FIRST RESULTS FROM THE 2012-2013 TOLBACHIK FISSURE ERUPTION

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1. Introduction

On November 27, 2012, at 17:15 local time (5:15 UTC), to the south of Ploskiy Tolbachik Volcano **(Fig. 1)**, lava started to flow from a formed submeridional strike fissure. The fissure zone was about 5 km long; its altitude varied from 2200 to 1500 m. On November 28, an ashfall was detected as far as 100 km to the NNE, as well as lava gushing out of two eruptive centers: having altitudes 2000 m (the upper vent) and 1500 m (the lower vent). Loud rumble was heard in the settlements 40-50 km far from the fissure. Over the period November 29-30 (see also **Table 1** for details) a moderate explosive activity and lava effusion were detected at the upper vent accompanied by intense lava fountains and fast travel of lava flow in the lower part of the fissure. On December 1 the activity of the upper vent stopped. The length of the lava flow emerged from the upper part of the fissure exceeded 9 km; it occupied the territory of 5.6 km^2. Since early December the eruption has been concentrated in the lower vent and was accompanied by effusion of liquid lava of the Hawaiian type from a 1-kilometer-long fissure at the height of 1500-1600 m.

The current eruption at the Tolbachinskiy Dol was named a "The Institute of Volcanology and Seismology 50^{th} Anniversary Fissure Tolbachik Eruption" (FTE-50). Two main vents at the Northern and Southern parts of the fissure were called after eminent Russian volcanologists "The Igor Menyailov Vent" **(Fig. 2)** and "The Sophia Naboko Vent" **(Fig. 3)** respectively.

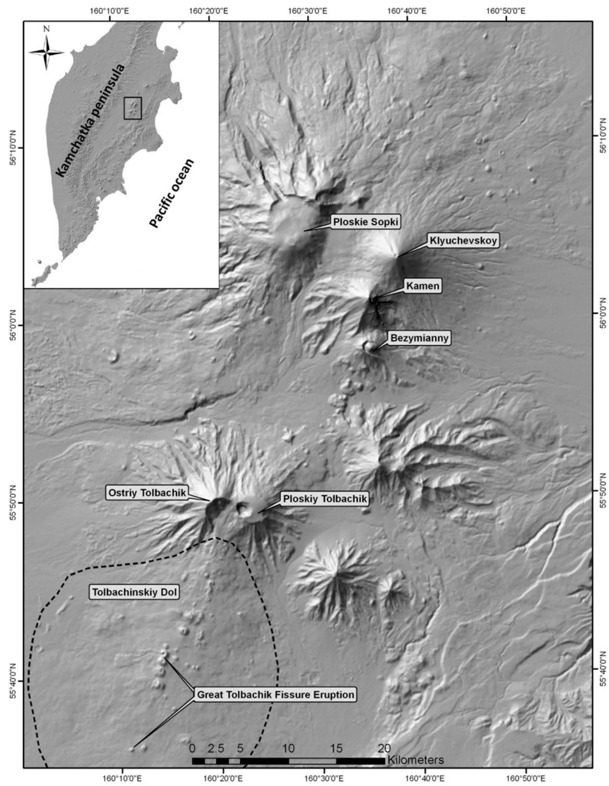

Figure 1. Map of Klyuchevskaya Group of volcanoes. Topographic base – DEM SRTM X-band (DLR).

2. Tectonic setting and eruptive history during the last 10 ka

The FTE-50 eruption is a reconfirmation of a continuous high activity at the Tolbachik regional zone of cinder cones (usually called Tolbachinsky Dol, **Fig. 1**). This activity could be considered as a result of powerful endogenous catastrophe which happened about 10 ka BP and led to formation of the vast lava shields having total area of 1,035 km^2 within which the Tolbachinsky Dol is the largest one (~900 km^2) **(Fig. 1)**. The arc-shaped fault zone extending for 60 – 70 km went through the edifice of the large Ploskiy Tolbachik volcano (at that time being already extinct and having altitude ~3800 m and volume about 140 – 150 km^3). It resulted in the collapse of the apical part and of the southern sector of the volcano and cardinally changed its morphology. The 3.5 km wide caldera of the Hawaiian type was formed at the top of Ploskiy Tolbachik, inside which the shield volcano was built, with the volume ~ 12 km^3 and weight ~ $30*10^9$ tons. At the same time the huge collapse (the diameter of failure cirque ~ 3 km and fallen rock volume ~ 1.5 – 2 km^3) had destroyed the apical part of neighboring extinct Ostriy Tolbachik volcano. Since that time the magma inflow at the Southern sector of the Klyuchevskaya Volcanic group was mainly controlled by this fault zone. Within 10- 2 ka BP

Table 1. The chronology of events during The Institute of Volcanology and Seismology 50th Anniversary Fissure Tolbachik Eruption, November 27th, 2012 – May 2013.

Date, time (UTC)	Observations
2012/11/26, 14:00	The earthquake swarm ($M \leq 2.25$, depth < 5km) was registered.
2012/11/27, 5:15	The beginning of eruption. Strong earthquakes indicate the fissure opening.
2012/11/27, 8:00	Lava effusion begins (as indicated by volcanic tremor). Moderate ash-falls in Northern direction over 100 km far from the eruptive center are detected. Lava is effusing from the fissure of the Menyailov vent.
2012/11/27, ?	Opening of the Naboko vent, ash-falls in N-NW direction.
2012/11/28	Lava fountaining from two eruptive centers (Menyailov vent and Naboko vent) is clearly visible from distance over 40 km. The area of lava fields exceeds 14 km^2
2012/12/30	The eruption from the Menyailov vent ended. Lava continues fountaining from Naboko vent.
2012/12/13	The area of lava fields exceeds 20 km^2
2012/12/10	Lava flow has reached its maximum extent ~16 km. The frontal part of the flow stopped near the old cinder cone Belaya gorka. Since that time, all lava flows are layered on top of each other at their movement to the SW.
2012/12/23	Lava flow about 1 km long moves towards SW from Naboko vent
2013/01/01	A crater is formed on the slope of the new cinder cone of the Naboko vent. Ash and bombs are exploded from this crater. Lava is continuously gushing from the main cinder cone.
2013 end of January	The continuous gushing of lava from the Naboko vent cinder cone stopped. Instead, separate explosions with bombs are going on
2013/02/03	The intensive movement of lava flows towards SW from the Naboko vent. Their length is 5 km already
2013 March-May	Gradual decrease of the volcanic tremor to 3-3.5 mkm/sec. Lava flows continue to effuse to the SW from the Naboko vent

predominantly sub-alkaline high-Al basalts were erupted along the whole fault zone including the Ploskiy Tolbachik caldera. The average intensity of the discharge of magma was about $17*10^6$ tons/year.

Since 2 ka BP until now the eruptions of sub-alkaline high-Al basalts-basaltic andesites and high-Mg basalts were sub-simultaneous, but took place only to the south from the Ploskiy Tolbachik volcano. Over the period from 2 to 1 ka BP the intensity of the discharge was $38*10^6$ tons/year; from 1 ka BP until now it is about $10*10^6$ tons/year.

During the last 10 ka of the activity of the Tolbachik regional zone of cinder cones about 80 km^3 of mafic rocks have been erupted, with a total weight of $173*10^9$ tons. The peculiar feature of the Tolbachik regional zone is the predominant orientation in the location of all eruptive centers (cinder and lava cones, fissures) along the zone strike. The same is true for the eruptive centers of the present eruption.

Table 2. The eruptions in Tolbachinsky Dol during the last 1000 years (after GFTE, 1984).

Name of eruption or corresponding cinder cone	years	Erupted mass(tons)
The Great Fissure Tolbachik Eruption	1975-1976	$3.8*10^9$
Fissure eruption on the Southern slope of Plosky Tolbachik	1941	$0.16*10^9$
Krashyi cone, Zvezda vent	1740	$0.43*10^9$
Vysokaya cone	~1000	$4.56*10^9$

Historical eruptions in this zone occurred in 1740, 1941, and over the period 1975-1976 **(Table 2)**. The latest eruption in 1975-1976 named as Great Fissure Tolbachik Eruption (GFTE) was documented as the largest known basalt eruption in the Kurile-Kamchatka volcanic belt. It was studied in details and resulted in numerous papers (Volynets et al., 1976; Fedotov et al., 1976; Tokarev, 1976, and many others) and a complete monograph (GFTE, 1984).

The GFTE started on June 6, 1975 and stopped on December 10, 1976. It consisted of two stages: the first one known as the Northern Vent lasted over the period from June 6 to September 15, 1975 and the second one named the Southern Vent lasted from September 16, 1975 to December 10, 1976. Total amount of the erupted products was estimated to be 2.17 km^3. Lava covered the territory of 44.73 km^2.

3. Overview of FTE-50 activity

The new eruptive centers are located to the south of Ploskiy Tolbachik and closer to the volcano comparing to GFTE **(Fig. 4)**. According to seismic data, the fissures started to form on November 27, 2012, at 17:15 local time. Lava started gushing at 20:00; the fountains were accompanied by effusion of lava flows. A swarm of weak earthquakes with

Figure 2. The explosive eruption of the Menyailov vent on December 29th, 2012.

Figure 3. The gushing fissure of the Naboko vent cuts through the older Krasniy cone. December 29th, 2012.

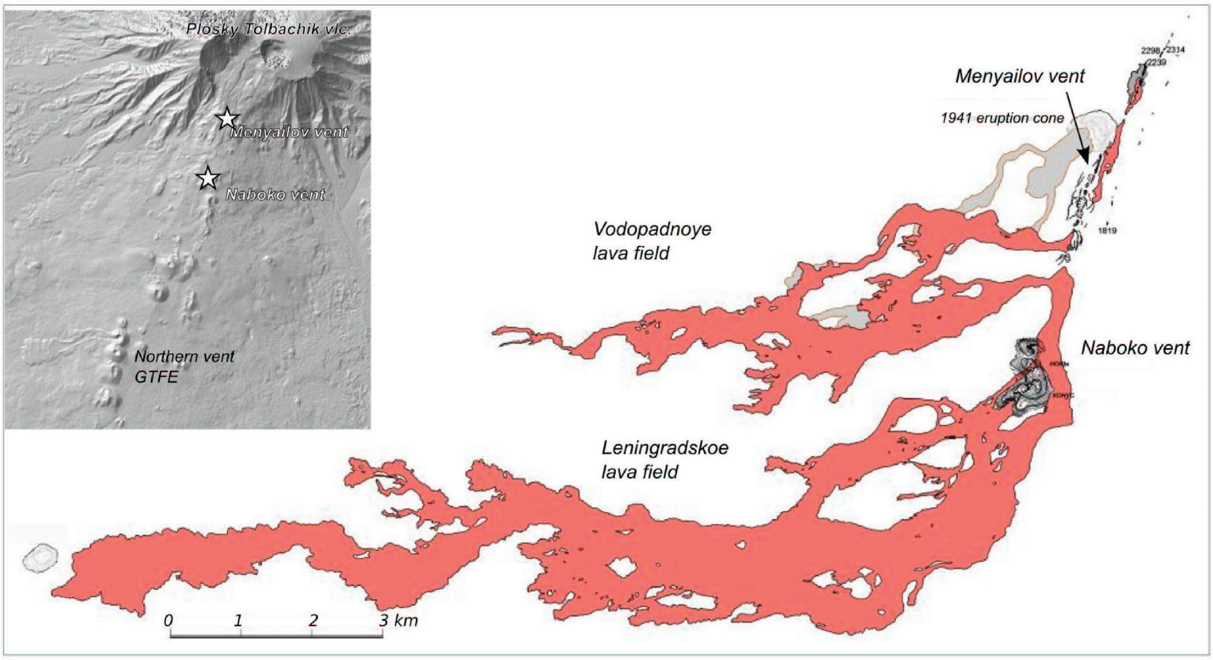

Figure 4. The diagram showing locations of centers of modern eruption and the map of lava fields as updated on December 13, 2012. Red color corresponds to the FTE-50 lava flows, grey – to the lava flows of the 1941 eruption.

maximum magnitude of 2.25 at a depth of 5 km was registered 15 hours prior to the event. In contrast to this eruption, a swarm of strong earthquakes was registered 10 days prior to the GFTE, which allowed predicting both time and place of the event (Tokarev, 1976).

The peculiarity of the current eruption is in its effusive character; the volumetric explosivity coefficient (the ash and lava volume ratio) is about 3%. Ash emissions were observed in the beginning of the eruption during the activity of the upper vent. They accompanied the opening of the fissure and lava intrusion into the ice massif and permafrost rocks covering the south slope of Ploskiy Tolbachik Volcano. Besides, a month after the beginning of the eruption, short-term ash emissions from the lower vent were observed during formation of the new eruptive centers **(Fig. 5)**. Ashfalls were detected 100 km to the north-north-west and east from the center of the eruption. The areal density of ash deposits comprised 500 g/m^2.

Small cinder cones or walls were formed along the fissure during the eruption in the area of both vents **(Fig. 6)**. On December 13, 2012 the total volume of erupted tephra was 0.008 m^3. Preliminary results from the analysis of AIRS satellite data using the algorithm (Prata, 2007) allow estimation of the SO_2 emission for the first days of the eruption (November 27-28). The emission of SO_2 comprised ~ 50,000 tons. The cloud containing gas, under meteorological factors drifted to the north- west **(Fig. 7)**. On November 28, it was located in the area of the south coast of the East Siberian Sea; its area was about 190 thousand km^2. Over the period of the next few days it drifted to the West and reached Kola Peninsula.

Lavas are the main products of the eruption. At the initial stage the fissure was producing violently moderately viscous aa lava flows. During the first 43 hours the eruption formed two vast lava fields, which were named "Vodopadny" and "Leningradsky" **(Fig. 4)**. **Table 3** contains data on these flows. Lava flows were formed by lava of Hawaiian pahoehoe type. They are 1 – 2 m thick near the outlet and 3-5 m thick in the front part. The eruption forms various types of sculptured lava flows like rope-shaped lava and pillow lava, as well as extended lava channels and tubes. The maximum measured melt temperature was about 1100°C. Lava density estimated by the average chemical composition of the Menyailov vent rocks is 2.65 – 2.58 g/cm^3 at 1100°C and H_2O content 0 – 1% (Bottinga, Weill, 1970); according to direct measurement it is 2 – 2.2 g/cm^3. Lower measured

Table 3. Lava flow parameters, based on the data from the aerial survey on December 13, 2012.

	The Vodopadny flow	The Leningradsky flow
Area, km^2	5.654	17.035
Volume, km^3	0.027	0.208
Average thickness, m	4.8	12.2

Figure 5. Fountains of lava and ash emissions from the growing cinder cone of the Naboko vent, January 4th, 2013.

Figure 6. Lava fountains and explosions from the craters of the growing cinder cone of the Naboko vent, January 11th, 2013.

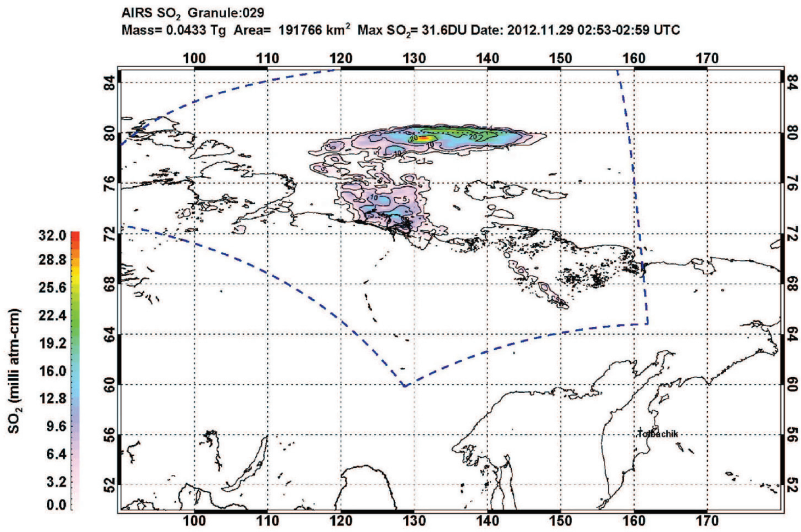

Figure 7. Location of the sulphur dioxide cloud produced by the FTE-50 (data from the AIRS satellite images on November 29, 2012, 02:53 UTC). The concentration is given in DU. One DU is equal to 0.01 mm of thickness of the compressed ozone layer at 0 C° or 2.69*10 20 of ozone molecules m^2. Dotted line denotes the boarders of the satellite image.

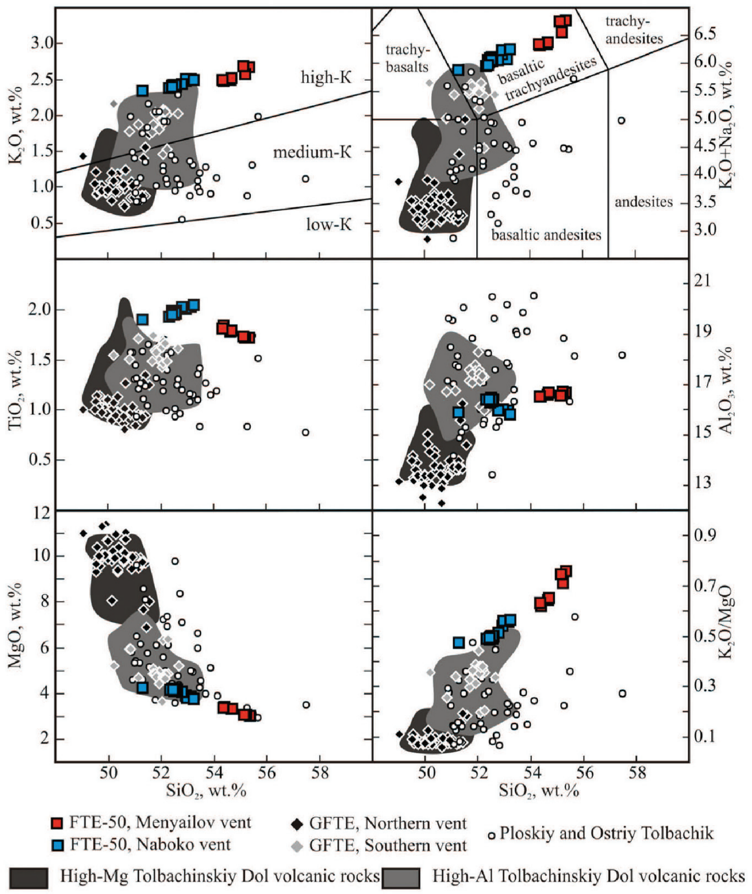

Figure 8. Harker diagrams for FTE-50 volcanic rocks, Ploskiy Tolbachik and Ostriy Tolbachik stratovolcanoes, the GFTE, and the regional zone. Composition of rocks from Tolbachinskiy Dol after (Fedotov et al., 1984; Volynets et al., 1978; Churikova et al., 2001; Portnyagin et al., 2007), Ostriy and Ploskiy Tolbachik volcanoes - after (Portnyagin et al., 2007; Ermakov and Vazheevskaya, 1973). Discrimination lines for diagram K_2O-SiO_2 and K_2O+Na_2O – SiO_2 after (Le Maitre, 1989).

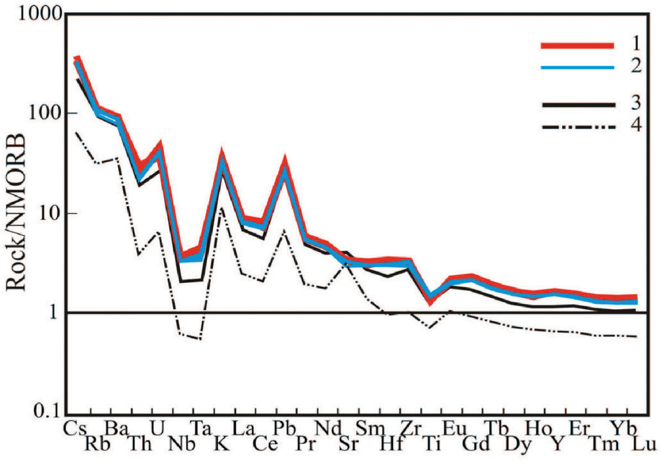

Figure 9. Distribution of REE and other incompatible microelements in FTE-50 volcanic rocks. Legend: 1-2 – FTE-50: 1 – Menyailov Vent, 2 – Naboko Vent; 3-4 – GFTE: 3 – Southern Vent, 4 – Northern Vent. Concentrations of elements in N-MORB after (Sun and McDonough, 1989).

density is caused by captured gas component. The effective lava viscosity at the initial stage of eruption is estimated to be 10^4 Pa*s while and in January 2013 it decreased down to (1.5 – 3) 10^2Pa*s.

4. Petrology and geochemistry of the volcanic rocks erupted from November 27th until the end of January

In the beginning of the eruption high potassium aluminous basaltic trachyandesites appeared on the surface. Rocks of the initial stage of the eruptiondiffer from the previously erupted rocks of Tolbachinskiy Dol area by their higher silica content **(Fig. 8)**. Besides, the composition of recently erupted rocks differs also from composition of rocks of Tolbachik stratovolcano by their lower alumina content. From December, when the activity was concentrated in the Naboko vent, the composition of rocks changed rather sharply: silica content dropped up to 2 wt. % and remained at this level until the end of January; MgO, TiO_2 concentrations and Mg# increased; K_2O, Na_2O concentrations and K_2O/MgO ratio decreased. The first portions of the lavas of the Naboko vent, erupted during the period of December 2nd-7th, can be considered as interim between the lavas of the Menyailov vent and the more recent lavas of the Naboko vent. The composition of the erupted rocks remains practically constant during December and January. This change in composition was accompanied by the slight changes in the petrography of rocks: at the middle of December the amount of phenocrysts increased; also, bigger Pl (up to 1-1.5 cm in diameter) and Ol (up to 3 mm in diameter) phenocrysts appear, although the overall structure of the rocks remains aphyric. The distribution of the incompatible elements in the volcanic rocks of the Menyailov and Naboko vents is rather similar **(Fig. 9)**; all rocks are moderately enriched in HFSE even compared to the Southern vent of GFTE, but still carry typical subduction signature with high LILE/HFSE ratios and prominent Nb-Ta anomaly; rocks of the Menyailov vent have a bit higher concentrations of REE and other incompatible elements then rocks of the Naboko vent, but the elemental ratios remain constant, which could be interpreted as a result of fractionation of a single parental melt. The prominent Eu anomaly at REE distribution patterns indicates that Pl fractionation substantially influenced the composition of magma of the new eruption.

5. Estimations of the volumes of erupted rocks

It is possible to make rough preliminary estimations of the expected total volume of erupted rocks and the duration of the eruption. The discharge of magma chamber for large fissure eruptions could be described by a simple model (Machado, 1974; GFTE, 1984):

$$\Omega(t) = \Delta\mathrm{B}\left(1 - e^{-\frac{tW_0}{\Delta\mathrm{B}}}\right) \qquad (1)$$

where $\Omega(t)$ – is the volume of magma, erupted by time t, ΔB – is the volume of magma resulted in the excess pressure in the chamber before the eruption, W_0 – the initial magma discharge. This model assumes the exponential decrease of discharge rate and constant conduit diameter. It allows us to estimate the maximal discharge rate at the beginning of the eruption, the total volume of eruptive material and the duration of the eruption, according to the series of measurements of the erupted rocks volume

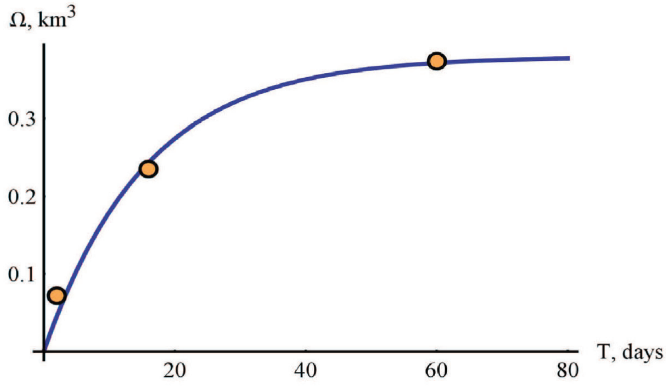

Figure 10. Change of the volume of the erupted products in time. Circles denote data from the aerial survey and processed satellite images from the eruption zone. The line denotes the approximation (1).

in time.

Figure 10 shows the volumes of lava fields on November 29, 2012 and December 13, 2012 obtained from aerial photography and satellite images on January 26, 2013 (data EO-1 NASA), approximated by the theoretical dependence (1). This approximation gives the following estimations: the maximum volume of the eruption ΔB=0.38 km^3 the maximum discharge rate at the beginning of the eruption W_0=250 m^3/s, the duration of the eruption was expected to be 140 days. However, the eruption lasts noticeably longer (~180 days at the time of submitting this manuscript). It may be explained by rather probable existence of several intermediate magma chambers, which are not considered by the applied simple model. The observed magma discharge at the beginning of the eruption (by the data of aerial photography on November 29, 2012) exceeds 400 m^3/sec. This significant difference between estimated and actual discharge is due to the fact that lava have been effused practically along the whole of the 4-5 km long fissure, whereas the formula was introduced for channel of constant cross-section. Usually during fissure eruption, the lava erupts along the whole fissure for the first few hours and then the lava continues erupting from several eruptive centers (GFTE, 1984).The eruption continues, exhibiting moderate effusive activity.

Acknowledgements

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