and Buzevich, A.V., Basic models for the sources of variations affecting the vertical component of the atmospheric electric field, *Vestnik KRAUNTS, Nauki o Zemle,* 2007, no. 2, iss. 10, pp. 60–64.

Cimarelli, C., Alatorre Ibargüengoitia, M.A., Aizawa, K., et al., Multiparametric observation of volcanic lightning: Sakurajima volcano, Japan, *Geophys. Res. Lett.,* 2016, vol. 43, no. 9, pp. 4221–4228. https://doi.org/10.1002/2015GL067445

Dowden, R.L., Brundell, J.B., and Rodger, C.J., VLF lightning location by time of group arrival (TOGA) at multiple sites, *J. Atmospher. Solar-Terr. Phys.,* 2002, vol. 64, no. 7, pp. 817–830. https://doi.org/10.1016/S1364-6826(02)00085-8

Druzhin, G.I., Pukhov, V.M., Sannikov, D.V., and Malkin, E.I., VLF–direction finder to investigate natural radio radiations, *Vestnik KRAUNTS, Fiz.-Mat. Nauki.,* 2019, no. 27, iss. 2, pp. 95–104. https://doi.org/10.26117/2079-6641-2019-27-2-95-104

Efimov, V.A., Oreshkin, V.A., Firstov, P.P., et al., Using the EF-4 electrostatic fluxmeter for studies of geodynamic processes, *Seismicheskie Pribory,* 2013, vol. 49, no. 4, pp. 35–46.

Firstov, P.P., Akbashev, R.R., Khozvort, R., et al., Atmospheric electrical effects during the November 16, 2014 explosion on Shiveluch Volcano, *Izv. RAN, FAO,* 2017, vol. 53, no. 1, pp. 29–37.

Firstov, P.P., Akbashev, R.R., Zharinov, N.A., Marsimov, A.R., Manevich, T.M., and Melnikov, D.V., Electrification of eruptive plumes discharged by Shiveluch Volcano in relation to the character of the responsible explosion, *J. Volcanol. Seismol.,* 2019a, vol. 13, no. 3, pp. 172–184. www.pleiades.online/en/journals/search/?name=volsei

Firstov, P.P., Cherneva, N.V., Akbashev, R.R., et al., Atmospheric-electric effects from volcano eruptions on Kamchatka peninsula (Russia), in *Proc. SPIE 11208, 25th International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics*, 2019b, 1 120 874. https://doi.org/10.1117/12.2540356

Firstov, P.P., Kotenko, T.A., and Akbashev, R.R., Increased explosive activity of Ebeko Volcano in April–June, 2020, *Vestnik KRAUNTS, Nauki o Zemle,* 2020a, no. 2, issue 46, pp. 10–15. https://doi.org/10.31431/1816-5524-2020-2-46-10-15

Firstov, P.P., Malkin, E.I., Akbashev, R.R., et al., Registration of atmospheric–electric effects from volcanic clouds on the Kamchatka Peninsula (Russia), *Atmosphere*, 2020b, vol. 11, no. 6. https://doi.org/10.3390/atmos11060634

Firstov, P.P., Akbashev, R.R., Malkin, E.I., et al., Atmospheric electrical effects during a strong explosive eruption of Bezymyanniy volcano (Kamchatka Peninsula, Russia) on December 20, 2017, in *IOP Conference Series: Earth and Environmental Science (EES),* 2021.

Girina, O.A., Manevich, A.G., Melnikov, D.V., et al., The 2016 activity of volcanoes in Kamchatka and on the North Kuril Islands as reported by the KVERT, in *Vulkanizm i svyazannye s nim protsessy* (Volcanism and Associated Processes), Proc. XX regional science conference devoted to Volcanologist's Day, March 30–31, 2017, Petropavlovsk-Kamchatsky: IViS DVO RAN, 2017, pp. 8–10.

Girina, O.A., Loupian, E.A., Melnikov, D.V., et al., *Bezymianny volcano eruption on December 20, Sovr.* Probl. Dist. Zond. Zemli Kosm., 2018. P. 88–99.

Gorshkov, G.S., and Bogoyavlenskaya, G.E., *Vulkan Bezymyanny i osobennosti ego poslednego izverzheniya v 1955–1963 gg.* (Bezymyannyi Volcano and Its Last Eruptions in 1955–1963). Moscow: Nauka, 1965.

James, M.R., Lane, S.J., and Gilbert, J.S., Volcanic plume electrification—Experimental investigation of fracture charging mechanism, *J. Geophys. Res.,* 2000, vol. 105, no. B7, pp. 641–649. https://doi.org/10.1029/2000JB900068

Lacks, D.J. and Levandovsky, A., Effect of particle size distribution on the polarity of triboelectric charging in granular insulator systems, *J. Electrostat.,* 2007, vol. 65, no. 2, pp. 107–112. https://doi.org/10.1016/j.elstat.2006.07.010

Lane, S.J. and Gilbert, J.S., Electric potential gradient changes during explosive activity at Sakurajima volcano, Japan, *Bull. Volcanol.,* 1992, vol. 54, pp. 590–594.

Malkin, E.I., Cherneva, N.V., Firstov, P.P., et al., Dirty thunderstorms caused by volcano explosive eruptions in Kamchatka by the data of electromagnetic radiation, *IOP Conf. Ser.: Earth Environ. Sci.,* 2021, 946 .012015. https://doi.org/10.1088/1755-1315/946/1/012015

Malkin, E.I., Cherneva, V.I., Makhlai, D.O., et al., Remote sensing techniques for monitoring the eruptions of Shiveluch and Bezymianny volcanoes, *Vestnik KRAUNTS: Ser. Fiz.-Mat. Nauki,* 2023, vol. 43, no. 2, pp. 141–165. ISSN 2079-6641. https://doi.org/10.26117/2079-6641-2023-43-2-141-165

Mather, T.A. and Harrison, R.G., Electrification of volcanic plumes, *Surveys in Geophysics,* 2006, vol. 27, pp. 387–432.

Mendez Harper, J., Cimarelli, C., Cigala, V., et al., Charge injection into the atmosphere by explosive volcanic eruptions through triboelectrification and fragmentation charging, *Earth Planet. Sci. Lett.,* 2021, vol. 574(14). Retrieved from https: www.sciencedirect.com/science/article/pii/S0012821X21004179. https://doi.org/10.1016/j.epsl.2021.117162

Meng, Z., Tianjun, Z., Wenmin, M., and Chaochao, G., Volcanoes and climate: Sizing up the impact of the recent Hunga Tonga-Hunga Ha'apai volcanic eruption from a historical perspective, *Advances in Atmospheric Sciences,* 2022, vol. 39, pp. 1986–1993. https://doi.org/10.1007/s00376-022-2034-1

Miura, T., Koyaguchi, T., and Tanaka, Y., Measurements of electric charge distribution in volcanic plumes at Sakurajima volcano Japan, *Bull. Volcanol.,* 2002, vol. 64, pp. 75–93.

Mueller, S.B., Ayris, P.M., Wadsworth, F.B., et al., Ash aggregation enhanced by deposition and redistribution of salt on volcanic ash surfaces in eruption plumes, *Sci. Rep.,* 2017, 7, article number: 45762.

Rulenko, O.P., An Experimental Study of the Electrification of Volcanic Clouds, *Extended Abstract of Cand. Sci. (Phys.–Math.) Dissertation*, St. Petersburg, 1994.

Rulenko, O.P. and Tokarev, P.I., Atmospheric electrical effects of the Great Tolbachik Fissure Eruption in July–October, 1975, *Byull. Vulkanol. St.,* 1979, no. 56, pp. 96–102.

Rulenko, O.P., Klimin, N.N., Dyakonova, I.I., and Kiryanov, V.Yu., Studies in the electrification of plumes due to spraying of volcanic ash, *Vulkanol. Seismol.,* 1986, no. 5, pp. 17–29.

Shevtsov, B.M., Firstov, P.P., Cherneva, N.V., et al., Lightning and electrical activity during the Shiveluch volcano eruption on 16 November 2014, *Nat. Hazard Earth Syst. Sci.,* 2016, vol. 16, pp. 871–874. https://doi.org/10.5194/nhessd–16–871-2016

Smitha, C.M., Van Eaton, A.R., Charbonnier, S., et al., Correlating the electrification of volcanic plumes with ash fall textures at Sakurajima Volcano, Japan, *Earth Planet. Sci. Lett.,* 2018, vol. 492, pp. 47–58. https://doi.org/10.1016/j.epsl.2018.03.052

Thomas, R.J., Krehbiel, P., Rison, W., et al., Lightning and electrical activity during the 2006 eruption of Augustine Volcano, in *The 2006 Eruption of Augustine Volcano,* Alaska, U.S. Geological Survey, 2007, Ch. 25, pp. 579–608.

Van Eaton, A.R., Schneider, D.J., Smith, C.M., et al., Did ice-charging generate volcanic lightning during the 2016–2017 eruption of Bogoslof volcano, Alaska? *Bull. Volcanol.,* 2020, vol. 82. https://doi.org/10.1007/s00445-019-1350-5

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