ISSN 0742-0463, Journal of Volcanology and Seismology, 2019, Vol. 13, No. 3, pp. 172–184. © Pleiades Publishing, Ltd., 2019.
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Electrification of Eruptive Plumes Discharged by Shiveluch Volcano in Relation to the Character of the Responsible Explosion

P. P. Firstov[a, *], R. R. Akbashev[a], N. A. Zharinov[b], A. P. Maksimov[b], T. M. Manevich[b], and D. V. Mel'nikov[b]

[a] *Kamchatka Branch, Federal Research Center Unified Geophysical Service, Russian Academy of Sciences, bul'var Piipa, 9, Petropavlovsk-Kamchatskii, 683006 Russia*

[b] *Institute of Volcanology and Seismology, Far East Branch, Russian Academy of Sciences, bul'var Piipa, 9, Petropavlovsk-Kamchatskii, 683006 Russia*

**e-mail: firstov@emsd.ru*

Received July 5, 2018; revised August 14, 2018; accepted January 22, 2019

Abstract—It is shown that the rate of explosive eruptions on Shiveluch Volcano has become increasingly high during recent years, which makes the monitoring of the volcano using all available means highly urgent. We seek to introduce another technique into the multidisciplinary monitoring of explosive eruptions by analyzing responses in the vertical component of the atmospheric electric field (E_ZAEF) during the passage of eruptive plumes. We considered two Shiveluch eruptions that were different in vigor that occurred on December 16, 2016 and on June 14, 2017.The signals in the E_ZAEF were selected using multidisciplinary observations, viz., satellite-based observations, seismic, and infrared observations. Signals of negative polarity were recorded in the E_ZAEF dynamics in the near zone (<50 km) for both eruptions at once as ash began to fall. In the first of these cases, the ash–air plume was "dry"; thus, the aero-electrical structure was of the "negatively charged plume" type. The intense explosion that occurred in the second of these cases sent a great amount of ash and volcanic gases into the atmosphere, with 98% being steam; the result was a dipole aero-electrical structure due to eolian differentiation in the near zone. In the far zone (>100 km), the explosion produced a signal of positive polarity coming from an aero-electrical structure of the "positively charged plume" type from the aerosol column.

DOI: 10.1134/S0742046319030035

INTRODUCTION

The atmospheric electric field (AEF) is a sensitive indicator of high-energy processes that occur both in the atmosphere and in the lithosphere. The variations in AEF parameters are not restricted to cloud structures and storm discharges, which mostly form a global electric circuit (Mareev, 2010); other connections also exist between local electric fields in the atmosphere and geodynamic processes (earthquakes and volcanic eruptions) (Ponomarev et al., 2011).

Long-term continuous observations of the electric field gradient in the near-ground layer of the atmosphere, which controls the intensity of the vertical electric component in the atmosphere (E_ZAEF), form an experimental basis from which to start the study of the local electric effects in the atmosphere. The explosive activity of Kamchatka volcanoes discharging volcanic ash into the atmosphere where eruptive plumes are formed is another local source of aero-electrical structures.

The volcanic plumes that occasionally extend for some hundreds of kilometers carry large electric charges that can be recorded by ground-based instrumentation. Monitoring of E_ZAEF in the near-ground layer can reveal the presence of eruptive plumes, even ones with low saturation with aerosol particles of fine-grained ash (Mather and Harrison, 2006).

The Northern Group of Volcanoes in Kamchatka is a unique object to use to examine the electrification of eruptive plumes (Fig. 1). The frequent explosive eruptions of andesitic Shiveluch and Bezymyannyi volcanoes when coupled with suitable winds enhance the probability of the passage of eruptive plumes above the villages of Klyuchi and Kozyrevsk, where fluxmeters are installed (KZYG and KLYG, see Fig. 1). The first results from measurement at these sites were described in (Akbashev and Firstov, 2017; Firstov et al., 2017a; Shevtsov et al., 2016; Firstov et al., 2017b). The present paper gives an account of the variations in E_ZAEF at KZYG and KLYG during the passage of eruptive plumes produced by Shiveluch eruptions of varying genesis.

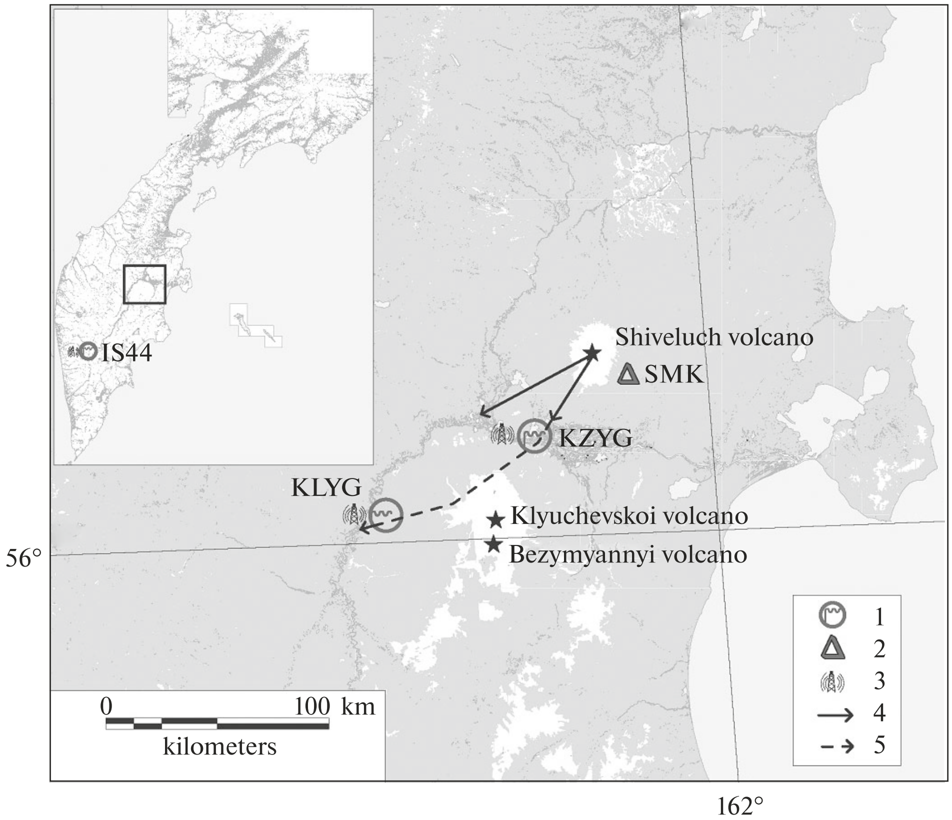

Fig. 1. A sketch map showing the stations for recording AEF intensity and infrasound waves in the Northern Group of Volcanoes area and the paths of eruptive plumes due to two Shiveluch eruptions that had a response in EZ AEF. Locations of instruments: (1) fluxmeter; (2) telemetry seismic station; (3) microbarograph; (4, 5) paths of phenomena due to eruptions (4 for December 16, 2016 and 5 for June 4, 2017). The inset shows the location of the Northern Group of Volcanoes in Kamchatka and the IS44 infrasound station.

A BRIEF DESCRIPTION OF THE ACTIVITY OF SHIVELUCH

This northernmost active andesitic volcano in Kamchatka is a dilapidated volcanic edifice ~60–70 ka old, its base is 45 × 40 km and the area is at least 1300 km^2. The main summit stands 3283 m above sea level (a.s.l.).[1] The present-day edifice includes three main elements, namely, Old Shiveluch, an old caldera, and the active Young Shiveluch (*Deistvuyushchie vulkany ...,* 1991).

There have mostly been two types of eruption on Shiveluch in the last 10000 years of historical time, viz., catastrophic explosive eruptions of the "directed explosion" type and smaller eruptions that produced extrusive domes.

The last catastrophic eruption occurred on November 12, 1964. It destroyed several domes and produced a 1.5 × 3.0-km crater with a complex shape and a field of resurgent deposits due to the "directed explosion" ~1.5 km^3 in volume. These events were followed by Plinian-type activity, discharging 0.3 km^3 ash and pyroclastic flows 0.3–0.5 km^3 in volume (Gorshkov and Dubik, 1969; Belousov and Belousova, 1996).

The 16-year intermission of the volcano's activity until August 1980 was replaced by the growth of an extrusive dome within a new crater that has continued with some short breaks until the present time and was accompanied by explosive eruptions. Continuous observations of the dome showed that the rate of growth and the lava discharge have not been constant over time. Three phases can be distinguished in the formation of the extrusive dome from 1980 until now (Zharinov and Demyanchuk, 2013).

The first phase (August 1980 through late 1981) involved the formation of the extrusion. The appearance of the first lava portion in the form of individual blocks being forced upward in the middle of the crater was not preceded or accompanied by either seismic or volcanic activity. The formation of the dome was accompanied by destruction of some of its blocks, resulting in incandescent avalanches and small pyroclastic flows. The growth was occurring at a mean rate of 0.8 m/day during this period; the dome reached a relative height of 135 m by the end of 1981.

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[1] Elevations are above sea level throughout the paper.

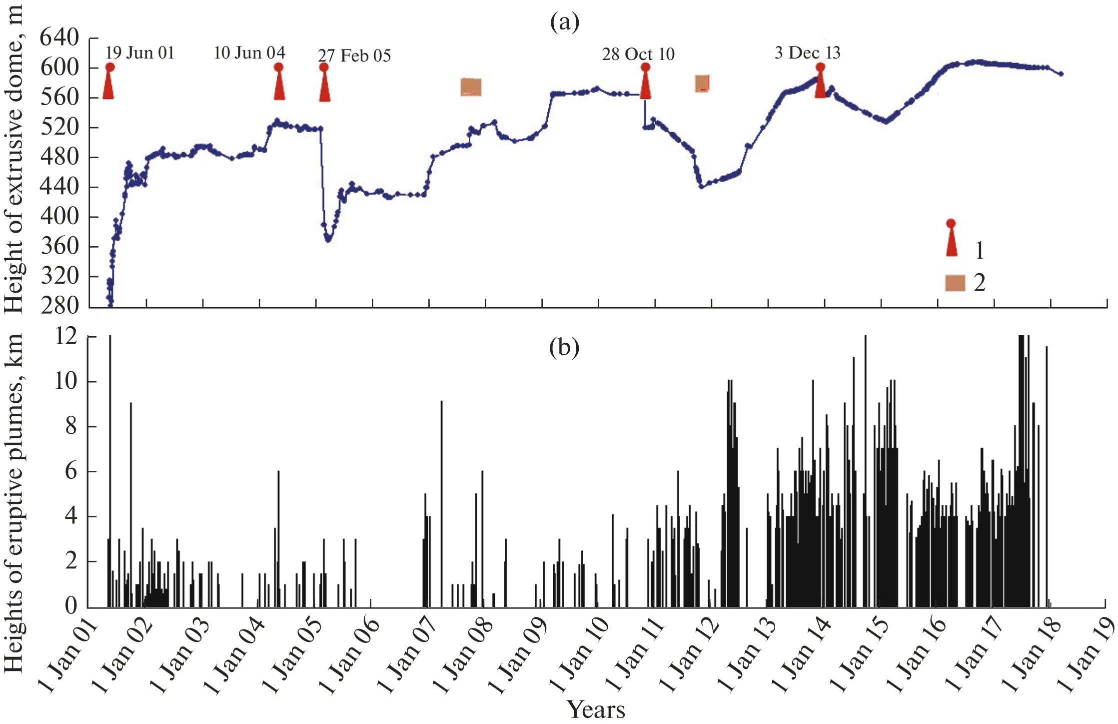

Fig. 2. The dynamics of the 2001–2017 extrusive–explosive eruption of Shiveluch Volcano. (a) the maximum height of lava dome, as inferred from theodolite measurements from the village of Klyuchi; (b) height of steam–gas and ash discharges. (1) large explosive eruptions followed by lowering or partial destruction of the dome; (2) periods when viscous lava flows were discharged onto the slopes of the lava dome.

The second phase (April 1993 through January 1995) involved intrusive and explosive activity preceded by a powerful explosive eruption in April 1993 (Zharinov et al., 1995; Zharinov and Demyanchuk, 2008; Firstov et al., 1994; Khubunaya et al., 1995); the activity was accompanied by the upward forcing of new extrusions at the summit of the central dome and by discrete explosions of varying intensity. In some cases, eruptive columns rose to reach the tropopause heights (10–12 km), with the ash plume traveling for some hundreds of kilometers.

The third phase, from May 7, 2001 until the present, was under observation to monitor the growth of the extrusive dome and to count the discharges (Fig. 2). These data were used to study changes in the extrusive dome profile and to estimate the volume and discharge rate of the ejecta (Zharinov and Demyanchuk, 2013).

A few quiet years were followed by a resumption of seismic activity on May 7, 2001 accompanied by a series of ash ejections and a rapid growth of the extrusive dome, which had added nearly 200 m to its height between May and October 2001 (see Fig. 2a).

Along with this extrusive and explosive activity, low effusive events discharging short viscous lava flows occurred later (see Fig. 2a). Powerful explosive eruptions involving partial destruction of the extrusive dome took place on February 27, 2005 and October 28, 2010. The 2 years following the February 27, 2005 eruption saw no more than three to four ash discharges annually. In 2007, a lava crown was formed at the summit of the dome and viscous lava flows occurred, providing evidence of a lower gas saturation of the magma.

A quiet squeezing-up of lava flows continued in 2008 accompanied by explosive eruptions that occurred as frequently as six times in a year. An increase in explosive activity reaching a rate of 20 explosions per year and the growth of the dome were observed in 2009–2010 (see Fig. 2b). A powerful explosive eruption that destroyed the east side of the dome occurred on October 28, 2010.

The growth of an extrusive dome with subsequent partial destruction of it during large explosive eruptions is characteristic for volcanoes that discharge hornblende andesites. This is due to the high viscosity and gas saturation of hornblende andesite magma. High viscosity impedes degassing in the residual melt, thus making the process longer and, at the same time, produces a large rigid lava plug that stops the conduit, thus preventing a free release of the gas phase from the magma into the atmosphere. As a result, the volatile gases that are released from the magma are subjected to greater pressure; these gases are the driving force of the extrusive process that culminates in powerful explosions. This leads to destruction of part of the dome. The rigidity of the extrusive dome and the pres-

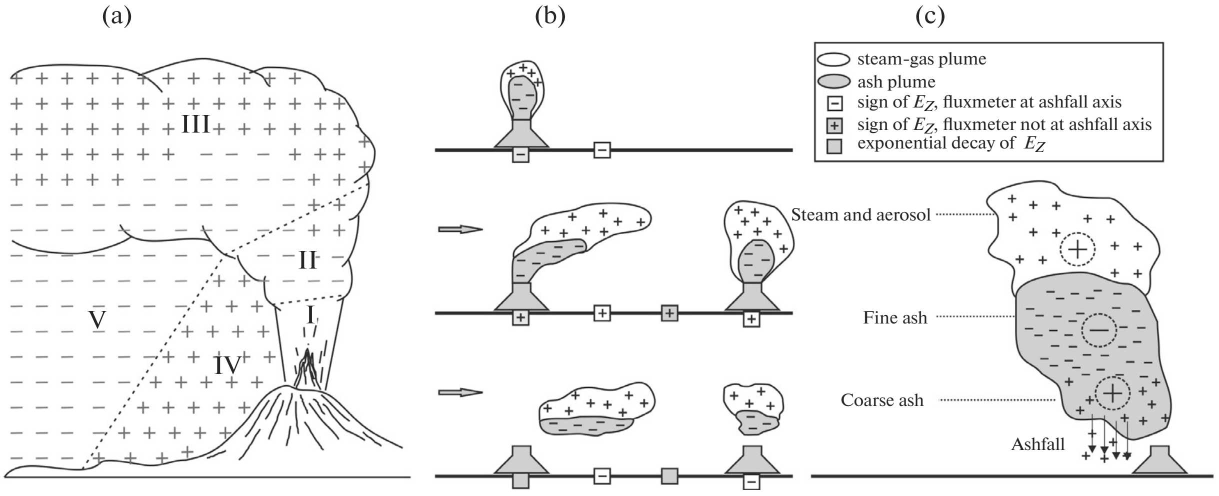

Fig. 3. A diagrammatic drawing of models for the generation of electrical structures in an eruptive plume. (a) in the near zone (Rulenko, 1994); (b) a sketch showing the separation of charges during the generation of a volcanic plume by wind action according to (Miura et al., 2002); (c) separation of charges in eruptive plumes as inferred from field observations on Sakurajima Volcano, after (James et al., 1998). (I) separation of charges under gravity action in the initial region at a weak wind; (II) plume generation in a self-similar region under wind action; (III) plume in the buoyancy zone; (IV) region of coarse-grained fraction deposition; (V) region of tephra deposition.

sure of the gases that accumulate in the magma lead to a large grain-size range in the ejecta containing considerable amounts of powder-size particles. The process repeats itself subsequently, because the volcanic conduit remains filled with magma.

Subsequently, the rate of explosions was also increasing from 37 in 2011 reaching 70 in 2016; however, there have been no sudden decreases in dome height. In 2016–2017, the height of the extrusive dome stabilized at an approximate height of 600 m as measured from its base. This value seems to be its limiting height, since incandescent avalanches began to occur and some explosions involved rockfalls. In our opinion, the two processes compensated for the further dome growth by squeezing out the extrusion.

SOME INFORMATION OF THE ELECTRIFICATION OF VOLCANIC PLUMES

The electrification of eruptive plumes during eruptions has been studied by many researchers. The earliest works (Hatakeyama, 1949; Hatakeyama and Uchikawa, 1951) dealing with the electrification of volcanic plumes showed that volcanic ash particles acquire considerable charges during eruptions, both positive and negative, with E_Z AEF reaching high values. As an example, it was 1.2 kV/m at a distance of 250 km from Akita-Yake-Yama Volcano in Japan.

Field observations made during the Great Tolbachik Fissure Eruption (GTFE) in July–October 1975 in Kamchatka (Rulenko, 1994; Rulenko and Tokarev, 1979), as well as on Sakurajima Volcano (Japan) during its 1995 eruption (James et al., 1998; Miura et al., 2002), yielded descriptions of charge configurations in eruptive plumes (Figs. 3a, 3b), with the sign and magnitude of E_Z AEF both being variable. The GTFE observations gave ±30 kV as the maximum/minimum values of E_Z AEF, which are the limits of the measuring apparatus (Rulenko, 1994).

Rulenko (1994), Miura et al. (2002), Mather and Harrison (2006) showed that magma fragmentation (destruction) plays a great part in the electrification of an eruptive plume during the initial phase. The second phase involves separation of particles of different sizes in an eruptive column and later on in the eruptive plume. This leads to charging of different polarities and to spatial separation of the charges in an eruptive column and in the ashfall region under the plume. For the first of these cases, the separation is due to gas-dynamic resistance as a gas–ash jet is hurled into the air, and in the second, it is due to gravitational differentiation. It may well be that a large contribution into the origination and separation of charges in a volcanic plume is due to thermo-electron emission and thermoelectricity, among many other physical and physicochemical processes (Adamchuk and Titov, 1984).

As an eruptive plume is moving away from its eruption center, the coarse-grained ash fraction falls and aerosol is formed, resulting in a change in the charge configuration (see Fig. 3c).

THE INSTRUMENTATION AND METHODS OF OBSERVATION

The recording of E_Z AEF in the middle of the Kamchatka Peninsula is of special interest, because it is there that the Northern Group of Volcanoes is situated, which includes four active volcanoes: Shiveluch, Klyuchevskoi (the highest, 4750 m, and the most productive in Eurasia), Bezymyannyi, and Plosky Tolbachik (see Fig. 1). EF-1 and EF-4 electrostatic fluxmeters to record E_Z AEF were installed at seismic stations operated by the Kamchatka Branch of the Federal Research Center Unified Geophysical Service of the Russian Academy of Sciences (KB FRC UGS RAS), Klyuchi (KLYG) and Kozyrevsk (KZYG) near the Northern Group of Volcanoes. Along with traditional problems of atmospheric electricity such as unitary variation, global electrical circuits, etc., data from these stations allow one to study atmospheric electrical effects that occur during the formation and propagation of ash–gas plumes produced by explosive volcanic eruptions.

The specifications of the EF-4 electrostatic fluxmeter designed by V.A. Efimov are listed in Table 1 (Efimov et al., 2013). It should be noted that the EF-1 fluxmeter (the prototype of EF-4) has a wider dynamic range, ±6 kV/m. The use of a small powerful valve engine and surface mounting allowed the device to be confined within a rectangular case with external dimensions of 120 × 200 × 45 mm. The device consumes little power, which is very important for setting up a network of unattended stations to record E_Z AEF for monitoring the explosive activity of Kamchatka volcanoes. The device is installed shutter down in order to protect the mechanical part from dense and very wet snow (so-called “ice rain”). The EF-1 fluxmeter with an expanded range of measurable E_Z AEF has been operated in Kamchatka since March 2008. The sensor has been a very reliable device for the entire period of its use (Efimov et al., 2013).

The selection of signals on records of E_Z *AEF* due to eruptive plumes was based on integration of data from seismic, infrared, and satellite-based monitoring for the activity of Kamchatka volcanoes. A network of seismic telemetry stations (STS) is operated in the Shiveluch area by the KB FRC UGS RAS, including Sorokina (SRK), Semkorok (SMK), and Baidarnaya (BDR). Two seismic stations in the Northern Group of Volcanoes area contain channels (KLYA, KZYA) that record infrasound in the 0.03–10 Hz frequency range (Makhmudov et al., 2016), in addition to video observation. As well, there is the IS44 international infrasound station at a distance of 458 km from the volcano (see Fig. 1, inset) where infrasound oscillations are recorded in the range 0.003–10 Hz using an aerial consisting of 4 microbarographs to be able to determine the station–source azimuth.

The digital data acquired from the STS and from the infrasound channels were processed using the DIMAS interactive software (Droznin and Droznina, 2010).

Satellite-based monitoring of explosive volcanic activity in Kamchatka is carried out in real time using the Uniskan-36 receiving station as part of KVERT work at the Institute of Volcanology and Seismology (IV&S) FEB RAS (Gordeev and Girina, 2014). Eruptive plumes are formed and propagate due to atmospheric stratification. Balloon sounding is carried out twice every day at the Klyuchi Meteorological Observatory (Kamchatka Agency for Hydrometeorology and Monitoring of Environment), enabling the direction and velocity of travel to be determined for eruptive plumes produced by explosive eruptions in the Northern Group of Volcanoes (http://www.esrl.noaa.gov/raobs/intl/intl2000.wmo). The Klyuchi Observatory is 48 km southwest of Shiveluch Volcano (see Fig. 1).

Table 1. The specifications of the EF-4 electrostatic fluxmeter

Range of measured field intensity	±2 kV/m
Upper cutoff frequency	5 Hz
Output resistance	2 kΩ
Output voltage	±5 V
rms error of measurement	5 mV
Power supply voltage (direct current)	10–14 V
Consumed current in operating mode	180 mA
Operating temperature	–40...+80 °C
for humidity	0–100%
Operating mode	continuous

An integrated approach based on geophysical and satellite-based techniques enables signal selection in E_Z AEF due to the passage of gas–ash plumes produced by Shiveluch eruptions.

THE CHARACTERISTICS OF DISCRETE EXPLOSIONS BASED ON DATA FROM REMOTE MONITORING AND ON STUDIES OF VARIATIONS IN E_Z AEF DUE TO THE PASSAGE OF ERUPTIVE PLUMES

The eruptive plume due to the Shiveluch eruption that took place at 22:31 on December 16, 2016, as reported by the KB FRC UGS RAS (http://www.emsd.ru/~ssl/monitoring/main.htm) had a height of 5.6 km as estimated from the intensity of the seismic signal (Bliznetsov and Senyukov, 2015).[2] In approximately 2 hours after the eruption, an ashfall was recorded at the village of Klyuchi with intensity 20 g/m^2.

We consider the propagation of the eruptive plume due to this eruption as inferred from wind stratification (balloon sounding) and space imagery taken at that time. The space images received at the Uniskan-36 station at intervals of 90 minutes (Figs. 4a, 4b) revealed the eruptive plume moving driven by wind at an azimuth of ~75° and a velocity of ~17 m/s. According to the atmospheric stratification this corresponds

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[2] UTC times are used throughout the text of this paper.

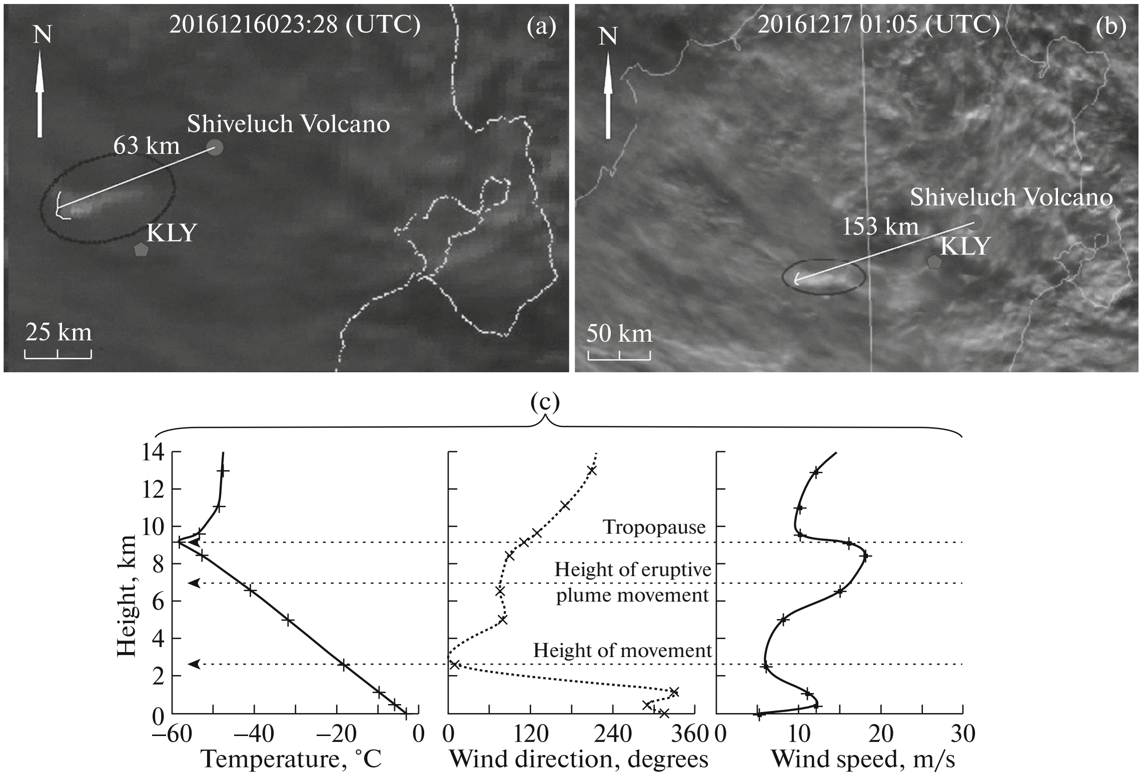

Fig. 4. The propagation of the eruptive plume due to the Shiveluch eruption of 22:31 December 16, 2016 and atmospheric stratification as inferred from balloon sounding at the Klyuchi weather station. (a, b) satellite images (Terra MODIS) of the eruptive plume acquired in real time at the Uniskan-36 receiving station operated by IV&S FEB, (c) temperature and wind stratification of the atmosphere at 00:00 on December 17, 2016.

to the azimuth and wind speed at heights of 6.5–8.0 km (see Fig. 4b).

If this was true, no ash could fall at the village of Klyuchi; however, in approximately 2 hours an ashfall began whose intensity was ~20 g/m^2. The second eruptive plume responsible for the ashfall must have been driven by wind at azimuth ~45° and speed ~5 m/s, which is consistent with the atmospheric stratification at a height of 2.5 km (see Fig. 4c). No such eruptive plume can be seen on satellite images.

Seismic and infrasound methods are reliable techniques for remote monitoring of explosive volcanic activity. While the former of these techniques provides information on the intensity and duration of the explosive process, the latter gives an indication of its degree of nonstationarity and the intensity of ash discharge into the atmosphere.

The explosive earthquake (EE) as recorded at SMK lasted ~15 minutes; it accompanied the December 16, 2016 explosion and was rather weak ($A_{\max} = 4$ μm/s) and strongly contaminated with noise (Fig. 5a). We filtered the record by a highpass filter (HPF) with cutoff frequency $f_{\text{off}} = 0.5$ Hz and then calculated the power spectral density (PSD) of the signal (see Fig. 5b). The PSD was almost constant relative to the background in the frequency range 1–10 Hz; one can also see a PSD segment extending to 20 Hz, which is not typical of EEs (Firstov et al., 2012).

The acoustic signal was not detected on records of the microbarograph at the nearest station (KLYA). Overall, the explosion can be dubbed "flow-through," that is, a long-continued discharge of an ash–gas mixture.

The ashfall at Klyuchi was accompanied by a negative single-polarity anomaly in the AEF whose lowest value was −1.23 kV/m and the total duration was ~45 minutes (15 minutes for the leading edge and 30 minutes for the trailing edge). Judging from the trailing edge of the E_Z AEF anomaly (Cherneva et al., 2007), one can say that the eruptive plume was a thin aero-electrical feature that was moving horizontally at a height of 2.5 km. Eolian differentiation made the plume long laterally, ~9 km; this value was estimated from the duration of the anomaly trailing edge and the wind speed at 2.5 km height.

The eruptive plume ejected by Shiveluch at 16:26 on June 14, 2017 as reported by the KB FRC UGS RAS (http://www.emsd.ru/~ssl/monitoring/main.htm) rose to a height of ~12 km as estimated from the intensity of the accompanying seismic signal (Bliznetsov and Senyukov, 2015).

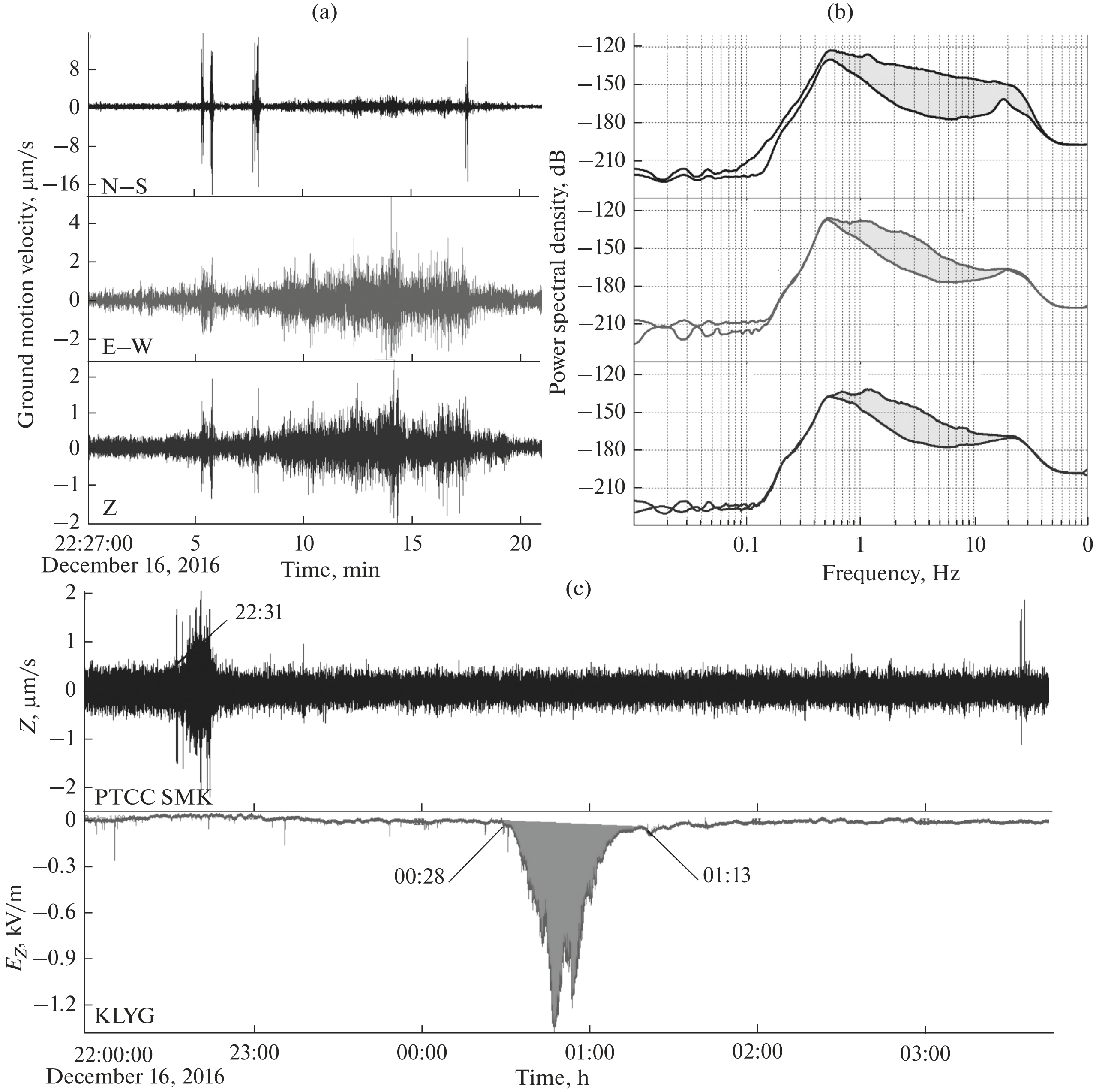

Fig. 5. Three components of the ground motion velocity due to a seismic signal at SMK that accompanied the explosive Shiveluch eruption of December 16, 2016, when filtered by an HPF with cutoff frequency $f_{\text{off}} = 0.5$ Hz (a), power spectral density of the seismic signal (b), a record of the seismic signal and variations in E_ZAEF (c). Grey shading shows the response in E_ZAEF to the passage of the second eruptive plume.

It can be seen in satellite images (HIMAWARI-8 due to Regional and Mesoscale Meteorology Branch NOAA/NESDIS, http://rammb.cira.colostate.edu/) that an almost circular eruptive plume ~70 km across was formed in 34 minutes after the eruption at a height of 9 km (Fig. 6a). The plume then moved toward the village of Klyuchi at a velocity of 12 m/s, as inferred from wind stratification (see Figs. 6a, 6b, 6c). The eruptive plume began to form during the first few minutes after the start of the explosive eruption recorded by a video camera installed at KLYG to monitor the activity of Shiveluch Volcano (see Fig. 6d).

The eruptive plume arrived at Klyuchi almost an hour later, shedding 100 g/m^2 ash (see Fig. 6e). The plume then traveled toward Klyuchevskoi Volcano (see Fig. 6f) and reached the village of Kozyrevsk at 21:33 where some very fine ash was deposited.

The explosive earthquake that accompanied the eruption had a duration of approximately 10 minutes

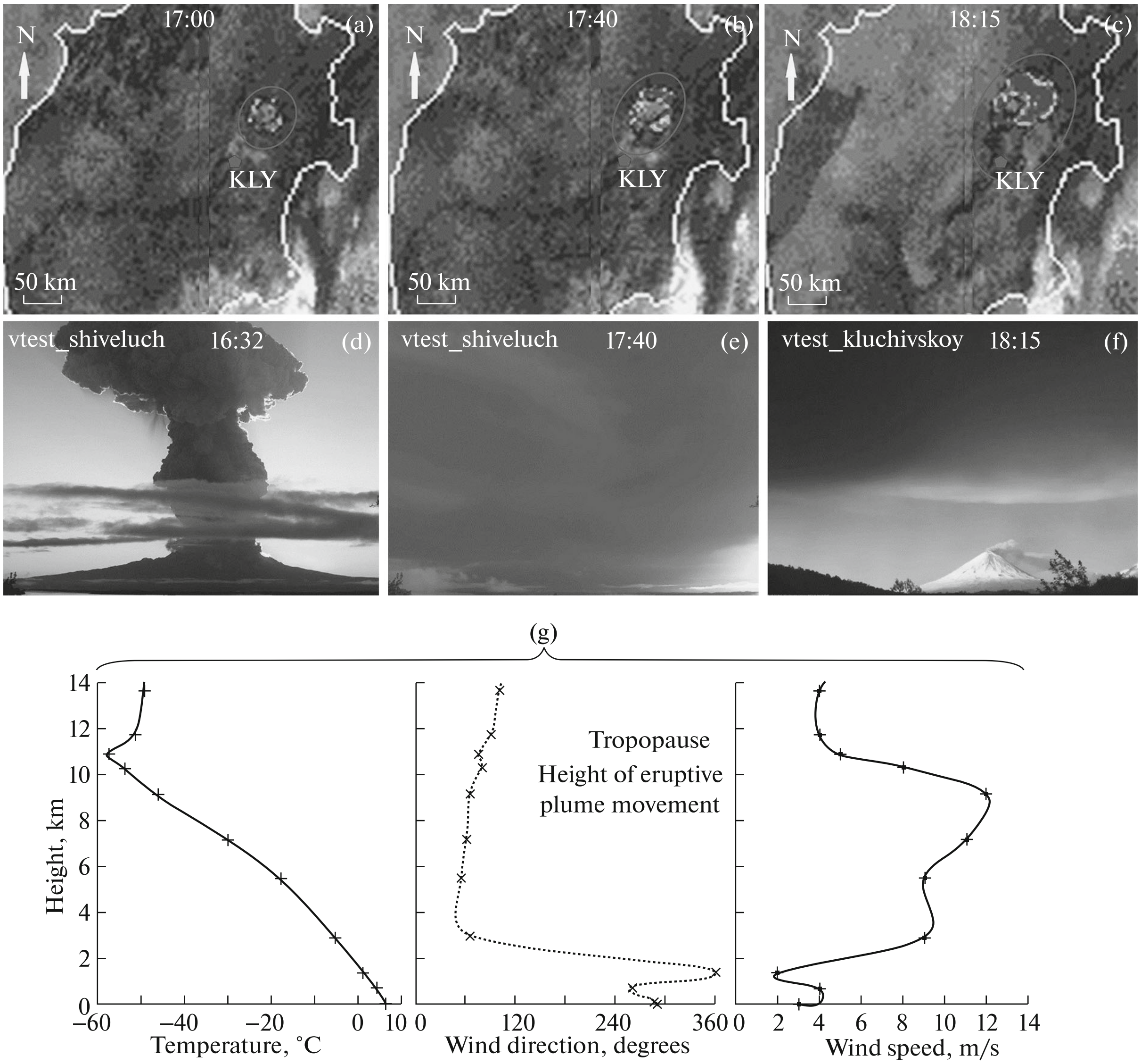

Fig. 6. The propagation of the eruptive plume due to the 16:26 June 14, 2017 eruption of Shiveluch Volcano as inferred from HIMAWARI-8 satellite images (a, b, c) (http://rammb.cira.colostate.edu), the evolution of the eruptive plume as recorded by a video camera (d, e, f), temperature and wind stratification of the atmosphere as inferred from balloon surveying (g).

on the SMK record. The instrumentation had a limited dynamic range and thus, was unable to record the maximum amplitude of ground motion velocity; however, one can surmise that the amplitude exceeded $A_{\max} > 400$ μm/s (Fig. 7a). The PSD for the 3-minute record of this EE reaches the maximum at a frequency of 1 Hertz, and is confined to the range 0.4–10 Hz, which is typical of EEs (Firstov et al., 2012).

The eruption was accompanied by a shock wave in air (SWA) that was gradually converted to an infrasound wave and was recorded by all microbarographs in Kamchatka (Fig. 8). The delay relative to the seismic signal at SMK, which may be assumed to be the start of the eruption, was 2.19 min for KLYA and 5.28 min for KZYA.

The records at IS44 show two arrivals of separate infrasound trains related to the propagation of the sound ray in the stratospheric and in the tropospheric waveguide.

The energy of the explosion process can be estimated to a first approximation using the SWA parameters by calculating the TNT equivalent (Q) in kg by the method that is in use to estimate the detonation of explosives. Based on the similarity law, one usually handles the SWA parameters in relation to converted distance $\overline{r} = r/Q^{1/3}$.

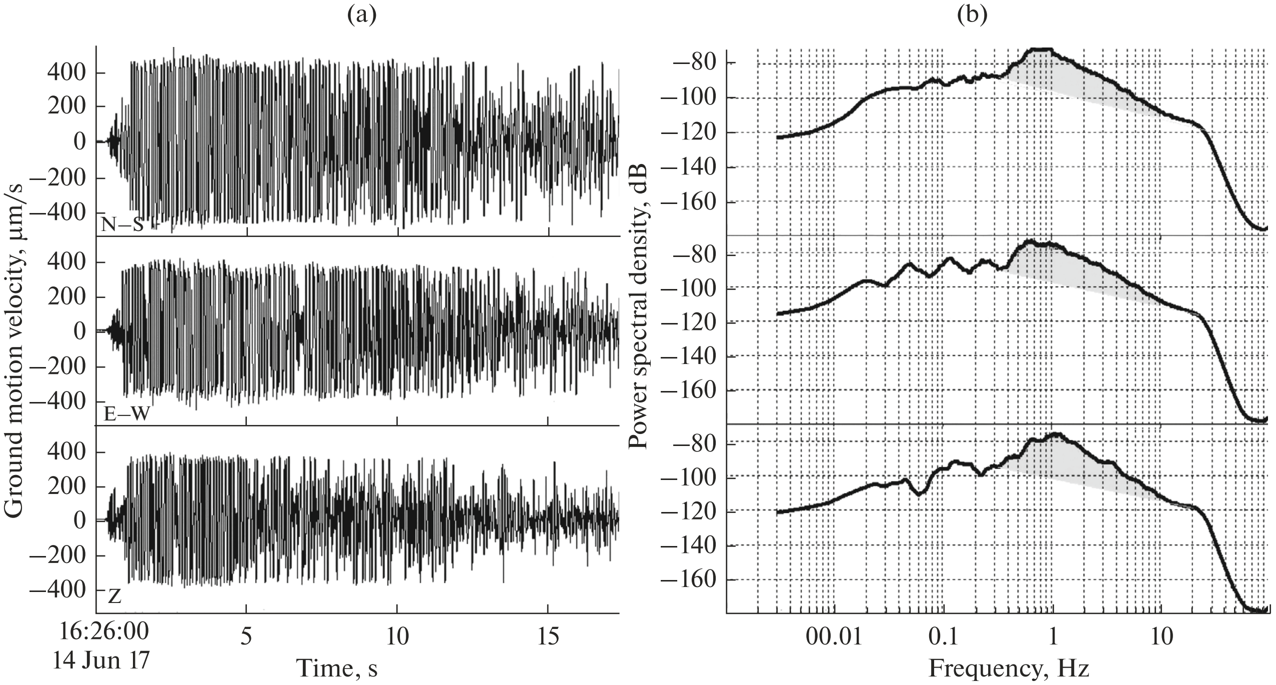

Fig. 7. Three components of ground motion velocity due to a seismic signal recorded at SMK, which accompanied the explosive Shiveluch eruption of June 14, 2017 (a), power spectral density of a 180-s seismic signal segment (b).

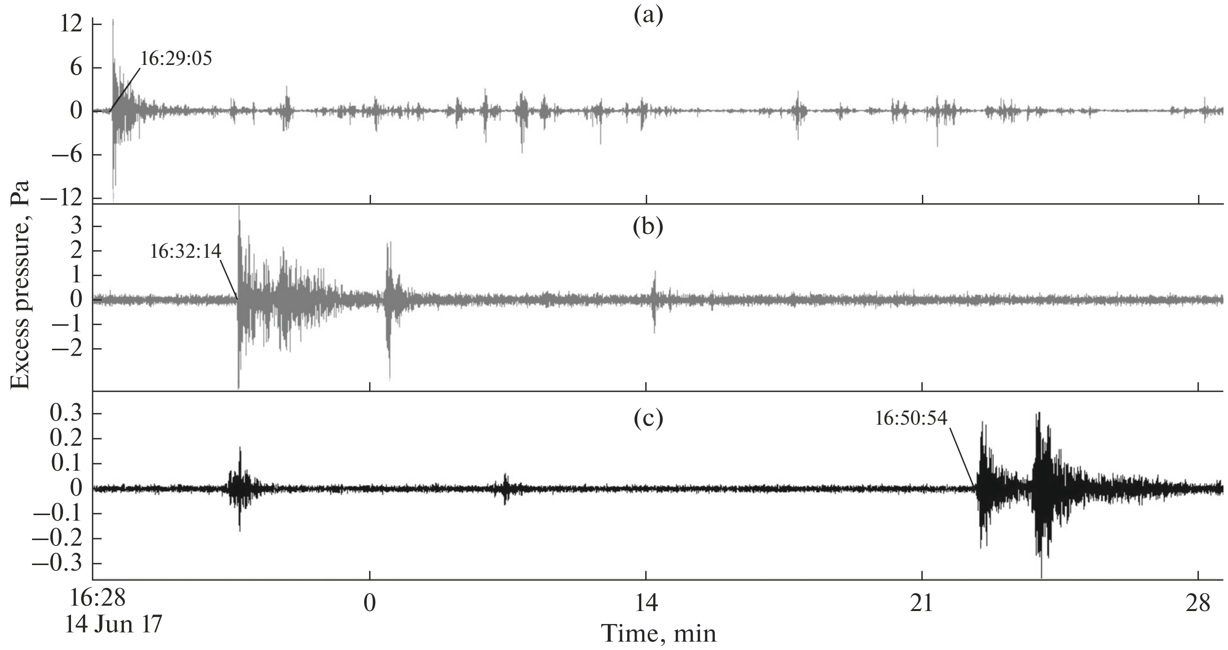

Fig. 8. Records of the air wave that accompanied the June 14, 2017 eruption at acoustic stations: KLYA (a), KZYA (b), and IS44 (c).

The numerous studies in SWA propagation from blasts resulted in several empirical relations that have the form of power polynomials. We used the empirical relation $I_+ = 220Q^{2/3}\big/r$ (Tseitlin and Smolii, 1981) and the pulse magnitude of the duration τ as calculated from $I_+ = \int_0^\tau \Delta P(t)dt$, Pa s, to find the estimate $Q = 4 \times 10^3$ kg. It should be noted that the relation $I_+ = f(Q)$ is applicable in the interval $10 < \overline{r} < 100$, hence our estimate of Q is a lower bound. Summing

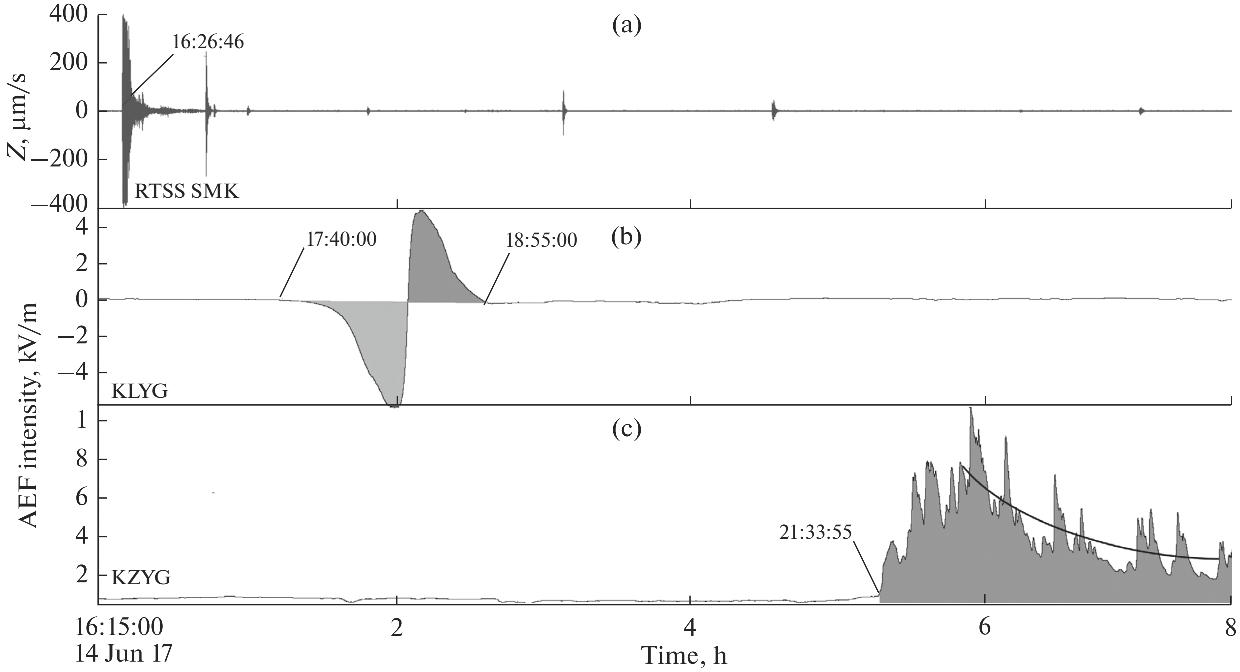

Fig. 9. Record fragments: the vertical ground motion velocity at SMK SMK (a) and the AEF intensity at KLYG (b) and at KZYG (c).

up, we can say that the June 14, 2017 explosion started with a strong blast followed by a gradually decaying discharge of an ash–gas mixture from the vent during 10 minutes.

The fortunate combination of "fair weather conditions" and wind direction during the June 14, 2017 eruption enabled the response of E_Z AEF to be recorded during the passage of the eruptive plume over Klyuchi and Kozyrevsk. Since the start of the ashfall at Klyuchi (17:40) there was a decrease in E_Z AEF to –6 kV/m that was replaced with a sudden jump in E_Z AEF to reach +5 kV/m (Fig. 9). The much greater amplitude of the negative phase compared with the first case is consistent with the considerable amount of ash (~100 g/m^2) that was deposited at Klyuchi.

Cherneva et al. (2007) found the response in E_Z AEF due to 3D charges of simple configurations transported by wind and residing above a conductive surface. These authors found simulated curves in dimensionless variables. The anomaly has a shape that is reminiscent of the variation in E_Z AEF for a horizontal dipole whose axis is along the motion and passes through the recording site. The dipole seems to have been formed by eolian differentiation, with large ash particles being negative in the frontal part of the eruptive plume and positive in the delayed aerosol part of the plume.

Atmospheric stratification and kinematic parameters of the anomaly can be used to estimate the dipole parameters, as follows: the motion starts 40 km from KLYG; the dipole moves at 36 km/hour; the dipole center is at a height of $z = 9$ km above ground; and the intercharge distance is 2.5 km. Based on these parameters, we shall calculate, to a first approximation, the dipole charge q from the relation

$$E_z = \frac{2q}{4\pi\varepsilon_0 z^2}, \quad q \approx 40 \text{ C},$$

where $\varepsilon_0 = 8.85 \times 10^{-12}$ C/V m, the electrical constant.

In approximately 5 hours the eruptive plume reached Kozyrevsk where the fall of some fine ash was recorded. The fluxmeter at KZYG recorded an anomaly whose shape was in agreement with a positively charged plume (Cherneva et al., 2007), indicating the fact that eolian differentiation produced an aerosol cloud involving a very small amount of very fine-grade ash.

DISCUSSION OF RESULTS

The extrusive dome of Shiveluch Volcano has stabilized in recent years at an approximate height of 600 m. Incandescent avalanches began to occur, with some individual explosions being accompanied by rockfalls. The extrusive cone seems to have reached the limiting possible height and the processes mentioned above compensate for the dome growth by squeezing up extrusive material.

Multidisciplinary data acquired by remote techniques were used to examine two explosions on Shiveluch Volcano. Observations of the electrification of eruptive plumes make a definite contribution to the

Table 2. The chemical composition of ashes ejected by Shiveluch Volcano

Date	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	CaO	MgO	Na_2O	K_2O	P_2O_5	LOI	Total	Fe_2O_3/FeO
16 Dec 16	65.80	0.44	15.40	1.24	2.38	0.08	5.14	2.60	4.87	1.43	0.14	0.29	99.82	0.52
14 Jun 17	64.20	0.59	15.30	2.35	2.44	0.09	5.50	3.30	4.43	1.22	0.14	0.37	99.95	0.96

The analyses were performed at the Analytical Center, Institute of Volcanology and Seismology (IV&S) FEB RAS, by Analysts A.A. Kuz'mina, N.Yu. Kurnosova, and V.M. Ragulina.

understanding of the physics of explosive eruptions. The usefulness of this method is due to two factors: "fair weather conditions," because the method is sensitive to variations of meteorological quantities; and the location of the fluxmeters relative to the source, which are to be installed with due consideration of the wind rose in the Shiveluch area based on multiyear observations. Bearing these restrictions in mind, even a few observations of the response of E_Z AEF to the passage of eruptive plumes are of great interest.

Even though there have been numerous explosive eruptions in the past (see Fig. 2), there have been few ashfalls at Klyuchi. From this it follows that reliable recording of E_Z AEF variations can be ensured by placing observing sites along the directions of the principal ashfall axes shaped by the wind rose.

The weak explosion of Shiveluch at 22:31 on December 16, 2016 that was probably accompanied by a rockfall was a "flow-through" lasting over 10 minutes. This resulted in an eruptive plume at a height of ~6 km that went southwest around KLYG. At the same time, the ash cloud due to the rockfall that was formed at a height of ~2.5 km went above Klyuchi and gave rise to an anomaly in E_Z AEF that is typical of cloud structures.

The powerful explosion of Shiveluch Volcano at 16:26 on June 14, 2017 was an "explosion" with a subsequent "flow-through." The resulting eruptive plume passed over two stations (KLYG, 48 km and KZYG, 109 km). While the plume had an electrical structure in the form of a dipole at the nearest site, this structure experienced an evolution at the farther site by eolian differentiation to become a negatively charged cloud.

Comparison between the parameters for the 2016 and 2017 explosions derived by remote techniques provide some idea of the potential of these techniques. We will also consider the chemical (Table 2) and grain-size (Fig. 10) compositions of the ash ejected by the explosions and deposited at Klyuchi.

The 2016 ash has a fresh, juvenile aspect and mostly consists of light, transparent, colorless plagioclase particles with a small admixture of mafic minerals. The 2017 ash also contains an appreciable amount of oxidized fragments of the same minerals having a rusty brown color, indicating some portion of resurgent material. This is also borne out by the chemical analyses. The ashes are practically identical in their chemical composition, being medium-potassium calc-alkaline dacites. However, the 2017 ash is slightly less acidic compared with the 2016 ash and exhibits an appreciably higher degree of oxidation, as follows from their Fe_2O_3/FeO ratios, with the respective values being 0.96 and 0.52.

The grain-size compositions of the ashes are shown in Fig. 10. Both of the ashes (2016 and 2017) sampled at Klyuchi show similar distributions; however, the 2017 ash has slightly larger grains (see Fig. 10). For comparison purposes we also quote the grain-size distribution for the ash sampled in the upper reaches of the Baidarnaya River in 2017. It is only natural that the ash sampled at 7 km from the vent has much larger grains compared with the ash that was wind-transported for a distance 48 km.

It follows from the results of grain-size and chemical analyses of the ashes that the 2016 ash was due to a weaker eruptive event that occurred after a rockfall or an incandescent avalanche descended. The 2017 ash reflects a more powerful explosive event compared with that in 2016, with the event involving an appreciable part of external, oxidized part of the intrusion. The Klyuchi ash has experienced eolian differentiation when compared with that sampled in the near zone around the volcano (see Fig. 10).

Although the grain-size and chemical compositions were very slightly different, the respective eruptive plumes had different aero-electrical structures for the two cases. This indicates that the physical pro-

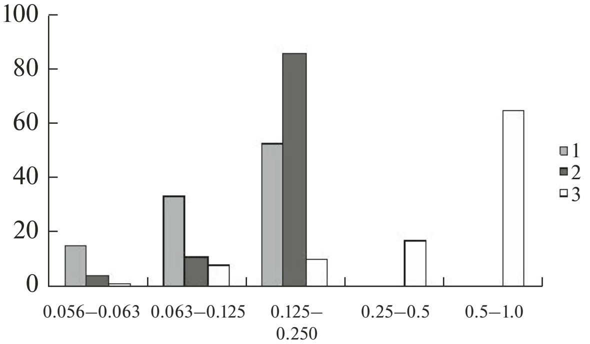

Fig. 10. The grain-size distribution of Shiveluch ashes. (1, 2) sampled at Klyuchi on December 16, 2016 and June 14, 2017, respectively, (3) sampled in the upper reaches of the Baidarnaya River on June 14, 2017 (by A.B. Belousov).

cesses related to the formation of an eruptive plume control its electrification. While the ash–air plume was "dry" in the first case, resulting in an aero-electrical structure of the "charged cloud type," the second case involved large amounts of ash and volcanic gases ejected into the air by the large explosion, with over 90% of the ejecta consisting of steam (Menyailov et al., 1991). For this reason a dipole aero-electrical structure was formed by eolian differentiation in the near zone (KLYG, $R = 48$ km) (see Fig. 3).

CONCLUSIONS

A new extrusive dome has been growing in the Young Shiveluch caldera since 1980. Such a long cycle of volcanic activity provides an opportunity for a planned study of eruption dynamics. Along with direct methods to study changes in dome morphology and to determine dome growth and changes in dome volume, other methods are important. One of these methods can be the study of electrification for eruptive plumes during explosive phases of an eruption. This study shows that the intensities of the atmospheric electrical field during the passage of eruptive plumes above the KLYG station due to the explosive eruptions of December 16, 2016 and December 14, 2017 are −1.2 and −6.0 kV/m, respectively. Such values of E_Z AEF can be sufficiently reliably identified upon the background of noise due to variations in meteorological quantities.

The creation of a network of stations to record E_z AEF in areas of active volcanoes will make it possible to derive some estimates for the size of volcanic aerosol and its dynamics during the evolution and transport of eruptive plumes. In addition, we can acquire significant data to update the transport of eruptive plumes that have low aerosol concentrations, which are undetectable by satellite-based instruments.

Special mention should be made of the fact that the intensity of electrical field is measured by remote techniques, which is important in surveying volcanoes such as Shiveluch that can produce powerful catastrophic eruptions of the "directed explosion" type.

ACKNOWLEDGMENTS

We thank V.S. Efimov for his great help in setting up the instrumentation, Yu.A. Vladimirov and R.A. Konev for help in operating the fluxmeters, as well as A.A. Koneva for help in figure drawing. We are very much in debt to P.M. Nagorskii for advice and constructive criticism that did much to improve the paper.

This work was supported in part by the Russian Foundation for Basic Research, project no. 18–35–00175/18.

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Translated by A. Petrosyan