ISSN 0742-0463, Journal of Volcanology and Seismology, 2014, Vol. 8, No. 4, pp. 203–217. © Pleiades Publishing, Ltd., 2014.
Original Russian Text © P.P. Firstov, A.A. Shakirova, 2014, published in Vulkanologiya i Seismologiya, 2014, No. 4, pp. 3–19.

Seismicity Observed during the Precursory Process and the Actual Eruption of Kizimen Volcano, Kamchatka in 2009–2013

P. P. Firstov and A. A. Shakirova
Kamchatka Branch, Geophysical Service, Russian Academy of Sciences,
Petropavlovsk-Kamchatskii, bul'var Piipa 9, 683006 Russia
e-mail: firstov@emsd.ru

Receied July 29, 2013

Abstract—Kizimen Volcano began to erupt in December 2010. The eruption was preceded by a precursory period of seismicity that lasted for 20 months. This paper discusses the space–time features of the precursory seismicity. We provide a brief description of this explosive and effusive eruption between December 2010 and March 2013. The eruption started with some explosive activity followed by extrusion of a viscous lava flow. The extrusion of viscous andesitic magma and the motion of the lava flow down the slope were accompanied by unusual seismicity in the form of the quasiperiodic occurrence of microearthquakes, the so-called drumbeat phenomenon. It is shown that the occurrence of a drumbeat was first recorded during the extrusion process at the volcano's summit. Subsequently, the drumbeat mode of activity was caused by the front of the viscous lava flow as it was moving down the slope. The dynamic parameters of the microearthquakes varied in accordance with the dimensions of the lava flow front. The motion of the main tongue of the lava flow (March to September 2011) gave rise to drumbeat I with energy classes of microearthquakes $K = 3–5.5$, while the second tongue, which was smaller than the first, produced drumbeat II with microearthquakes of $K < 3$ during its motion down the slope. In January 2013 we saw a phenomenon similar to the drumbeat that was recorded at the start of the eruption. This was caused by an obelisk being extruded at the volcano's summit.

DOI: 10.1134/S0742046314040022

INTRODUCTION

Kizimen (its absolute altitude is 2485 m; the coordinates of its summit are 55.13° N, 160.33° E) is an active volcano of the explosive–effusive–extrusive type that obtains its supply of magma from the mantle. It is situated in the eastern part of the Shchapina graben in the central Kamchatka depression (Fig. 1a). It can be seen in the tectonic map of the Gamchen Range and the Levaya Shchapina River valley that the area of this volcano is controlled by complex tectonics (see Fig. 1b).

A series of northwest trending faults cuts across the east wall of the Tumrok Range horst and is thought to extend into the bottom of the Shchapina graben, which is overlain by thick Quaternary deposits. The volcanic edifice itself is confined to a system of large-amplitude normal faults that trend northeast in the zone where the Shchapina graben is adjacent to the Tumrok Range horst [*Kamchatka ...,* 1974].

The erupted products have compositions that range between plagioclase basalts and hornblende quartz-bearing dacites [Shantser et al., 1991]. The immediately preceding eruption of Kizimen seems to have occurred in 1927–1928 [Piip, 1946].

The upper part of the volcano has a complex morphologic structure, consisting of a combination of several closely standing extrusive domes with their thick agglomerate mantles; the domes differ in size, degree of preservation, and age. The volcano has had four cycles of activity, each lasting 2500 to 3000 years, with the duration of the last cycle, IV, being near to the extreme value. Based on this fact, a well-grounded forecast was developed in 1992 that predicted a new cycle resulting from injection of a portion of fresh magma in the Kizimen source region [Melekestsev et al., 1992]. It was supposed that a long repose period may be followed by a new eruption of the directional explosion type after the classification of G.S. Gorshkov [1963] based on the lava composition. Three eruptions of this type have occurred during the last century, viz., on March 30, 1956 on Bezymyannyi Volcano, on November 12, 1964 on Shiveluch Volcano, and on May 18, 1980 on Mt. St. Helens. The new eruption started in December 2010, at 82 years since the preceding eruption, as a series of explosions, with each explosion being followed by a pyroclastic flow [Malik and Ovsyannikov, 2011]. At the time this paper was in preparation (July 2013) the Kizimen eruption did not follow the directional explosion scenario, but was occurring in an entirely different manner. At the time the manuscript was submitted to this journal, the eruption was occurring in

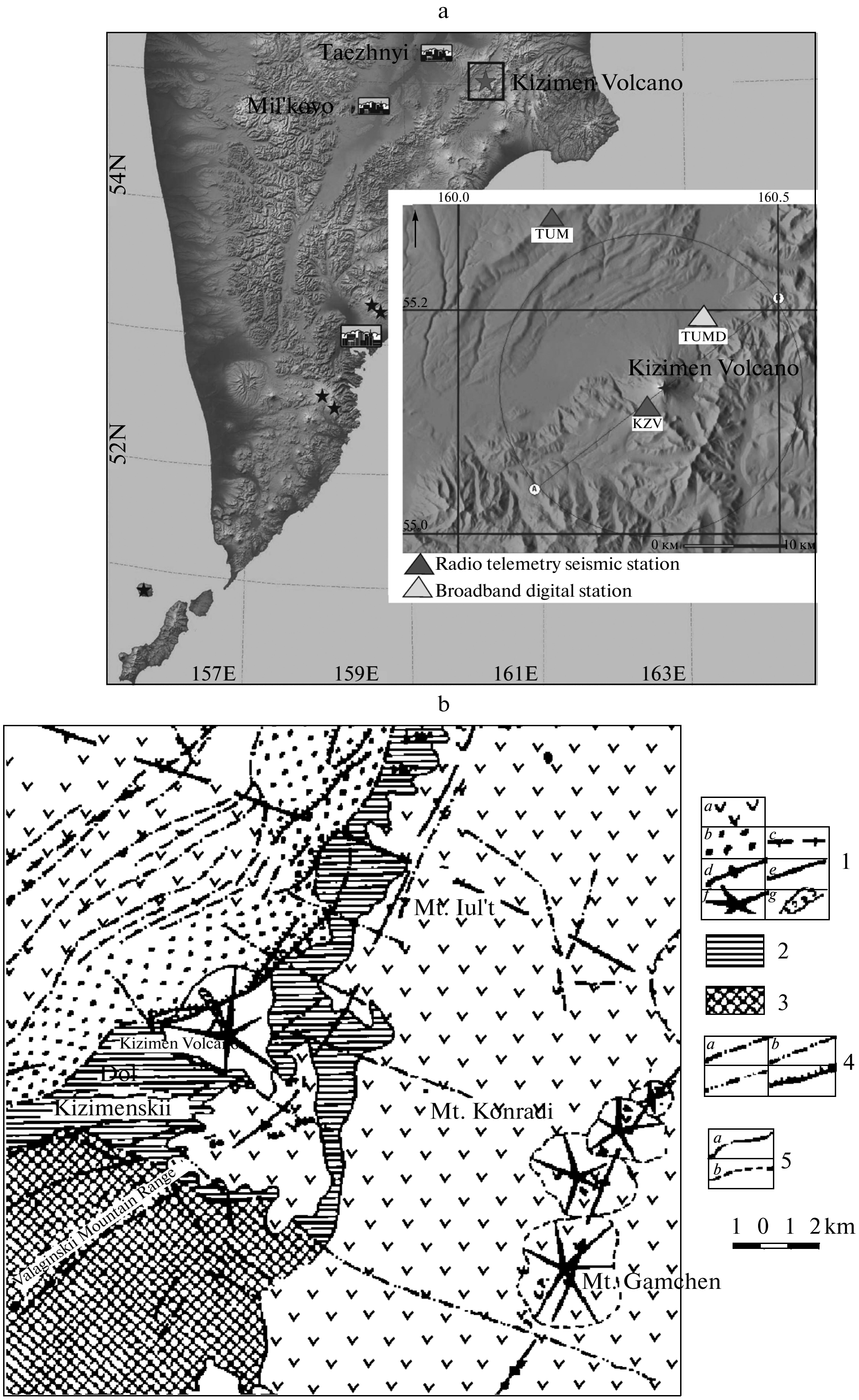

Fig. 1. The location and tectonic map of the area of Kizimen Volcano.

a, the location of Kizimen Volcano in the Kamchatka Peninsula, b, a tectonic map of the Gamchen mountain range and the Levaya Shchapina R. valley [*Kamchatka* ..., 1974].

(1) upper structural stage: *a* Holocene sheet deposits, *b* Shchapina R. graben, *c* axes of horst-like elevations, *d* axis of Gamchen mountain range accretional elevation, *e* axis of Tumrok–Nikol'skoe transverse zone, *f* Holocene and Upper Quaternary volcanoes, *g* Holocene lava flow; (2) Middle structural stage; (3) lower structural stage; (4) discontinuities: *a* certain, *b* inferred, *c* inferred extensions of faults beneath Quaternary formations, *d* faults in Holocene deposits; (5) geological boundaries: *a* certain, *b* inferred.

Table 1. The coordinates of the RTSSs that are the nearest to Kizimen Volcano and their altitudes above sea level

Station	Code	Latitude, deg N	Longitude, deg E	Altitude, m	Distance between crater and RTSS, km
Kizimen	KZV	55°113	160°294	1509	2.5
Tumrok	TUM	55°283	160°146	1213	20.0
Tumrok Springs	TUMD	55°203	160°399	486	6.0
Temporary station	KZVD	55°114	160°369	1222	3.0

the form of a slow extrusive process (extrusion of obelisks), producing pyroclastic flows and incandescent avalanches (landslides).

This study makes use of seismological observations to discuss the dynamics of this eruption and to attempt to provide an explanation of the unusual seismicity that accompanies the eruption based on the rheologic properties of Kizimen magma.

THE SEISMICITY OF THE KIZIMEN AREA BEFORE THE ERUPTION

Three radio telemetry seismic stations (RTSS) are currently operated near Kizimen Volcano by the Kamchatka Branch of the Russ. Acad. Sci. Geophysical Service (see Fig. 1a, inset). The TUM RTSS has been in operation since 2003 at a distance of 20 km northwest of Kizimen. In consideration of renewed seismicity in the Kizimen area that started in April 2009, KZV RTSS was installed 2.6 km southwest of the Kizimen summit in September in order to record the microearthquakes that were occurring in the volcanic edifice. The location of small earthquakes was aided by a new-generation digital broadband station (TUMD) at 6 km (see Fig. 1a) of the Kizimen summit that was installed in March 2011 [Chebrov et al., 2013]. A broadband CMG-5TD accelerometer (produced by GURALP) was operated for a few hours at KZV RTSS (the KZVD seismic station) during preventive maintenance work on April 29, 2012 in the area of the lava flow. The accelerometer can record ground acceleration between 0.1 and 2 g with a dynamic range of 140 dB in the frequency range 0–40 Hz (www.guralp.com). The coordinates of this RTSS and the temporary station, as well as the distances between these and the crater, can be found in Table 1.

A video camera was installed at the TUMD RTSS in July 2011 to keep track of the volcano's activity at a rate of an image per minute. This permitted us to bring in correspondence seismic signals and occurrences of volcanic activity of certain types.

The rate of volcano-tectonic (VT) earthquakes began to increase in the Kizimen area from April 2009, with a sharp rise in seismicity occurring in early July 2009. The lowest earthquake energy class as estimated from shear waves (K = logE, where E is energy at the earthquake source in Joules) for the seismicity in the area is $K_s = 5.8$[1] [Senyukov et al., 2011]. For the period from July 10 to December 31, 2009, over 8000 earthquakes with $K > 2$ have been recorded (the highest value was $K = 9.9$) with hypocenters in the depth range 5–11 km in the area of the volcano and its base [Garbuzova and Sobolevskaya, 2011]. The occurrence of VT earthquakes seems to have been due to deep-seated processes that were caused by the movement and ascent of magma, culminating in the eruption later.

According to the catalog of Kizimen earthquakes published by Kozhevnikova et al. [2012], the level of seismicity in the volcano area considerably increased in 2010. Figure 2 shows the distribution of $K \geq 7$VT earthquakes that were precursory to the eruption and a cumulative plot of inferred deformation $\xi = \Sigma E^{0.5}$ for the January–December 2010 period.

By the end of April the accumulated inferred deformation reached the value 2×10^6 $J^{0.5}$ and then continued to increase in a monotonic manner until October, to be followed by two intervals of increased seismic activity. The first of these took place in the second 10-day period of October, when a series of shallow $K > 10$ earthquakes occurred at depths of $H = -2$–4 km (the minus sign indicates the depth above sea level): October 1 to 9, $K = 10.9$; October 2 to 13, $K = 10.2$; October 3 to 19, $K = 11.2$ ($M_c = 5.2$). The second burst of seismic activity occurred in November 2010 with four $K > 10$ earthquakes ($H = -2$–8 km): November 1 to 12, $K = 10.1$; November 2 to 16, $K_s = 10.7$; November 3 to 27, $K = 11.4$ ($M_c = 5.0$); November 4 to 27, $K = 11.9$ ($M_c = 5.3$) [Kozhevnikova et al., 2012].

The total inferred deformation for 2010 was 8×10^6 $J^{0.5}$; the duration of the precursory seismic processes before the Kizimen eruption was 20 months. The period of increased seismicity (October 9 to 19 and November 12 to 27) was accompanied by a visible occurrence of volca-

---

[1] The suffix s is omitted here and throughout the paper.

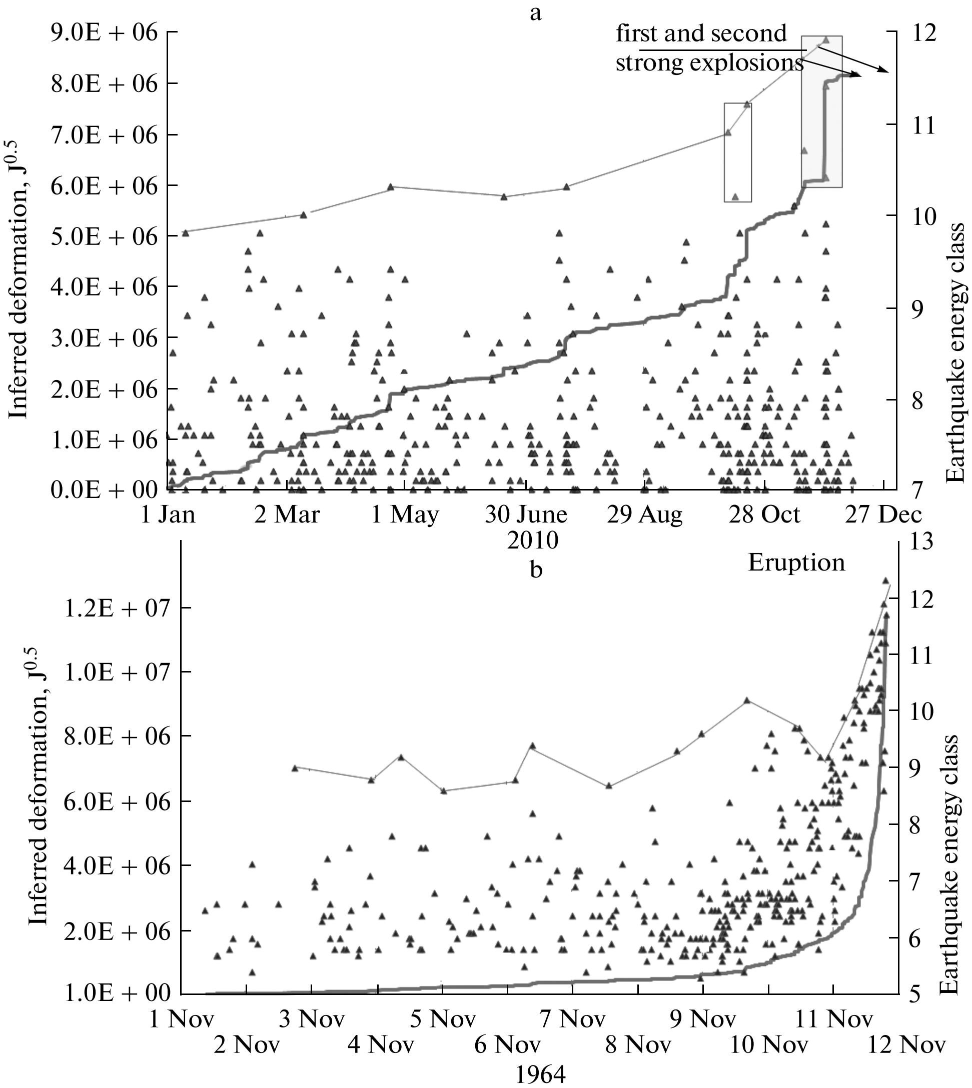

Fig. 2. A cumulative plot of the inferred deformation and the energy classes of earthquakes that preceded the eruption of Kizimen in 2010 and that of Shiveluch in 1964.

a $K \geq 7$ earthquakes for the period from January 1 to December 31 before the Kizimen eruption, b $K \geq 5.5$ earthquakes before the Shiveluch eruptions. Light lines show the variations in K_{max} and the rectangles mark the intervals of higher seismic activity on Kizimen Volcano.

nic activity in the shape of discrete explosions. Powerful explosions that ejected ash to heights of 10 km occurred on December 12 and 31, 2010.

It is of interest to compare the precursory seismicity prior to the Kizimen eruption with that before the 1964 directional explosion eruption of Shiveluch (see Fig. 2b).

The first smaller VT earthquakes in the Shiveluch area were recorded in January 1964; the next burst of seismic activity occurred in the form of a swarm sequence of VT earthquakes in late April–early May 1964, when 37 K = 6–10 earthquakes were recorded during 2 weeks. The epicenters of all earthquakes were within the volcanic edifice at depths of 0 to 10 km [Tokarev, 1991]. This swarm of VT earthquakes provided evidence of changed stress and strain in the deformed rock volume beneath the volcano associated with the emplacement and ascent of magma. After that swarm the seismicity rate began to decrease. A new burst of seismic activity started on November 1 and continued until the beginning of the eruption on November 11, 1964. During the last few days before the eruption 73 earthquakes were recorded with K = 8–12.3. The rate and energy of earthquakes began to rise sharply 7 h before the eruption. Five K > 11 earthquakes were recorded during that period. The largest earthquake (K = 12.3) occurred at 19 h 07 min[2] and a somewhat smaller event ($K_s = 11.7$) occurred at 19 h 30 min.

---

[2] Here and below the time is GMT.

The emplacement and accumulation of magma in the upper part of the volcanic edifice beneath the older domes produced a crypto-dome; the pressure increased as a consequence and large earthquakes began to occur. As a result, the edifice lost its continuity and this provoked a giant landslide of volume 1.5 km^3, which caused decompression in the crypto-dome and initiated the eruption [Firstov, 1996]. The net inferred deformation was 16×10^6 $J^{0.5}$ for 1964; the precursory seismicity before the Shiveluch eruption lasted 7 months, with the bulk of the seismic energy being released 2 days before the eruption.

We note that comparison of the respective seismicity periods that were precursory to these two eruptions gives the result that the inferred deformation and the rate of deformation were considerably higher for Shiveluch than for Kizimen. The slow-going seismicity of Kizimen indicates a very viscous and gas-depleted magma that was slowly moving upward. The magma body, probably a dike, has a complex configuration, as can be inferred from the distribution of VT earthquake hypocenters.

The spatial distribution of earthquake hypocenters that preceded and accompanied the Kizimen eruption is shown in Figs. 3a and 3b. Figure 3a shows a map of epicenters and a vertical cross section of $K > 5$ earthquake hypocenters for November–December 2010 and for January–February 2011 as inferred from data supplied by the seismic network of Kamchatka [Kozhevnikova et al., 2012]. Figure 3b shows a map of epicenters and a vertical cross section of smaller ($2 < K < 5$) VT earthquakes in the volcano area during the November 2009 to February 2011 period whose spatial positions were determined by the polarization method using earthquake records made at KZV RTSS [Shakirova and Kozhevnikova, 2011]. We determined the station–source azimuths and the angles of emergence from the first arrivals on three components (SHE, SHN, and SHZ) using the DIMAS program [Droznin and Droznina, 2010] for 780 earthquakes with S–P = 0.7–1.5 s, whose records had no amplitude limitations and showed distinct P-wave arrivals. The S–P values were used to find the station–hypocenter distance and the depth was calculated from $H = \cos\gamma R - h$, where γ is the angle of emergence for the polarization axis; R is the distance between the epicenter and KZV RTSS in km; and $h = 1.5$ km is the height of the RTSS above sea level.

It has been shown [Shakirova and Kozhevnikova, 2011] that the discrepancy between the hypocenter coordinates for VT earthquakes in the Kizimen area as found by the polarization method and those based on the RTSS data is 1.5 km for the epicenter location and 0.7 km for the depth. Two zones can be identified from epicenter density clusters: one is oval and extends for nearly 10 kilometers to the northeast, while the other is more compact and is like a circle of about 2 kilometers in diameter; it is adjacent to the volcanic edifice on the northeast (see Fig. 3). The hypocenter depths are between –1.5 and 8 km, with the bulk of events being at depths of 0–5 km. The projection of earthquake hypocenters onto the vertical cross section (A–B) also shows two zones: the one is dipping and lies southwest of the volcano (a northeast trending zone), while the other is in the form of a vertical column just beneath the volcano (see Fig. 3b). The hypocenter depths increase away from the volcano in the first zone. The northeast trending zone is also well expressed in the 2010 seismicity before the eruption (see Fig. 3a). The zone of higher seismicity beneath the volcano seems to have been related to the beginning of an intrusive process at depths of 0–8 km and can well be classified as a local tectonic stress field. The northeast trending zone seems to be a reflection of the subregional stress field as a consequence of Kizimen being at the side of the Shchapina graben. The interaction between the local and the regional stress field have produced a rather complex configuration of the seismic volume that had become active before the eruption.

Volcano-tectonic earthquakes continued to occur during the 2011 eruption, with their hypocenters being northeast of the volcano (see Fig. 3d) at depths of 0 to 5 km obviously tending to cluster at two faults trending northwest, see Fig. 1b. It is possible that the seismic activation of these structures was related to adjustment toward reaching the isostatic equilibrium to accomodate an excess mass in the shape of a lava flow more than 0.5 km^3 in volume on the eastern slope of the volcano.

A BRIEF DESCRIPTION OF THE KIZIMEN ERUPTION

The Kizimen crater contained a dome of effusive lava before the eruption with no traces of fumarole activity. Fumarole activity was exceptionally high at a site situated on the northern slope of the volcano, about 400 m down from the summit, with a set of powerful solfataras that have been observed to have been active since 1825 [Ditmar, 1901]. A new fumarole was noticed near the volcano's summit on its southeastern slope on October 16, 2010. The first steam–gas explosion with some ash was observed to occur at the fumarole on November 11, 2010, with the activity of the older fumarole remaining unaffected [Senyukov et al., 2011].

The fumarole activity in the volcano's crater sharply increased after the November 11, 2010 explosion, when an ash-charged steam–gas cloud rose to a height of 1.5 km above the summit. The air-borne survey performed by V.N. Dvigalo on November 21, 2010 revealed the first changes in the summit structure, with new thermal patches and fumarole fields appearing there. A basin that was open southeastward was also detected; this seems to be the volcano's crater [Mel'nikov et al., 2011]. No information on the volcano's activity is available between November 22 and December 9, because the volcano was inaccessible to visual and satellite observation owing to bad weather. The first seismic signals that might provide

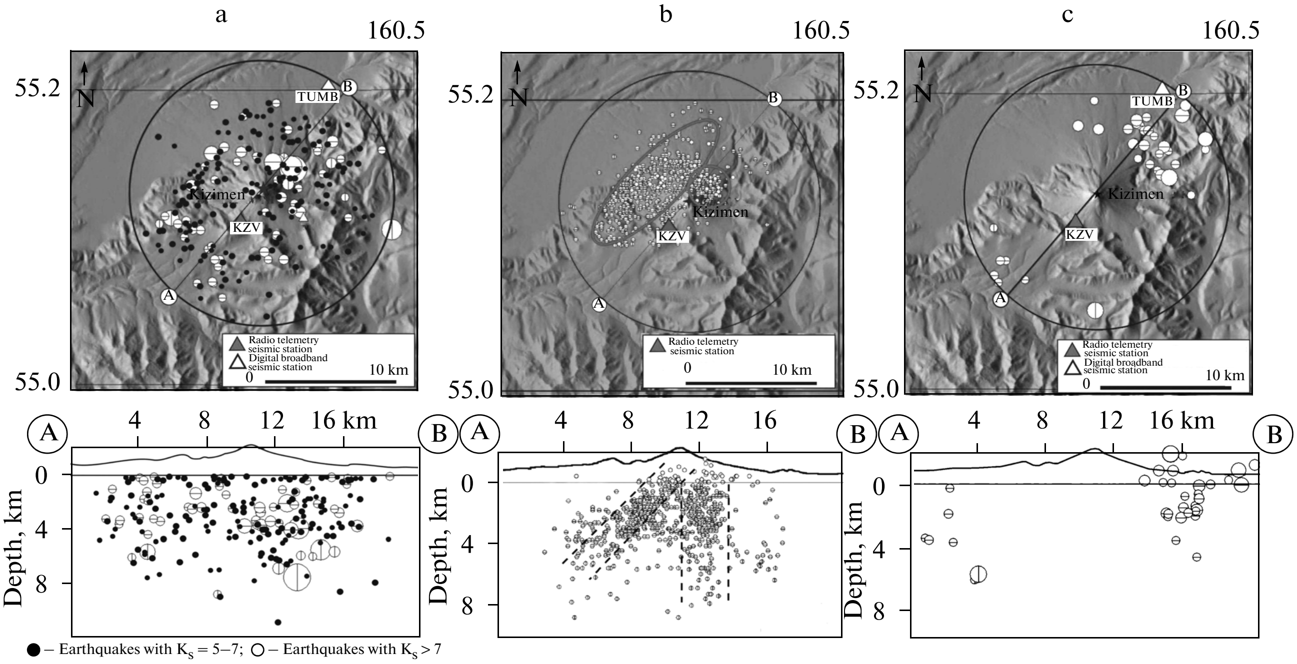

Fig. 3. A map of epicenters of earthquakes before the Kizimen eruption and the projection of earthquake hypocenters onto the vertical plane along the AB cross section.

a for K > 5 earthquakes in November–December 2010 and in January–February 2011 as located by the RTSS network (operated by the Kamchatka Branch of the Geophysical Service of the Russian Academy of Sciences) [Kozhevnikova et al., 2012], b for 2 < K < 5 earthquakes for the period November 2009 to February 2011 as located by the polarization method [Shakirova and Kozhevnikova, 2011], c for K ≥ 7 earthquakes recorded in 2011.

evidence of explosions and debris avalanches were recorded on December 9, 2010, with a sudden burst of seismic and volcanic activity occurring during the night of December 9 to 10 [Senyukov et al., 2011]. Ash explosions were seen to rise to heights of 1 kilometer as observed from the Ipuin cordon 23 km west of the volcano in the morning of December 10. Subsequent observation detected practically continuous discharges of eruptive plumes that were charged with ash and had varying lengths, with nearly every explosion being followed by a pyroclastic flow or a stone avalanche [Malik and Ovsyannikov, 2011].

The extrusion of the viscous dacitic lava flow and the generation of an intracrater extrusion must naturally have been accompanied by auto-explosive stone avalanches, as was observed on the Bezymyannyi andesidacitic volcano [Malyshev, 2000]; this was also noticed on Kizimen Volcano.

The strong explosion that occurred at 19 h 49 min on December 12, 2010 was accompanied by acoustic and seismic effects. The ash plume due to this explosion propagated northwestward at the tropause height (~10 km), as deduced from satellite observations and deposited ash at the villages of Kozyrevsk (110 km) and Tigil' (300 km). Weak explosive activity took place later, as inferred from seismic data; the next powerful explosion occurred at 17 h 56 min on December 31 and was also accompanied by acoustic and seismic effects. Satellite observations showed that the plume due to this event propagated southwestward. Ash fell in the town of Petropavlovsk-Kamchatskii 230 km away from the volcano. Estimates based on an analysis of a record of the acoustic signal gave a 4 × $10^6 m^3$ as the volume of ash [Firstov and Makhmudov, 2011].

The December activation of the volcano led to destruction of the top of the summit in 2010 and started the extrusion of viscous andesitic magma. The lava flow was first noticed on the eastern slope of the volcano in late February 2011 and then descended to the cone base [Malik and Ovsyannikov, 2011].

Figure 4 shows a map of ejecta deposits from Kizimen as of September 5, 2011 [Mel'nikov et al., 2011]. By that time the lava flow was about 2 kilometers long and had deposited an extensive pyroclastic flow in the southeastern sector of the volcanic edifice and a thin ash layer northwest of it. As of September 5, 2011, the lava flow had expanded to reach a length of about 4 km (V.N. Dvigalo, personal communication). That same figure also shows an approximate outline of the lava flow for March 15, 2012 as drawn from a satellite photograph (courtesy D.V. Mel'nikov).

By that date the lava flow, which consisted of two tongues, had reached the gently sloping plain (2°–5°) that had been formed of older pyroclastic flows at the volcano base (see Fig. 4). According to visual observations, the new northeastern tongue relative to the lava flow was formed in October 2011. Figure 5a (September 14, 2011) shows a lava flow that consisted of a single tongue and an active zone in the lateral part of that flow where the new tongue was in the making. By December 2011 the northeastern tongue had been completely formed (see Fig. 5b). By June 2012 the lava flow had stopped moving (see Fig. 5c).

During the entire period of eruption the volcano showed one unusual activation on December 13, 2011, when a series of pyroclastic flows were discharged and were recorded by the video camera installed at the TUMD RTSS 6 km from the volcano crater. Figure 6 shows photographing frames of the eruptive cloud at intervals of 1 minute, as the pyroclastic flow was descending at 23 h 22 min on December 13; one can clearly discern that the eruptive cloud began to form at the moment when the pyroclastic flow came sliding from the transit zone into the braking zone onto the gently sloping plain. As the pyroclastic flow was descending, it produced a turbulent ash-charged air flow above it due to heat and gas release, with the air flow moving along with it. As the lower part of the pyroclastic flow body experienced sudden deceleration, heat and gases were intensively released to supply the ash-charged air flow. The air flow then tore itself away and passed a few tens to a few hundreds of meters beyond the boundary of the pyroclastic flow deposits. The descent and generation of the pyroclastic flow were accompanied by seismic signals, which were recorded at KZV and TUMD RTSSs [Firstov and Shirokova, 2012a, b].

By the end of May 2012 an extrusive obelisk began to be squeezed out at the volcano summit, which was also reflected in the seismic effects.

THE “DRUMBEAT” DYNAMICS DURING THE GENERATION OF THE LAVA FLOW IN 2011–2012

The extrusion of viscous andesitic lava and lava flow movement were accompanied by an unusual seismicity that has not been previously observed during the eruptions of Kamchatka andesitic volcanoes. The KZV and TUMD RTSS seismograms showed quasiperiodic occurrence of microearthquakes with similar record shapes and identical amplitudes lasting between a few tens of minutes and a few tens of days. Such seismicity was first recorded a few hours before the ash discharges on December 9, 2010; it seems to have been caused by the extrusion of the very first portion of lava material. Afterwards a similar seismicity was recorded on December 23, 2010 and on January 23, 2011, while such microearthquakes (with a quasiperiodicity of 8 to 50 s and energy class $K = 2.0–5.5$) began to be recorded continuously since May 13, 2011 [Firstov and Shakirova, 2011; Shakirova et al., 2011]. This kind of seismicity involves a distinctive feature of its own, viz., the maximum amplitudes of individual earthquakes are nearly constant over long time intervals.

When the microearthquakes were separated by very small time intervals, the record coalesced, became continuous, and reminded one of spasmodic volcanic tremor. The American volcanologists coined the term “drumbeat” to describe quasi-regular occurrence of microearthquakes that were recorded during the extrusion of individual blocks of viscous magma on the Mt. St. Helens extrusive dome in 2004 [Iverson et al., 2006; Moran et al., 2007; Matoza et al., 2009, Matoza and Chouet, 2010].

The variations in the frequency of occurrence and maximum amplitudes of microearthquakes for May–June 2011 are illustrated by Fig. 7 showing 4-hour segments of microearthquakes recorded at KZV RTSS with varying amplitude factors, k, for four dates (May–June 2011). While discrete microearthquakes can still be seen in Figs. 7a, 7b, and 7c, the record in Fig. 7d has coalesced and exhibits a nearly sinusoidal signal that resembles spasmodic volcanic tremor.

The “drumbeat” mode of activity experienced certain changes since October 12, 2011 that were clearly discernible by the eye. Smaller microearthquakes began to be recorded upon the background of those observed previously, with these smaller events being provisionally classified as a second type, “drumbeat” II (Fig. 8a). The microearthquakes in the drumbeat II mode were also quasiperiodic and had nearly constant amplitudes over long time intervals, but the double ground velocity amplitude (2 Å) varied in the 0.05–0.55 μm/s ($K = 2–4$) range, which is considerably below the value of 2 Å for the drumbeat I earthquakes during that period (see Figs. 8b and 8c). In 3 days after the drumbeat II mode appeared, the drumbeat I earthquakes ceased to be recorded.

Similarly to other volcanoes [Iverson et al., 2006; Moran et al., 2007; Matoza et al., 2009], the microearthquakes of both types have record shapes typical of long-period volcanic earthquakes with well-pronounced P and S arrivals (Figs. 8b, 8c).

We measured mean rates of microearthquakes per minute (f_D, min^{-1}) and mean A/T ratios (μm/s) in order to investigate the drumbeat dynamics, when the drumbeat occurred over short time intervals. We measured the same parameters in four one-hour intervals (6, 12, 18, and 24 h) during periods when the drumbeat occurred over long time intervals (Fig. 9).

Small drumbeat I microearthquakes with $A/T > 0.5$ μm that preceded the first explosions on the volcano were recorded on December 9, 2010. Small, short-lived, drumbeat I microearthquakes were also recorded 7 days

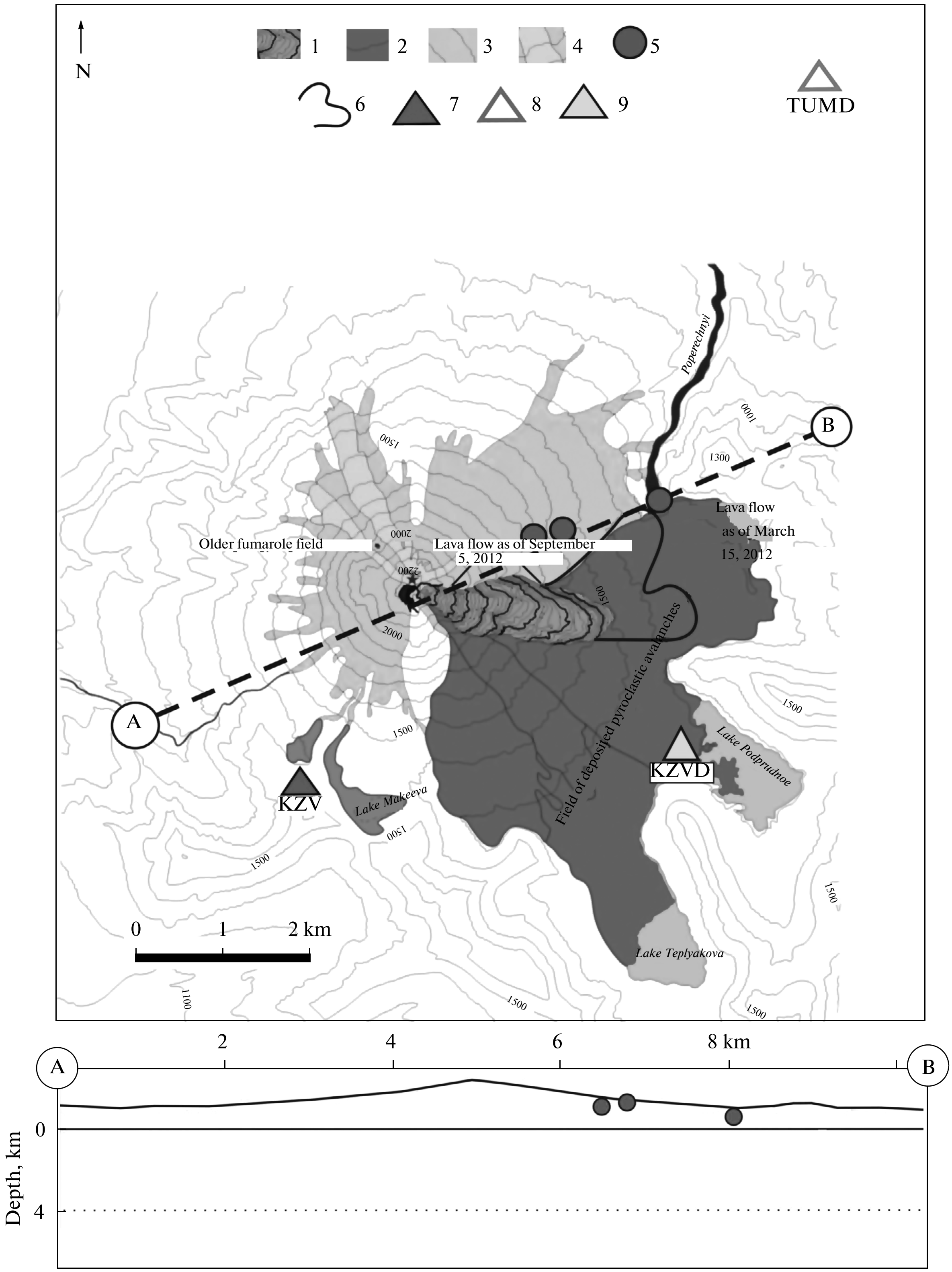

Fig. 4. A map of ejecta deposited by the eruption as of September 5, 2011 (compiled by V.N. Dvigalo) [Mel'nikov et al., 2011]. (1) the lava flow that had formed by September 5, 2011; (2) the main field of deposited pyroclastic avalanches of a few meters to a few tens of meters thick; (3) thin deposits of ash and the wind-borne material of pyroclastic avalanches; (4) basaltic andesite lavas discharged during the fourth eruption cycle; (5) front of lava flow as of March 15, 2012; (6) radio telemetry seismic stations; (7) temporary seismic station; (8) epicenters of drumbeat microearthquakes as recorded on April 29, 2012 and a vertical cross section with hypocenters of $4 < K < 5$ drumbeat microearthquakes projected onto the vertical plane along AB for April 29, 2012.

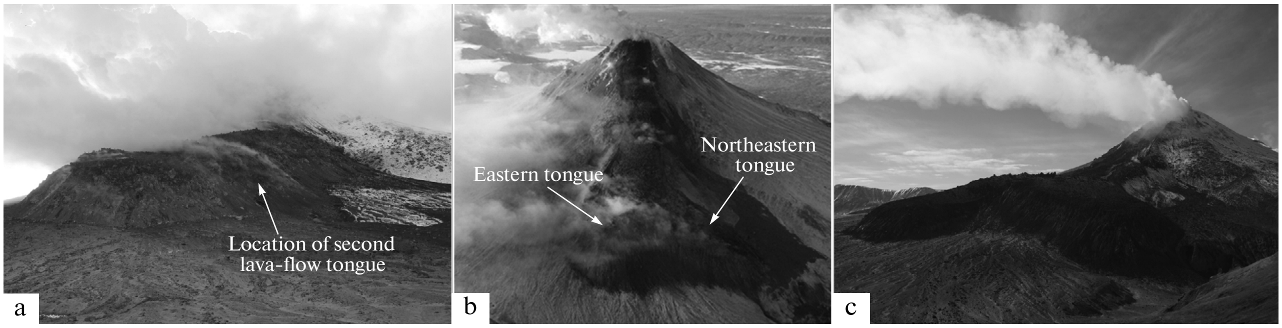

Fig. 5. The dynamics of the lava flow from Kizimen Volcano:
a September 14, 2011, photograph by V.V. Yashchuk; b December 23, 2011, photograph by S.A. Chirkov; c September 20, 2012, photograph by A.A. Shakirova.

Fig. 6. Photograph frames showing the descent of a pyroclastic flow at 23:22 GMT on December 13, 2011 at intervals of 1 minute.

prior to the largest explosion, on December 31. After the lava flow appeared and until May 11, the drumbeat I mode was recorded sporadically, with the exception of March 9–19, when the drumbeat I mode was observed during a few hours every day at the rate $f_D = 1–7$ min^{-1} and with A/T < 2 μm (see Fig. 9a). Since mid-May 2011 both of these parameters, f_D and A/T, began to increase progressively, reaching the values $f_D = 6$ min^{-1} and A/T = 5 μm by the end of May; afterwards the latter parameter began to decrease monotonically until the end of June, reaching the value A/T = 1 μm/s, and then KZV RTSS ceased operation for nearly a month (see Fig. 9). The next peak of activity in the drumbeat I mode occurred during the second ten-day period of September, when comparatively rare events with $f_D \leq 1.0$ min^{-1} were recorded, but the microearthquakes were rather large for this mode of occurrence (A/T = 4.5 μm).

The drumbeat II mode which began on October 12 at first involved small microearthquakes with A/T < 0.5 μm and $f_D = 8$ min^{-1}. Subsequently, the rate dropped to one event per minute; almost no microearthquakes were recorded between November 25 and January 12, but this period saw frequent pyroclastic flow eruptions.

The signals that accompanied pyroclastic flows had durations and shapes unlike those for VT earthquakes and the drumbeat earthquakes. Those signals lasted at least 30 s. For example, numerous pyroclastic flow eruptions occurred during 4 hours on December 13, 2011. They were clearly discernible on the envelopes of seismic signals as recorded at KZV and TUMD RTSSs and constructed with a time constant of 4 seconds (Fig. 10a). During that period 16 pyroclastic flows were discharged at similar intensities, plus 10 smaller ones. Figure 10b shows an example of a signal due to a pyroclastic flow of average intensity (marked by an arrow in Fig. 10a), and its power spectral density on all three components can be seen in Fig. 10c. The frequency band concerned is 1–6 Hz when measured at –10 dB of the maximum.

The drumbeat mode began to be recorded on January 12, 2012 and was recorded until early June 2012; from that time until the end of that year only explosive earthquakes due to discrete explosions and pyroclastic flow eruptions were recorded. The drumbeat mode began to be recorded again in late December, with this seismicity being due to the extrusion of the obelisk at the volcano summit.

RESULTS AND DISCUSSION

We will now compare the occurrence of seismic effects as recorded during the Kizimen eruption from December 2010 to December 2012 with the volcanic activity of Kizimen (see Fig. 9). As a rule, the drumbeat mode is gener-

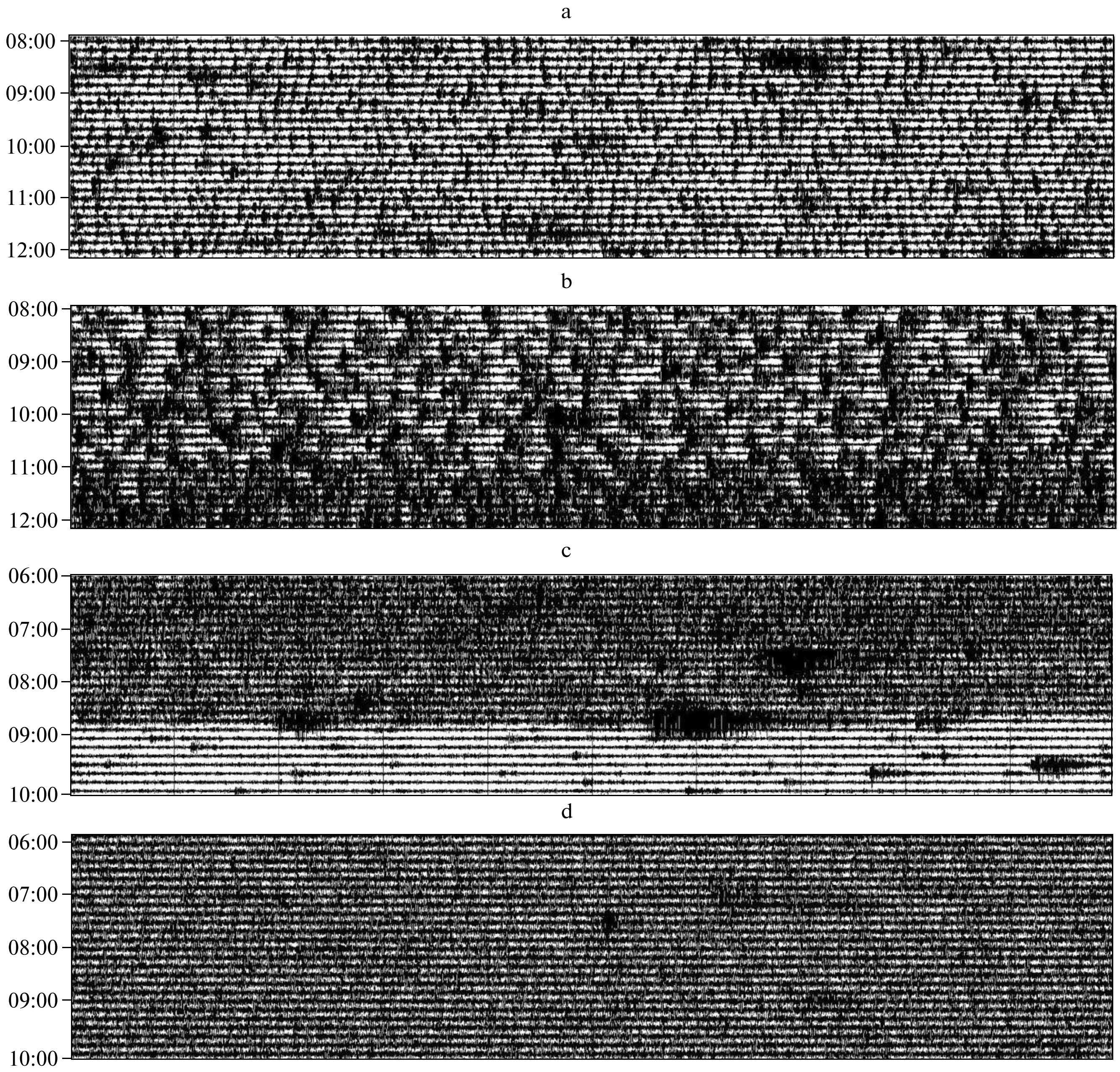

Fig. 7. Four-hour segments of records of seismic effects that accompanied the May–June 2011 eruption of Kizimen and were recorded at KZV RTSS on the horizontal N–S component.

a drumbeat May 14, k = 13; b drumbeat June 1, k = 30; c drumbeat June 12, k = 40; d spasmodic volcanic tremor on June 28, k = 8. k is relative magnification.

ally related to the squeezing-out of extrusive domes on andesitic volcanoes [Cruz and Chouet, 1997; Iverson et al., 2006]. The occurrence of two drumbeat modes concurrently with the formation of the second lava tongue provides evidence that such microearthquakes can also be generated during the movement of viscous andesitic flows [Shakirova, 2012].

We sought to confirm the above hypothesis by considering the time difference between P arrivals at TUMD and KZV ($t_{\mathrm{TUMD}} - t_{\mathrm{KZV}}$) and the S–P times for both stations at six dates where we could reliably identify drumbeat microearthquakes with clear S and P arrivals. As can be seen in Fig. 9c, one observes statistically significant patterns in the variation of wave arrivals at the two stations. The increase in S–P at KZV from 0.7 to 1.5 s with the rms error $\sigma = 0.2$ s and the decrease in t t_{TUMD}-t_{KZV} from 0.9 to 0.5 s with $\sigma = 0.1$ provide evidence that the earthquake epicenters were progressively moving away

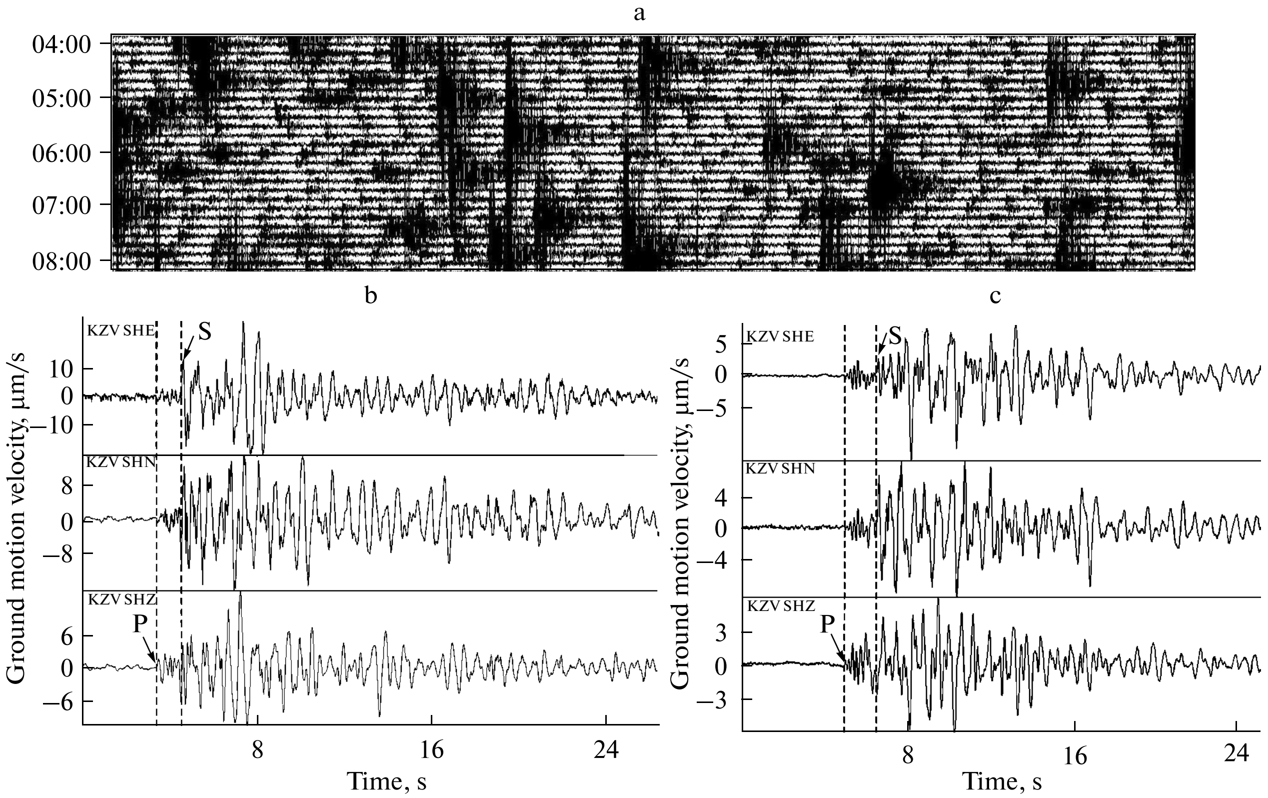

Fig. 8. A segment of a seismogram made at KZV RTSS with drumbeat events and their waveforms.
a four-hour segment of drumbeat II earthquakes upon the background of drumbeat I on the horizontal N–S component, k = 2, October 11, 2011; b waveform of a drumbeat I earthquake on three components as recorded on October 11, 2011; c waveform of a drumbeat II earthquake as recorded on October 13, 2011.

from KZV and approaching TUMD. In that case the spatial positions of the lava flow and seismic stations (see Fig. 4) clearly indicate the generation of drumbeat microearthquakes at the front of the viscous lava flow during its movement.

The KZVD station was in short-lived operation on April 29 for the purpose of microearthquake location (see Table 1). All the nearest stations succeeded in recording three drumbeat microearthquakes during that period. The parameters of these earthquakes were determined using the Avacha travel–time table and the DIMAS program [Senyukov, 2006; Droznin and Droznina, 2010] (Table 2).

Figure 4 shows a map of eruption products deposited by Kizimen with an approximate outlines of the March 15, 2012 lava flow and located epicenters. The vertical cross section (see Fig. 4b) shows the hypocenters of these earthquakes. Two of these are 500 m north of the lava flow boundary, while the third is exactly at the boundary: the hypocenters of all the three earthquakes are near to the lava flow outline (see Fig. 4a). Considering that some uncertainties are inherent in the lava flow outline and epicenter location, it can to a first approximation be assumed that the microearthquakes were confined to the front of the lava flow and were caused by its movement. The occurrence of earthquakes that accompanied the move-

Table 2. The main parameters of drumbeat earthquakes as recorded by three stations on April 29, 2012

Date	Time	Latitude, deg N	Longitude, deg E	Depth, km	Energy class, K_S	Note
April 29, 2012	06:04	55°138	160°342	–1.2	4.4	Epicenters were near the lava flow boundary
	06:34	55°142	160°366	–0.7	4.9	
	07:09	55°138	160°347	–1.3	4.2	

Epicenters were near the lava flow boundary

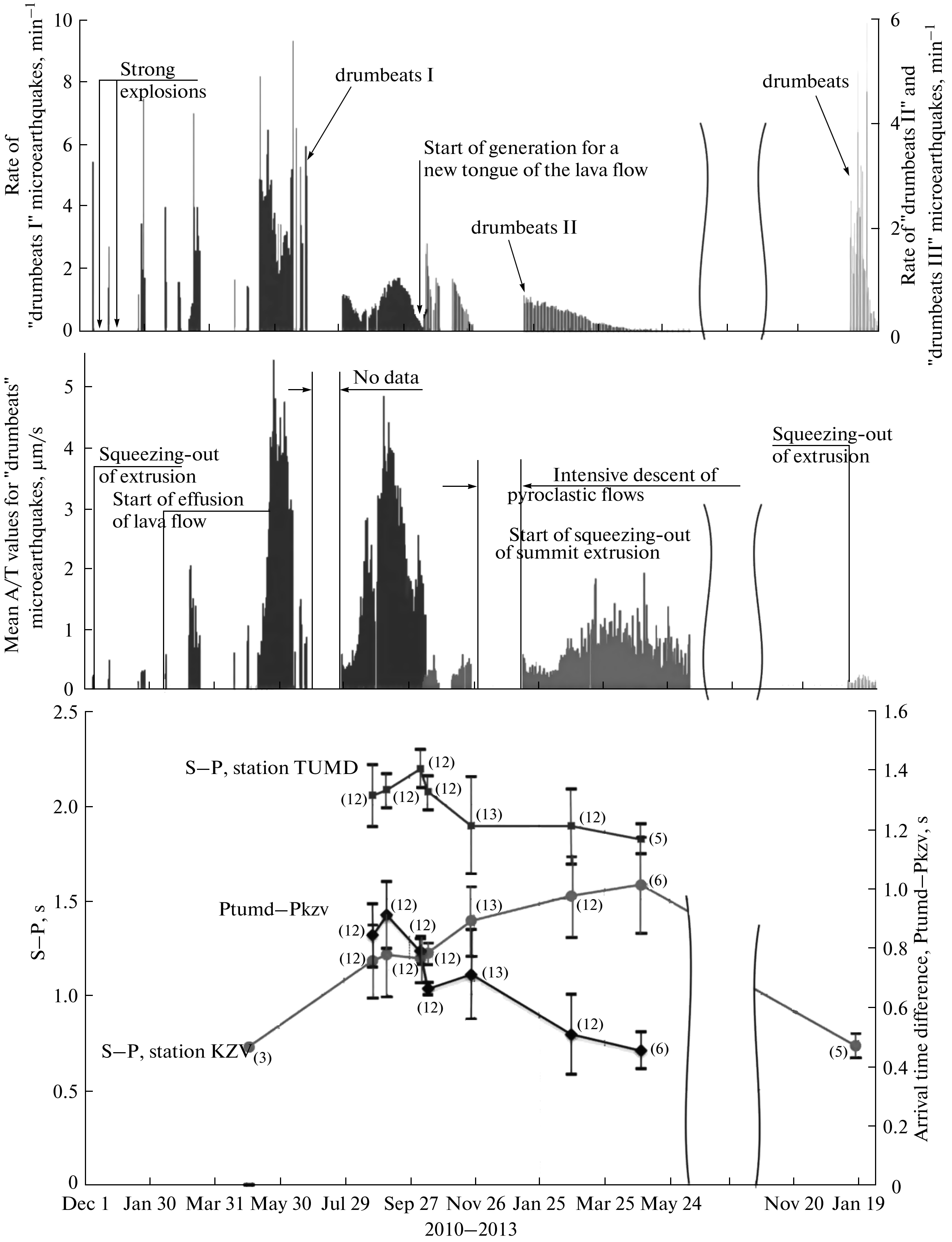

Fig. 9. The mean hourly rate of microearthquakes per minute (a) and mean hourly value of A/T (b) for the drumbeat type of activity for the period from December 1, 2010 to February 15, 2013 during the effusive–explosive eruption of Kizimen Volcano, the variation of S–P and the difference in P-wave arrival times at KZV and TUMD for the period from May 30, 2011 to February 30, 2013 (c).

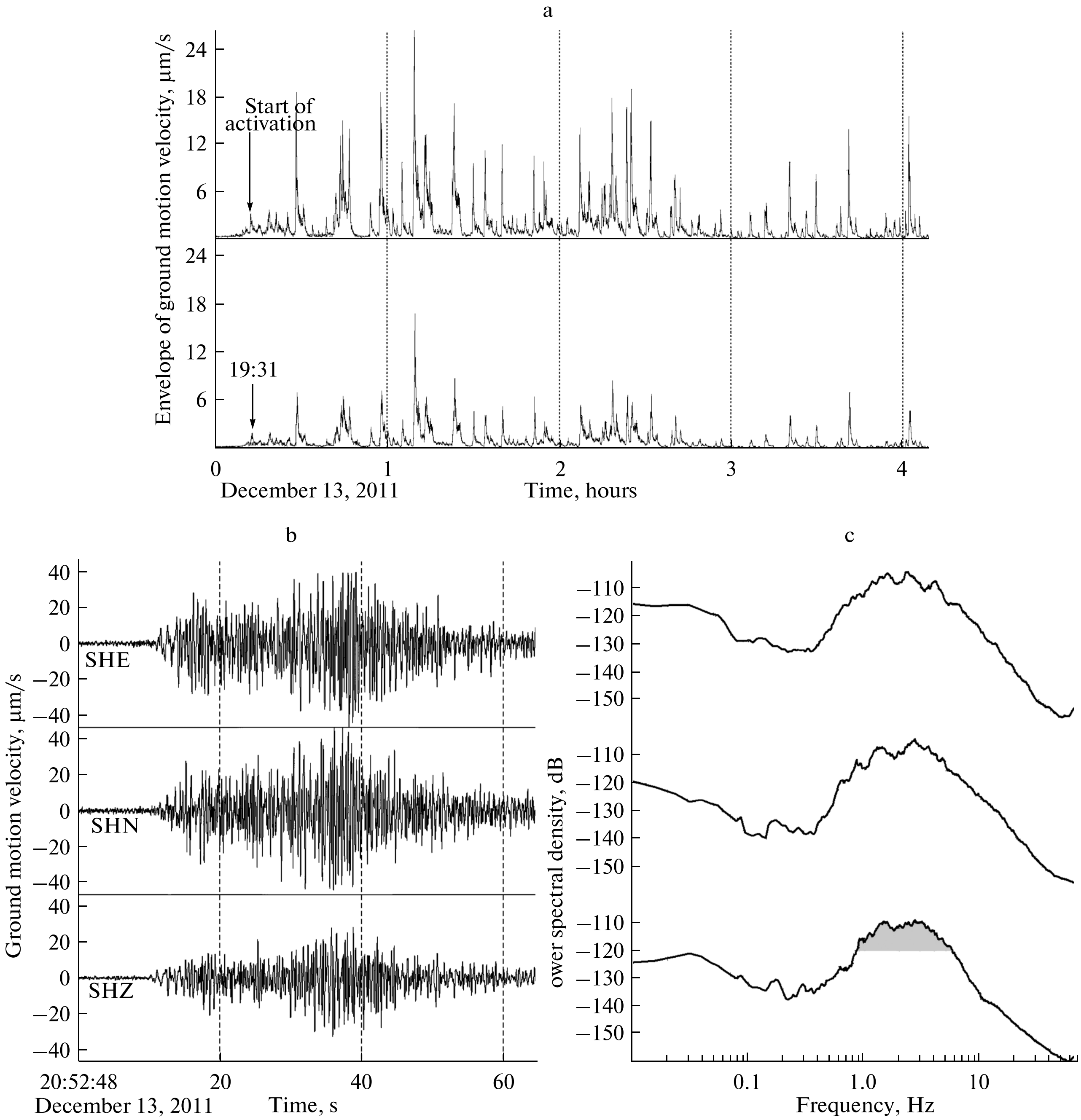

Fig. 10. The envelopes of records of seismic effects at KZV and TUMD that accompanied the descent of pyroclastic avalanches on December 13, 2011 (a), a sample record of a seismic event (marked by an arrow) that accompanied the eruption of a pyroclastic flow (b) and its power spectral density on three components (c).

ment of the lava flow indicates brittle fracturing, which seems to be due to the high viscosity of the Kizimen lava.

CONCLUSIONS

An explosive–effusive eruption of the andesitic Kizimen volcano began in December 2010 after 92 years of repose. The eruption was preceded by a slow-going seismic precursory process lasting over 18 months. A viscous lava flow about 5 km long was formed during the Kizimen eruption from December 2010 to February 2013. The two tongues of this flow covered the eastern and northeastern slopes of the volcano; as well an extensive field of pyroclastic flow was deposited. That same period typically saw microearthquakes of the drumbeat type recorded by the nearest RTSSs.

Remote observation techniques, seismic ones in the first place, and visual observation were used to identify several phases in the eruption for the period from December 2010 to December 2012.

(1) The first phase (December 9, 2010 to May 11, 2011) involved destruction of the upper part of the conduit and the generation of a summit extrusion accompanied by strong explosions and eruptions of pyroclastic flows. The radio telemetry seismic station (RTSS) nearest to the volcano, KZV (R = 2.6 km), recorded explosive earthquakes and microearthquakes of the drumbeat type during that period. The type in question is characterized by quasiperiodic occurrence of microearthquakes with quasi-constant amplitudes ($K < 5$) over long time intervals. Short-lived drumbeat occurrence (a few hours) is characteristic for the first phase.

(2) The second phase (May–October 2011) involved the extrusion of a lava flow descending toward the base of the volcano down its eastern slope with accompanying microearthquakes of the drumbeat type separated by pauses, occasionally as long as a few days. The highest intensity of this activity occurred in June and in September 2011.

(3) During the third phase (October 2011 to June 2012) a new tongue of the lava flow was forming and moving; this tongue separated from the eastern tongue at an altitude of 1300 m. The movement of this lava tongue was accompanied by microearthquakes of the drumbeat II type, which were much lower in intensity compared with the drumbeat I mode of activity. One notes another interval of time during that phase, viz., November 25, 2011 to January 12, 2012, which involved very frequent eruptions of pyroclastic flows with no microearthquakes occurring.

(4) Visual observation between June 2012 and January 2013 revealed a slow squeezing-out of an extrusive dome with accompanying low explosive activity and no drumbeat microearthquakes. These began to occur again in January, indicating a change in the rate of extrusion of viscous andesitic lava.

ACKOWLEDGMENTS

This work was supported in part by the Russian Foundation for Basic Research, grant no. 12-05-31186.

REFERENCES

Chebrov, V.N., Droznin, D.V., and Kugaenko, Yu.A., et al., The system of detailed seismological observations in Kamchatka in 2011, *J. Volcanol. Seismol.*, 2013, vol. 7, no. 1, pp. 16–36.

Cruz, G.F. and Chouet, B.A., Long-period events, the most characteristic seismicity accompanying the emplacement and extrusion of a lava dome in Galeras Volcano, Colombia, in 1991, *J. Volcanol. Geotherm. Res.*, 1997, vol. 77, pp. 121–158.

Ditmar, K., *Poezdka i prebyvanie na Kamchatke v 1851-1855 gg.* (A Voyage and Sojourn in Kamchatka during 1851–1855), St.Petersburg, 1901, Part 1.

Droznin, D.V. and Droznina, S.Ya., The DIMAS Interactive Program for Seismic Signal Processing, *Seismicheskie Pribory*, Moscow: IFZ RAN, 2010, vol. 46, no. 3, pp. 22–34.

Firstov, P.P., Reconstructing the dynamics of the Shiveluch catastrophic eruption of November 12, 1964 from data on wave disturbances in the atmosphere and on volcanic tremor, *Vulkanol. Seismol.*, 1996, no. 4, pp. 48–63.

Firstov, P.P. and Makhmudov, E.R., Estimating the amount of heat ejected into the atmosphere during strong explosive eruptions of andesitic volcanoes based on wave disturbances in the atmosphere, in *Problemy kompleksnogo geofizicheskogo monitoringa Dal'nego Vostoka Rossii* (Problems in Multidisciplinary Geophysical Monitoring of the Russian Far East), Proc. Third Science Conf., Petropavlovsk-Kamchatskii, October 9–15, 2011, Chebrov, V.N., Editor-in-Chief, Obninsk: GS RAN, 2011, pp. 159–163.

Firstov, P.P. and Shakirova, A.A., The seismic phenomena that accompanied the 2011 eruption of Kizimen Volcano, *Vestnik KRAUNTs. Nauki o Zemle*, 2011, no. 2, issue 18, pp. 7–13.

Firstov, P.P. and Shakirova, A.A., The 2009–2012 eruption of Kizimen Volcano and its repercussions in seismic phenomena, in *Materialy ezhegodnoi konferentsii, posvyashchennoi Dnyu vulkanologa* (Proc. Annual Conf. Devoted to Volcanologist's Day), Petropavlovsk-Kamchatskii: IViS DVO RAN, 2012a, pp. 76–81.

Firstov, P.P. and Shakirova, A.A., The seismic effects that accompanied the 2009–2012 eruption of Kizimen Volcano, Kamchatka, in *Sovremennye metody obrabotki i interpretatsii seismologicheskikh dannykh* (Modern Methods for the Processing and Interpretation of Seismological Data), Proc. VII Intern. Seismological School, Obninsk: GS RAN, 2012b, pp. 312–318.

Garbuzova, V.T. and Sobolevskaya, O.V., Seismic activation in the area of Kizimen Volcano in 2008–2010, in *Materialy regional'noi konferentsii, posvyashchennoi Dnyu vulkanologa "Vulkanizm i svyazannye s nim protsessy"* (Proc. regional conf. devoted to Volcanologist's Day: Volcanism and Related Processes), Petropavlovsk-Kamchatskii: IViS DVO RAN, 2011, p. 14–19.

Gorshkov, G.S., Directional volcanic explosions, *Geol. Geofiz.*, 1963, no. 12, pp. 41–46.

Iverson, R.M., Dzurisin, D., Gardner, C.A., et al., Dynamics of seismogenetic volcanic extrusion at Mount St Helens in 2004–2005, *Nature*, 2006, vol. 444, pp. 439–443.

Kamchatka, Kuril'skie i Komandorskie ostrova (Istoriya razvitiya rel'efa Sibiri i Dal'nego Vostoka) (Kamchatka, Kuril and Commander Islands (A History of Relief Evolution in Siberia and in the Russian Far East)), I.V. Luchitskii, Ed., Moscow: Nauka, 1974.

Kozhevnikova, T.Yu., Toloknova, S.L., Napylova, O.A., et al., A catalog of earthquakes on Kizimen Volcano in 2010 (Ml ≥ 3.3), in *Zemletryaseniya v Rossii v 2010 g.* (Earthquakes in Russia for 2010), Nuzhdina, I.N., Editor-in-Chief, Obninsk: GS RAN, 2012, pp. 172–174.

Malik, N.A. and Ovsyannikov, A.A., The eruption of Kizimen Volcano in October 201–March 2011, *Vestnik KRAUNTs. Nauki o Zemle*, 2011, no. 1, issue 17, pp. 7–14.

Malyshev, A.I., *Zhizn' vulkana* (The Life of Volcanoes), Yekaterinburg: UrO RAN, 2000.

Matoza, R.S., Garcés, M.A., Chouet, B.A., et al., The source of infrasound associated with long-period events at Mount St. Helens, *J. G. R.*, 2009, vol. 114, B04305, pp. 1–38.

Matoza, R.S. and Chouet, B.A., Subevents of long-period seismicity: Implications for hydrothermal dynamics during the 2004–2008 eruption of Mount St. Helens, *J. G. R.*, 2010, vol. 115, B12206. doi:10.1029/2010JB007839.

Melekestsev, I.V., Ponomareva, V.V., and Volynets, O.N., Kizimen Volcano, Kamchatka: A Future Mount St. Helens?, *Volcanology and Seismology*, 1993, vol. 14, no. 4, pp. 353–385.

Mel'nikov, D.V., Dvigalo, V.N., and Melekestsev, I.V., The 2010–2011 eruption of Kizimen Volcano in Kamchatka: The dynamics of eruptive activity and the geologic–geomorphologic effects as inferred from remote observations, *Vestnik KRAUNTs. Nauki o Zemle*, 2011, no. 2, issue 18, pp. 87–101.

Moran, S.C., Malone, S.D., Qamar, A.I., Thelen, W.A., Wright, A.K., and Caplan-Auerbach, J., Seismicity associated with renewed dome-building at Mount St. Helens, 2004–2005, in *A Volcano Rekindled: The Renewed Eruption of Mount St. Helens, 2004–2006*, Sherrod, D.R., Scott, W.E., and Stauffer, P.H., Eds., 2007, U.S. Geological Survey Prof. Paper 1750, Reston, VA, pp. 27–54.

Piip, B.I., Kizimen Volcano, *Byul. Vulkanol. St.*, 1946, no. 13, pp. 22–32.

Senyukov, S.L., Monitoring the Volcanic Activity in Kamchatka by Remote Sensing Techniques in 2000–2004, *Vulkanol. Seismol.*, 2006, no. 3, pp. 68–78.

Senyukov, S.L., Nuzhdina, I.N., Droznina, S.Ya., et al., The seismicity of Kizimen Volcano, in *Problemy kompleksnogo geofizicheskogo monitoringa Dal'nego Vostoka Rossii* (Problems in Multidisciplinary Geophysical Monitoring of the Russian Far East), Proc. Third Science Conf., Petropavlovsk-Kamchatskii, October 9–15, 2011, Chebrov, V.N., Editor-in-Chief, Obninsk: GS RAN, 2011, pp. 144–148.

Shakirova, A.A., The drumbeat mode of activity during the 2011 eruption of Kizimen Volcano, in *Materialy VIII regional'noi molodezhnoi nauchnoi konferentsii 1–2 dekabrya 2011 g.* (Proc. VIII Regional Young Scientists' Conference, December 1–2, 2011), Petropavlovsk-Kamchatskii: IViS DVO RAN, 2011, pp. 201–213.

Shakirova, A.A., The movement of a lava flow on Kizimen Volcano as the generator of the drumbeat mode of activity, in *Materialy X regional'noi molodezhnoi nauchnoi konferentsii 28 noyabrya 2012 g.* (Proc. X Regional Young Scientists' Conference, November 28, 2012), Petropavlovsk-Kamchatskii: IViS DVO RAN, 2012, pp. 127–139.

Shakirova, A.A. and Kozhevnikova, T.Yu., An analysis of earthquake hypocenter migration in the area of Kizimen Volcano using a variety of techniques in 2009–2011, in *Prirodnaya sreda Kamchatki* (The Natural Environment of Kamchatka), Proc. X Regional Young Scientists' Conference September 12–13, Petropavlovsk-Kamchatskii: IViS DVO RAN, 2011, pp. 195–206.

Shakirova, A.A., Makhmudov, E.R., and Firstov, P.P., Seismic phenomena on Kizimen Volcano in May–June 2011, in *Sovremennye nauchnye issledovaniya na Dal'nem Vostoke* (Contemporary Research in the Russian Far East), Proc. Young Scientists' Symposium, Yuzhno-Sakhalinsk, October 4–7, 2011, Yuzhno-Sakhalinsk: IROSO, 2011, pp. 129–133.

Shantser, A.E., Kutyev, F.Sh., Petrov, V.S., and Zubin, M.I., Kizimen Volcano, in *Deistvuyushchie vulkany Kamchatki* (Active Volcanoes of Kamchatka), vol. 2, Moscow: Nauka, 1991, pp. 18–23.

Tokarev, P.I., *Vulkanicheskie zemletryaseniya Kamchatki* (Volcanic Earthquakes of Kamchatka), Moscow: Nauka, 1981.

Translated by A. Petrosyan