



## Seismic monitoring of the Plosky Tolbachik eruption in 2012–2013 (Kamchatka Peninsula Russia)



S.L. Senyukov <sup>\*</sup>, I.N. Nuzhdina, S.Ya. Droznina, V.T. Garbuzova, T.Yu. Kozhevnikova, O.V. Sobolevskaya, Z.A. Nazarova, V.E. Bliznetsov

Kamchatka Branch of Geophysical Survey RAS, Petropavlovsk-Kamchatsky 683006, Russia

### ARTICLE INFO

#### Article history:

Received 27 November 2014

Accepted 19 June 2015

Available online 3 July 2015

#### Keywords:

Seismology

Kamchatka

Tolbachik volcano

Eruption

Earthquake

### ABSTRACT

The active basaltic volcano Plosky Tolbachik (Pl. Tolbachik) is located in the southern part of the Klyuchevskoy volcano group on the Kamchatka Peninsula. The previous 1975–1976 Great Tolbachik Fissure Eruption (1975–1976 GTFE) occurred in the southern sector of Pl. Tolbachik. It was preceded by powerful earthquakes with local magnitudes between 2.5 and 4.9 and it was successfully predicted with a short-term forecast. The Kamchatka Branch of Geophysical Survey (KBGS) of the Russian Academy of Science (RAS) began to publish the results of daily seismic monitoring of active Kamchatka volcanoes on the Internet in 2000. Unlike the 1975–1976 GTFE precursor, (1) seismicity before the 2012–2013 Tolbachik Fissure Eruption (2012–2013 TFE) was relatively weak and earthquake magnitudes did not exceed 2.5. (2) Precursory earthquake hypocenters at 0–5 km depth were concentrated mainly under the southeastern part of the volcano. (3) The frequency of events gradually increased in September 2012, and rose sharply on the eve of the eruption. (4) According to seismic data, the explosive–effusive 2012–2013 TFE began at ~05 h 15 min UTC on November 27, 2012; the outbreak occurred between the summit of the Pl. Tolbachik and the Northern Breakthrough of the 1975–1976 GTFE. (5) Because of bad weather, early interpretations of the onset time and the character of the eruption were made using seismological data only and were confirmed later by other monitoring methods. The eruption finished in early September 2013. This article presents the data obtained through real-time seismic monitoring and the results of retrospective analysis, with additional comments on the future monitoring of volcanic activity.

© 2015 Elsevier B.V. All rights reserved.

### 1. Introduction

The Klyuchevskoy volcano group (KVG) is located near the junction of the Kuril-Kamchatka and Aleutian arcs and is characterized by the highest rate of erupted material among volcanic centers in this subduction zone (Piip, 1956) (Fig. 1). The KVG includes 14 active and extinct volcanoes; Klyuchevskoy, Bezymianny and Pl. Tolbachik have been the most active in recent years (Figs. 1, 2). The large basaltic stratovolcano Pl. Tolbachik (55°49.5′ N, 160°23.5′ E, summit elevation 3080 m) forms a single mountain range with the neighboring extinct Ostry Tolbachik (Os. Tolbachik, 55°50.0′ N, 160°19.5′ E, summit 3682 m) and is situated in the southern part of the KVG (Dvigalo et al., 1991; Fedotov et al., 2011; Ermakov et al., 2014). Pl. Tolbachik has several features that distinguish it from other volcanoes in the Kuril-Kamchatka arc: a flat summit formed by a Hawaiian-type caldera 3 km in diameter, a smaller inner crater 1.7 km in diameter and 600 m deep located in the southern part of the volcano, two radial linear zones of cinder cones with a total length of 70 km (similar to Hawaiian volcanic rifts)

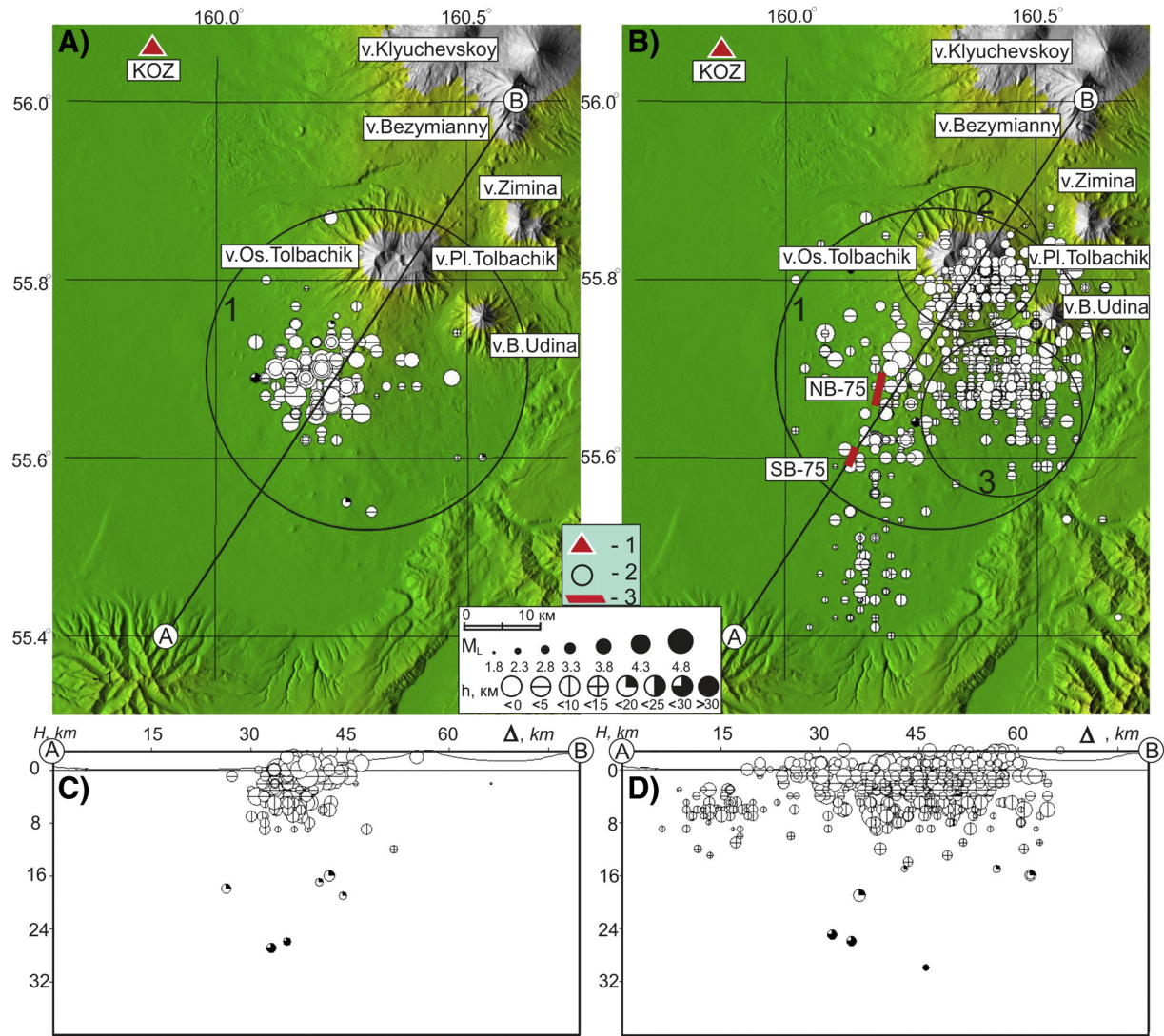
(Fig. 1), Pahoehoe lavas of the Hawaiian type, and the formation of lava tubes in the Tolbachik zone of cinder cones.

Fedotov et al. (2011) calculated the location and the size of the magma chamber using data on the evolution of the volcanic cone and its history of eruptions, magma discharge, deformation and earthquakes. The top of this chamber lies 2 km deep under the Pl. Tolbachik summit caldera, and its horizontal dimension is less than 6 km. The last three major Tolbachik eruptions occurred in 1941, 1975–1976, and 2012–2013, and occurred along the SSW “rift” zone. The total volume of ejected lava and tephra during these three eruptions was approximately 2.0 km<sup>3</sup> dense rock equivalent (DRE), a volume recalculated to a density of 2.8 g/cm<sup>3</sup> for non-vesiculated magma taken from the average densities of slightly vesicular lavas of 2.5 g/cm<sup>3</sup> and pyroclast densities of 1.1 g/cm<sup>3</sup>, which corresponds to an average rate of lava production of 0.86 m<sup>3</sup>/s for the last 72 years (Polyak and Melekestsev, 1981; Zelenski et al., 2014). According to this production, Pl. Tolbachik is one of the most powerful and productive volcanoes in the Kuril-Kamchatka arc.

Based on seismicity, the explosive–effusive 2012–2013 Tolbachik Fissure Eruption began at ~05 h 15 min UTC on November 27, 2012, between the top of Pl. Tolbachik and the Northern Breakthrough of the 1975–1976 Great Tolbachik Fissure Eruption (Senyukov et al., 2013b). The eruption produced three large lava fields extending up to 17.8 km

<sup>\*</sup> Corresponding author. Tel.: +7 9622803452.  
E-mail address: [ssl@emsd.ru](mailto:ssl@emsd.ru) (S.L. Senyukov).





**Fig. 2.** A) Map of epicenters located between January 01, 1971, and July 06, 1975; B) Map of epicenters located between July 06, 1975, and December 31, 1976. Shown in inset: 1—seismic station, 2—circles (1–20 km radius, 2–9 km radius, 3–10 km radius), 3—eruption centers (NB-75, Northern Breakthrough of 1975–1976 GTFE, and SB-75, Southern Breakthrough of 1975–1976 GTFE); C) Projection of all hypocenters from (A) on the vertical plane along the line A-B; D) Projection of all hypocenters from (B) on the vertical plane along the line A-B.

(Dvigalo et al., 2014); effusion ceased in early September 2013. The first results of various scientific studies have been published by several authors (Saltykov et al., 2012; Samoylenko et al., 2012; Edwards et al., 2013; Gordeev et al., 2013b; Volynets et al., 2013; Dvigalo et al., 2014; Ermakov et al., 2014; Fedotov et al., 2014; Zelenski et al., 2014).

## 2. Seismological observation and results

### 2.1. Seismological observation before 2000

Seismological observation of Kamchatka's volcanoes began with the installation of the KLY seismic station in the Klyuchi village in 1946 (Fig. 1). Initially, this seismic monitoring of volcanoes was carried out by the Kamchatka Volcano Observatory. From 1971–1979, monitoring was conducted by the Institute of Volcanology (IV) FED RAS (known today as the Institute of Volcanology and Seismology (IVS) FED RAS) and since 1979 by the KBGS RAS (Gordeev et al., 2013a). Detailed data

on the development of the seismic station network are presented by Chebrov et al. (2013).

Five seismic stations operated in 1975 at locations near present-day stations: KLY, ZLN, KOZ, ESO and MKZ (Fig. 1). According to the database of Institute of Volcanology and Seismology (<http://www.kscnet.ru/ivs/Seismo/>) a precursor earthquake swarm before 1975–1976 GTFE lasted from June 27 to July 06, 1975, and included 252 earthquakes with local magnitudes of  $M_L = 2.5$ –4.9 (Figs. 2A, 3). Epicenters were distributed within an ellipse-shaped area including the region where the new vents and cinder cones eventually appeared (Northern and Southern Breakthroughs; Fig. 2A). The depths of these earthquakes varied from 27 km to the surface, and the average depth was 2.5 km. The two strongest events (both  $M_L = 4.9$ ) occurred in the same place on July 02, at 07 h 10 min 52 sec and 07 h 34 min 19 sec UTC, at 8 km and 6 km depths, respectively. The 1975–1976 GTFE was successfully forecasted based on seismic data (Tokarev, 1976; Tokarev et al., 1984). A detailed description of the 1975–1976 GTFE seismicity was presented by Zobin (2012).

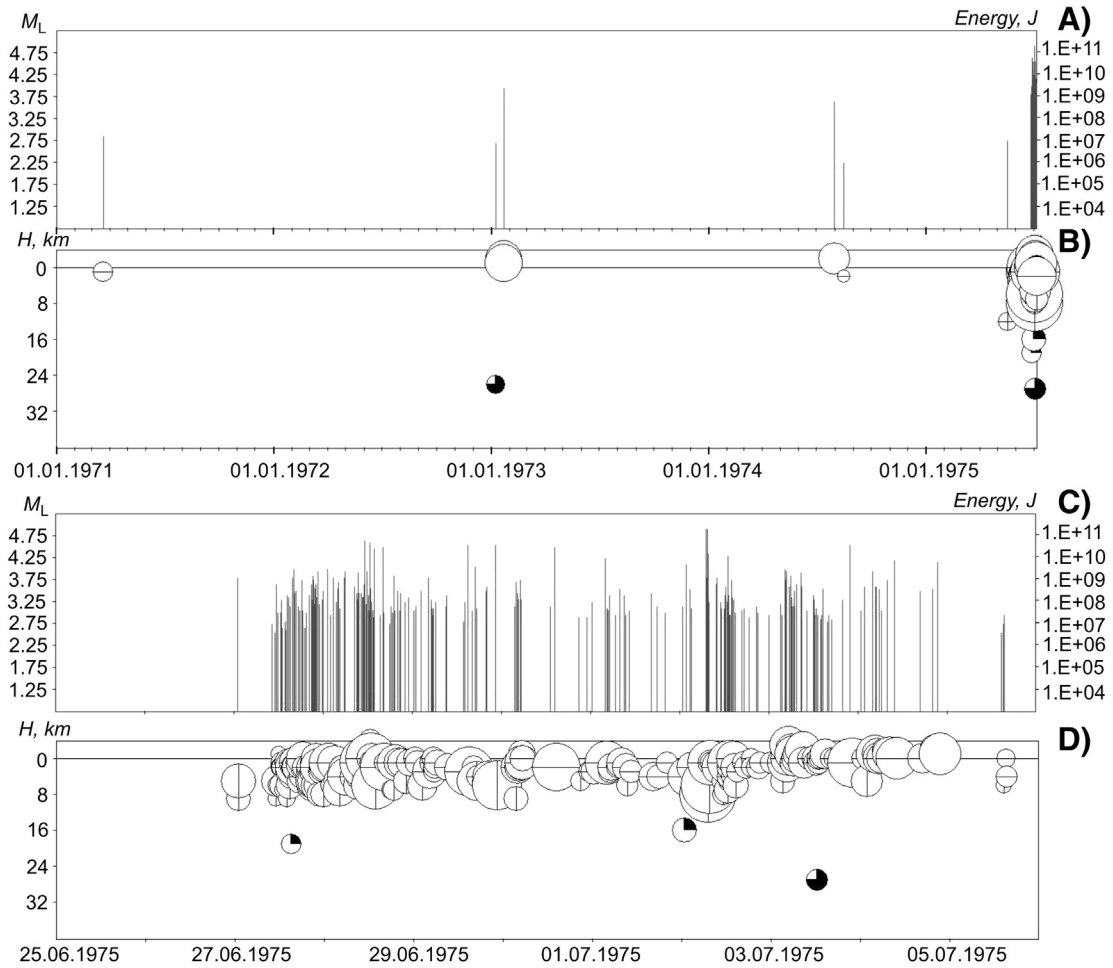


Fig. 3. Plots of the energy and the depth for earthquakes from the cylinder in Fig. 2A (20 km radius, (-3)-(+40) km depth range). A) and B) for the time period between January 01, 1971, and July 06, 1975. C) and D) for the time period between June 25, 1975, and July 06, 1975.

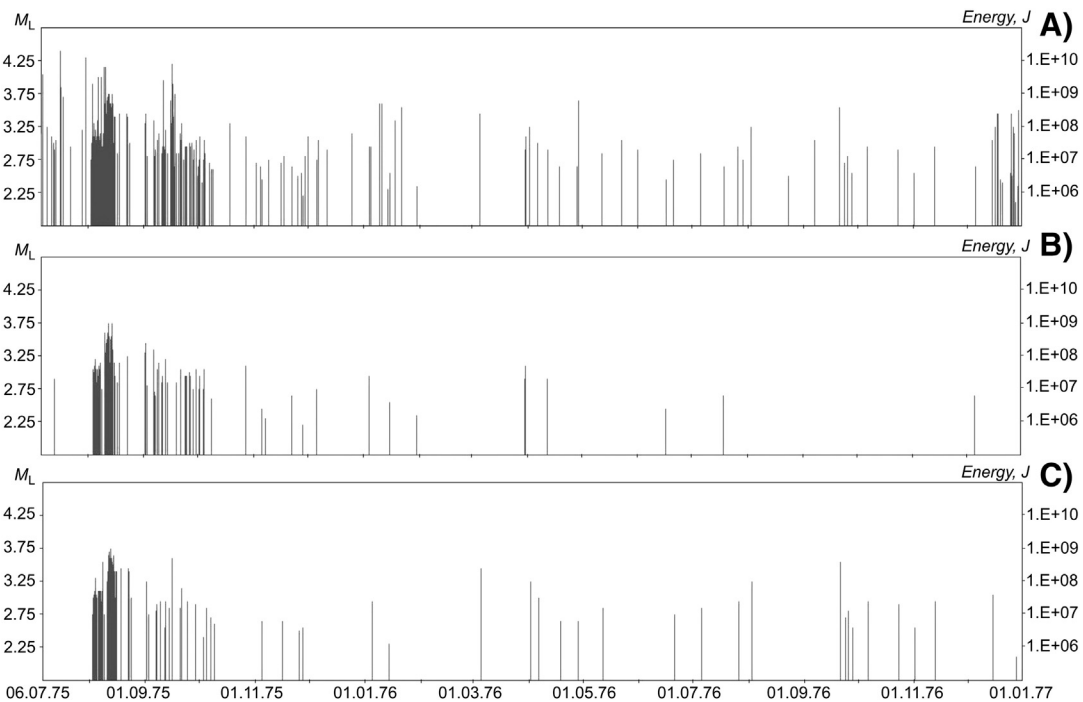


Fig. 4. Plots of the energy for earthquakes from the cylinders with depth range of -3 to +40 km in Fig. 2B for the time period between July 06, 1975, and December 31, 1976: A) 1 cylinder-20 km radius; B) 2 cylinder-9 km radius; C) 3 cylinder-10 km radius.

The Great Tolbachik Fissure Eruption lasted from July 06, 1975, to December 10, 1976. The initial phase of the eruption was purely explosive from the onset through July 27–29, 1975. Ash-gas plumes rose up to 18 km above sea level. A chain of new basaltic cinder cones grew up to 300 m in height and lava flows covered 45 km<sup>2</sup>. The first-formed Northern Breakthrough and the Southern Breakthrough began to erupt on September 17, 1975. Plots in Fig. 4 show the energy of the earthquakes during the eruption in different cylinders. It is interesting that seismic activity in cylinder 2 (near Pl. Tolbachik, Fig. 2B) and in cylinder 3 (Tolud zone, Fig. 2B) began at the beginning of August 1975, or several days after effusion of the first lava flow. We speculate that this may have occurred as crustal compensation related to effusion of a large amount of magmatic material. Evidence of the compensation process is the 154 m lowering of the crater bottom at Pl. Tolbachik's summit that occurred over the first 50 days of the eruption (Dvigalo et al., 1984).

## 2.2. Seismological observation and results, 2000–2013

Until 2000, the network of radio telemetry stations of KBGS RAS in the KVG region included the following stations: KRS, CIR, ZLN, LGN, KOZ, KPT and KMN (Fig. 1). The following stations were installed during 2000–2011: TUM (July 2003), KIR (August 2006), BZM (August 2006), BZG (August 2007), BZW (August 2007), KZV (September 2009), TUMD (March 2011). Most earthquakes in the time period 2000–2013 in the vicinity of Pl. Tolbachik area were registered by these radiotelemetric stations. These stations are equipped with short-period, 3-component seismometers with an eigenfrequency of 0.8 Hz. Seismic registration of velocity allows for the recording of seismic signals within a spectral range of 0.5–20 Hz and ~54 dB dynamic range, for a velocity limit value of about 40 microns per second.

In 2000, the Research Laboratory of Seismic and Volcanic Activity (RLSVA) of KBGS began to process all possible earthquakes in volcanic areas in near real-time and to present the results on the Internet (<http://www.emsd.ru/~ssl/monitoring/main.htm>) (Senyukov, 2013a). Fig. 5 shows a map with the epicenters and the projection of the hypocenters on the vertical sections for the period from January 01, 2000 to November 26, 2012. The volcano-tectonic earthquakes and hybrid events were registered in the region of Pl. Tolbachik in 2000–2013 only.

We used the HIPO program (Mel'nikov, 1990) to calculate the earthquake parameters for the time period between 2000 and 2009. Since 2010, we have used the DIMAS program (Droznin and Droznina, 2011). One velocity model was used in both programs, but different algorithms were applied. We compared the results of these two programs for a selected subset of 368 earthquakes. The results of this comparison show differences in epicentral locations of less than 1 km. DIMAS has approximately +1 km (upward) systematic deviation in depth, relative to HIPO, for –5 to +5 km depth range, and about –2 km (downward) deviation for depths of 5–40 km. At the same time, absolute horizontal and vertical mean location errors are 3 km for #1 and #2 regions, and 3.6 km for region #3, according to DIMAS (Fig. 5). Thus, the bias introduced by using different programs is smaller than the location accuracy; therefore, we decided to combine the catalogs obtained with these two different programs without relocating the earthquakes.

Fig. 5 also shows the position of the regional scoria-lava cones (Piip, 1956), marking the intersection of a deep-seated fault with the Earth's surface (Ermakov et al., 2014). This fault zone is 70 km in length and extends 20 km northeast and 50 km southwest from Pl. Tolbachik. Fedotov et al. (2010; 2014) have presented seismological evidence for the existence of a layer of “neutral buoyancy,” in which there is movement of magma from the intermediate magma chamber beneath Klyuchevskoy volcano (located at 25–35 km depth) toward the Tolbachik volcanoes at a depth of 15–20 km. Earthquake clusters near Zimina and Pl. Tolbachik volcanoes could be possible markers of this feeding path.

Fig. 6 shows the evolution over time of parameters of the earthquakes located within a 9-km radius of the summit of Pl. Tolbachik (black circle in Fig. 5). These graphs show that the magnitudes of

selected earthquakes prior to the 2012–2013 eruption did not exceed 2.5 and were much less than before 1975–1976 GTFE (Tokarev et al., 1984). Based on the experience of GTFE, the level of seismic activity for the Pl. Tolbachik area was defined as “high” if the daily number of localized earthquakes (N) with the  $M_L \geq 1.75$  exceeded 2, or if N exceeded 1 for events with  $M_L \geq 2.25$ . This “normal” level was exceeded between February 2000 and the 2012 eruption start on November 24, 2005; December 22, 2007; July 17, 2009; September 09, 2012; and on the following days in November of 2012: 10, 12, 13, 17, 25, and 26 (<http://www.emsd.ru/~ssl/monitoring/main.htm>).

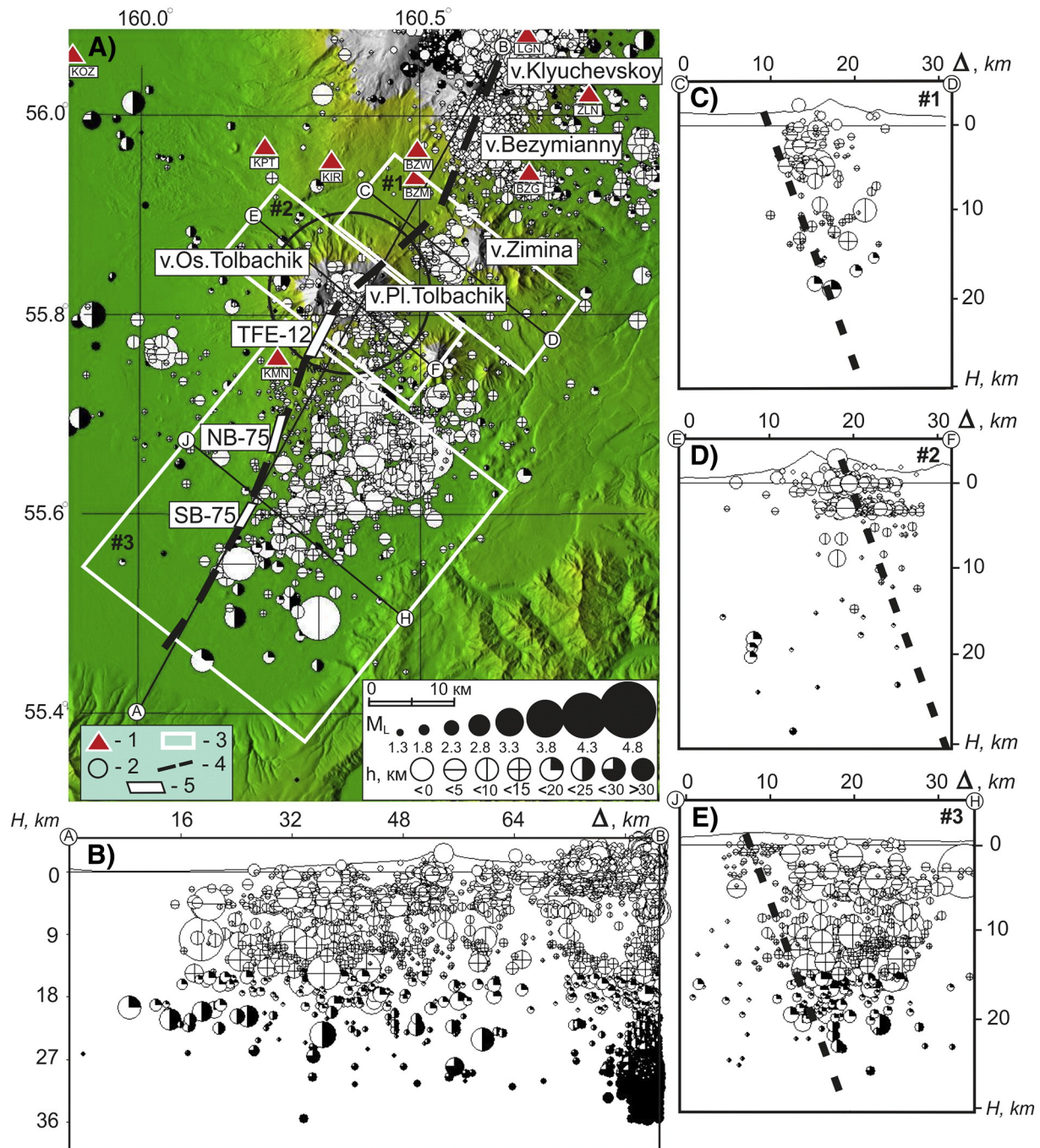
In accordance with the obligations of daily, real-time monitoring, the staff of RLSVA distributed by e-mail the following text reports about the Pl. Tolbachik activity to the Kamchatka Branch of the Russian Expert Council, IVS FED RAS (KVERT—Kamchatka Volcano Eruption Response Team); to the Alaska Volcano Observatory (AVO); to the Tokyo and Anchorage Volcanic Ash Advisory Centers (VAACs); and to other addressees on November 27, 2012 (Senyukov et al., 2013b):

- 1) At 02:18 UTC (local time = UTC + 12 h): “Earthquake swarm under Pl. Tolbachik volcano: earthquake number is 65 for November 26, depth is from –1 km to +5 km from sea level, local magnitude is from 1 to 2.25. Senyukov.”
- 2) At 05:45 UTC: “According to seismic data, an eruption of Pl. Tolbachik began on November 27 at 05:15 UTC. No satellite data, no video data. Senyukov.”
- 3) At 06:20 UTC: “According to seismic data a possible ash plume occurred on November 27 at 05:52 UTC using our experience to detect ash plumes from Bezymianny volcano. Strong seismicity is continuing. If an ash plume was generated, the approximate height of this ash plume was ~6.0 km or 19,672 ft above sea level (ASL). We have no experience to detect ash plumes at Pl. Tolbachik. No satellite data, no video data. Sobolevskaya.”

Beginning in 2003, KBGS implemented an original empirical method for detecting ash plumes and for estimating their heights based on the analysis of seismic records (Senyukov et al., 2013a). The method includes two stages. First, we analyze spectrograms from seismic events that correspond to known ash plumes. These signals show a predominant frequency content increasing from 1 Hz to 2–4 Hz, which is unusual for other local volcanic earthquakes. In a second step, we correlate the amplitudes of seismic signal envelopes (absolute ground velocity) with the ascent rate of the ash plume based on continuous video observation. Based on results of this correlation we use the integral of absolute ground velocity (or cumulative absolute ground displacement) as a proxy for the ash plume's height. In Kamchatka, this method has been implemented in real time and performs very well for several frequently active volcanoes with real-time monitoring networks. It allows us to make fast and adequate estimates of ash plume heights in the absence of visual and video data. The accuracy of our height estimation method is ~30% for Karymsky, Kizimen and Bezymianny volcanoes, and ~50% for Sheveluch volcano.

In 2012, Vitaly Bliznetsov designed and developed a computer program for the automatic detection of seismic signals accompanying ash emissions at seismically monitored, active volcanoes in Kamchatka (Bliznetsov and Senyukov, 2015). This program detected first the possible ash explosion from the 2012 Tolbachik eruption and informed the duty scientist of RLSVA.

The first visual confirmation of eruptive activity was received from the observers at “Kozyrevsk” (KOZ on Fig. 1) seismic station (communication by Yury and Natalya Ragunovich) at 10:00 UTC on November 27. Despite a snow storm, they saw ash explosions and glow above the crater of Pl. Tolbachik through a gap in the clouds. The RLSVA duty scientist, Oksana Sobolevskaya, received this information by phone and rebroadcast the observations by e-mail at 10:45 UTC. To this report she added information about possible ash emissions up to 10 km in height ASL, based on seismic data. Figs. 7B and 7C show the seismograms from KPT station (Fig. 5) with marked events.

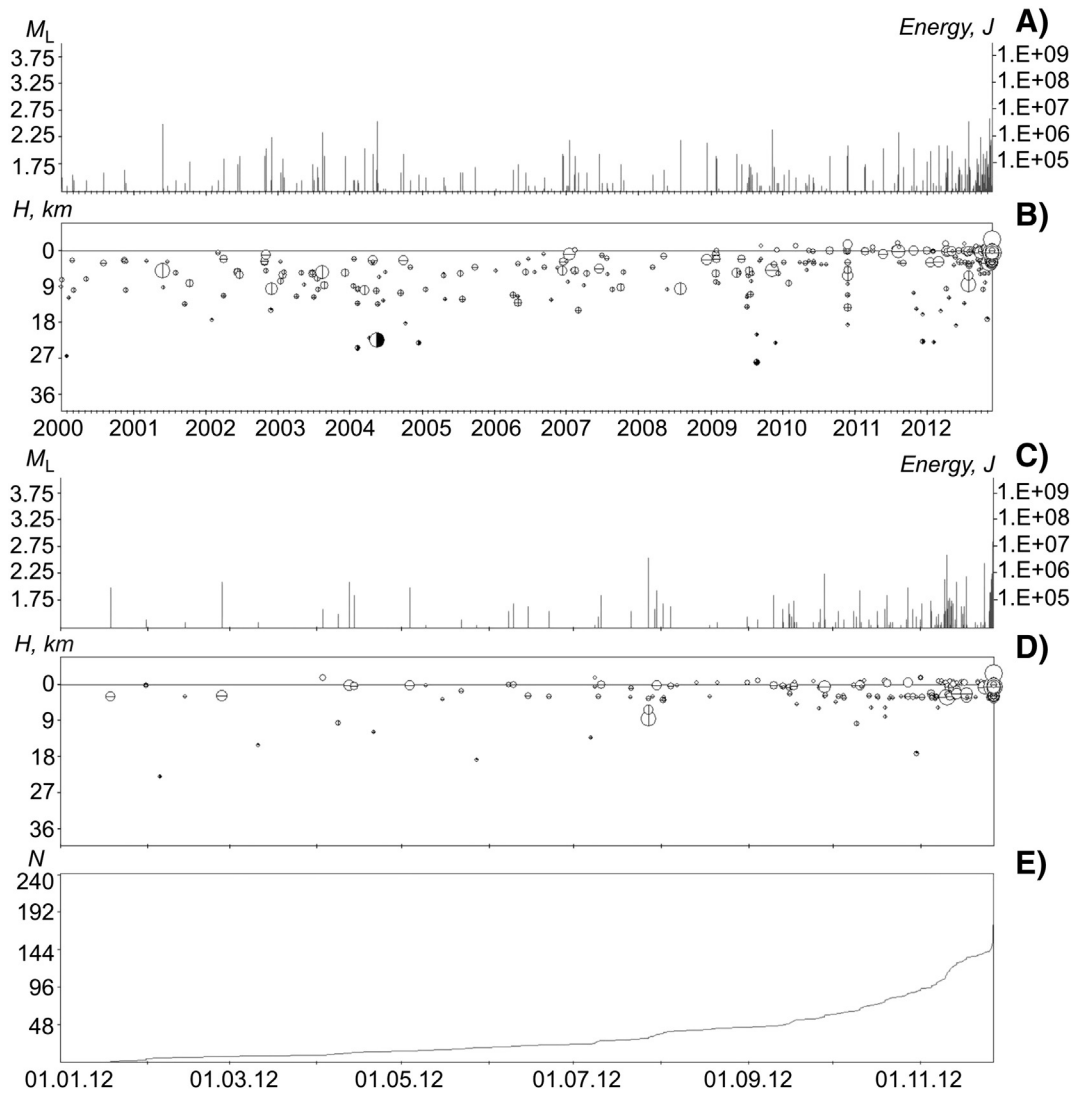


**Fig. 5.** A) Map of epicenters located between January 01, 2000, and November 26, 2012. Shown in inset: 1—seismic station, 2—circle with 9 km radius, 3—rectangle, 4—regional deep fault, 5—eruption centers: TFE-12, the 2012–2013 Tolbachik Fissure Eruption; NB-75, Northern Breakthrough of 1975–1976 GTFE; SB-75, Southern Breakthrough of 1975–1976 GTFE. B) Projection of all hypocenters from (A) on the vertical plane along line A-B. C) Projection of hypocenters from rectangular parallelepiped (rectangle #1 on the map, depth range of –3 to +30 km) on the vertical plane along line C-D. D) Projection of hypocenters from rectangular parallelepiped (rectangle #2 on the map, depth range of –3 to +30 km) on the vertical plane along line E-F. E) Projection of hypocenters from rectangular parallelepiped (rectangle #3 on the map, depth range of –3 to +30 km) on the vertical plane along line J-H.

Volcanic ash advisories centers in Tokyo and Anchorage could not find any evidence of this eruption using satellite tools because of the strong snow storm obscuring the ash cloud. The height of dense meteorological clouds was at least 10 km; therefore, the altitude of a possible ash plume was less than this height. The next morning, we received information about ashfall (up to 4 cm) in Mayskoe and Krasny Yar villages (Fig. 1). These villages are located ~50–60 km northwest of Pl. Tolbachik volcano. A constant strong hum from the volcano was heard in Klyuchi and Kozyrevsk settlements (Fig. 1). The first photo evidence of eruption was received on the morning on November 28, local time. Yury Demyanchuk (IVS FEB RAS) sent a photo of new ash deposit in Mayskoe

village to the RLSVA (Figs. 1 and 7A). This picture clearly shows two layers of new ash, separated by clean snow. This fact supports the interpretation of the seismological data of the explosive character of the first eruption stage and the presence of a pause from ~06 h to ~08 h UTC on November 27. The first thermal anomaly (08:28 UTC) and ash plume (15:04 UTC) at Pl. Tolbachik were noted in satellite analysis by AVO on November 28. A MODIS satellite image (from MODIS web site) clearly showed the ashfall on the snow-covered landscape extending northwest from the volcano on November 29.

Fig. 8 shows a comparison of the earthquake's distribution and the data of the morphological measurements taken during the initial stages



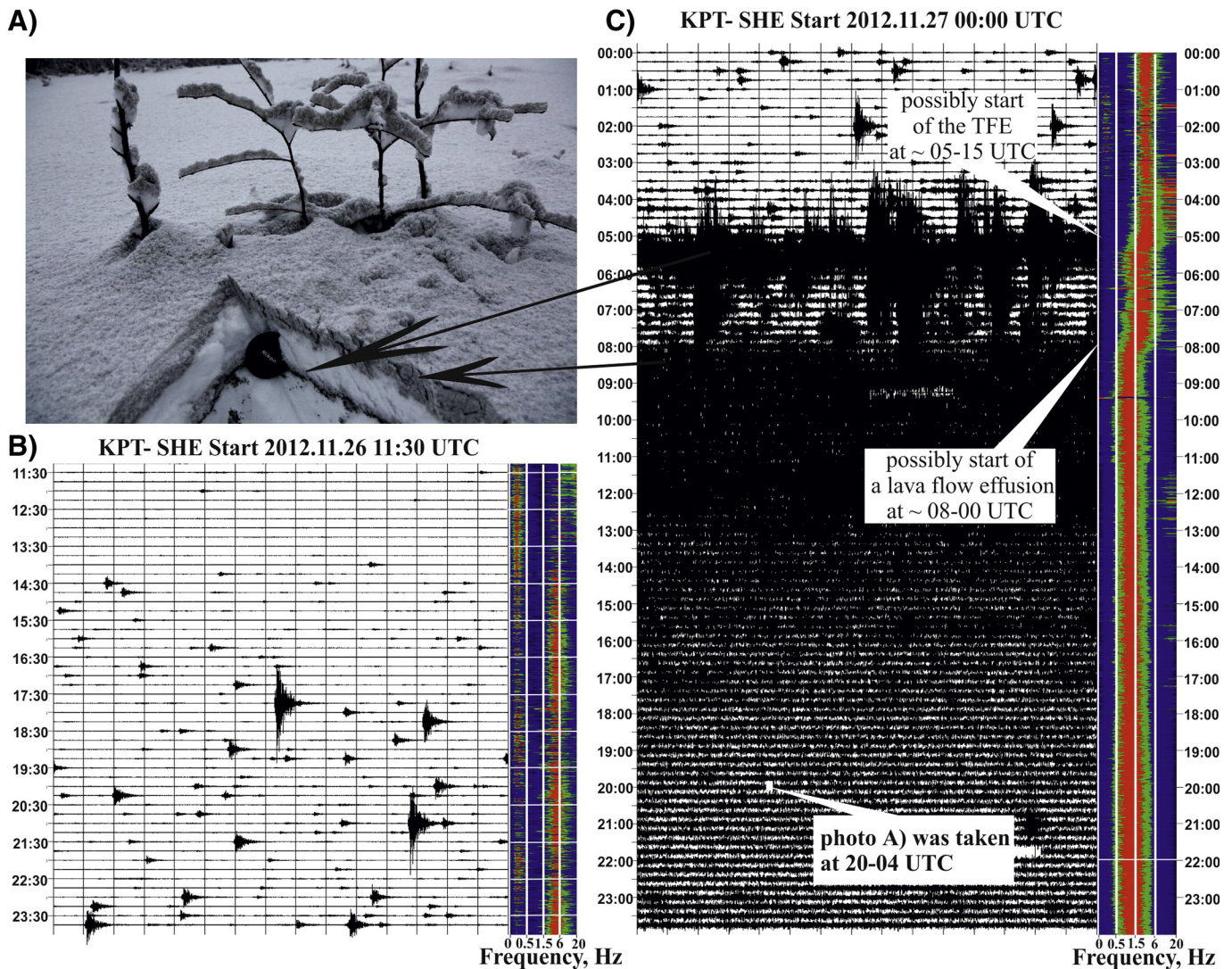
**Fig. 6.** Plots of the energy and the depth for earthquakes from the cylinder in Fig. 5 (9 km radius, depth range of  $-3$  to  $+40$  km). A) and B) for the time period between January 01, 2000, and November 26, 2012. C) and D) for the time period between January 01, 2012, and November 26, 2012. E) Cumulative number of earthquakes.

of the eruption. All earthquakes in Fig. 8 are  $-1$  to  $+5$  km deep with a vertical mean location error  $\pm 3$  km. Therefore, the vertical distribution is not relevant for this figure and is not shown. We use here the first results of photogrammetric studies. These results were obtained during a helicopter flight on December 13, 2012, and were published by Dvigalo et al. (2014). A new fissure or crack zone was 6 km in length and 350 m in width and extended from 2358 m to 1460 m altitude. Numerous eruptive centers were located along the new fissure or crack zone.

In Fig. 8D, the majority of the epicenters are located on the vicinity of a new “low eruptive vent” ( $\sim 1650$  m altitude; Dvigalo et al., 2014), which was named in honor of Sofya Naboko. This confirms good accuracy of the location of earthquake epicenters. Fig. 8A shows the epicenters before the eruption. Practically all earthquakes in the vicinity of Pl. Tolbachik between September 2012 and the beginning of the eruption were located in a narrow zone confined to the area of eventual intrusion of new magmatic material. This zone extends to the southeast from the crater of Pl. Tolbachik. Fig. 8B shows the epicenters of events that were used to determine the start of the eruption, in real time, on the ground, such as the reduction of the dominant frequency from previous events (Fig. 7C), a sharp increase of earthquake magnitude from  $\sim 2$  to 3.5 and a high density (repeatability) of events (each event started on the “tail” of the previous one). Some epicenters were located in the vicinity of the highest limit of the fault and near the “upper eruptive vent”

( $\sim 1870$  m altitude; Dvigalo et al., 2014) named in honor of Igor Menyailov, and others were located around the crater of the volcano on its perimeter. Such distribution could indicate an uplifting of the Pl. Tolbachik's cone and its cracking. Then, there was a pause from  $\sim 06$  h to 07 h UTC (Fig. 8C), after which the epicenters shifted to the largest “low eruption vent” (Fig. 8D). At approximately 08 h UTC, seismic events merged into a powerful continuous volcanic tremor, which corresponded to rapid effusion of a lava flow. This tremor was recorded steadily until August 23, 2013 (Fig. 9). After August 23, tremor amplitudes plummeted to zero, but then rose slightly several times until December 31, 2013. Tremor intensity had several peaks during the period of eruption, which may have been associated with the formation of new vents. However, because of the lack of continuous field observations, a correlation between these peaks and the appearance of new vents and other eruptive phenomena is not possible.

Fig. 10 shows the parameters of earthquakes recorded between November 27, 2012, and December 31, 2013. Strong volcanic tremors prevented processing of the weakest events. Nevertheless, we could conclude that a small number of seismic events occurred after the eruption in the vicinity of 2012–2013 TFE. A notable earthquake swarm occurred in region #3 on Fig. 10 (Tolud zone is situated to the east of the regional deep fault, Fig. 1) between November 30 and December 7. The strongest event occurred at 01 h 24 min UTC on November 30, at



**Fig. 7.** A) Photo of the snow section with fresh ash deposits; the diameter of the camera cover used for scale is 8 cm. The photo was taken at 20:04 UTC on November 27 near the Mayskoe village (Fig. 1) by Yury Demianchuk (IVS FEB RAS). B) and C) seismograms from KPT station (SHE channel) showing the seismicity before and during start of the eruption; the band to the right of the seismograms is a time spectrogram showing the change of the dominant frequency (red color, or more light on the black-and-white figure) (0 Hz—left border, 20 Hz—right border). Frequency bands used for this spectrogram are distributed non-linearly to emphasize the range between 0.5 and 5 Hz.

4.7 km depth, and had a local magnitude of 4.6. It should be noted that the swarm of earthquakes in the Tolud zone started a few days after the beginning of the lava flow effusion, as it was in 1975, possibly as a crustal compensation process. Further confirmation of this hypothesis is the fact that—despite the generally large number of surface earthquakes in Tolud zone—there was no eruptive activity on the Earth's surface at the same time. A detailed study of the relationship of earthquakes with the eruptions in different regions of KVG might allow us to understand the mechanism of seismicity leading up to eruption.

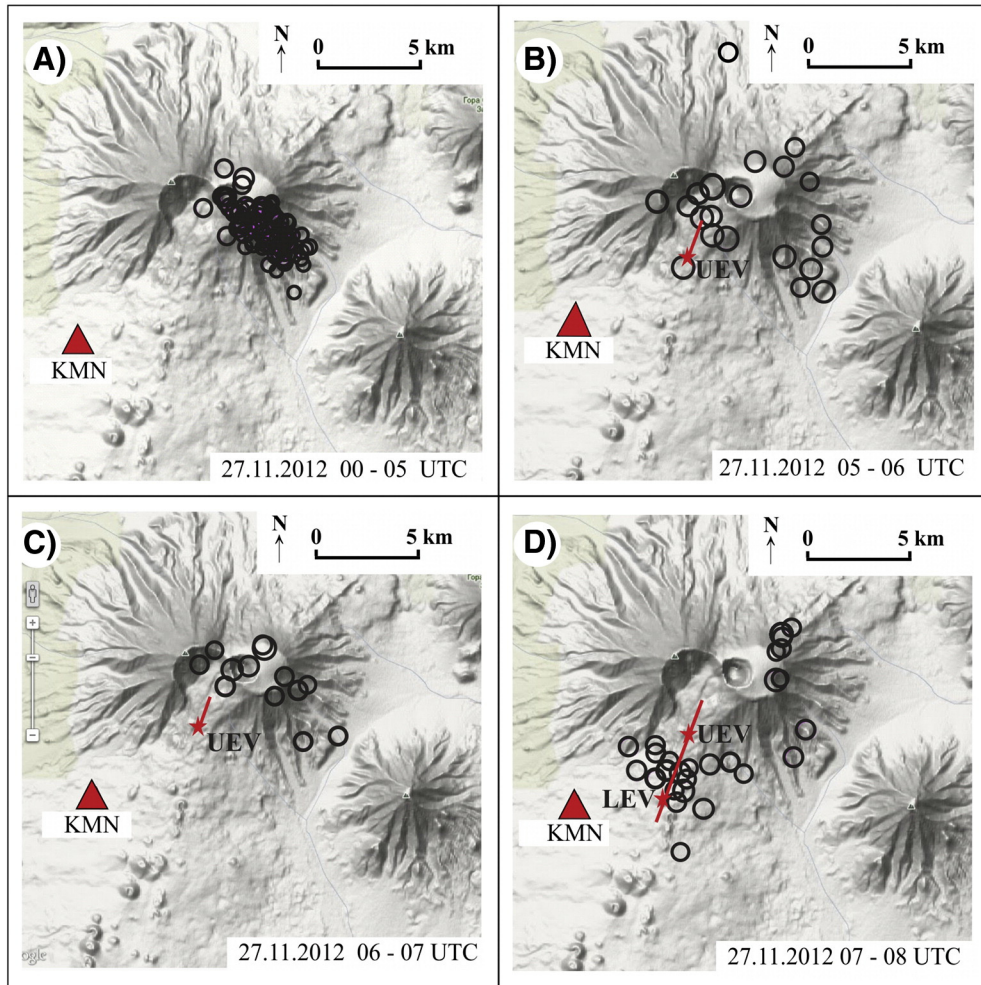
### 3. Defining the threshold seismicity level for alarm from a retrospective analysis

Before starting the study of the threshold seismicity level of Pl. Tolbachik, we must recall the work of Pavel Tokarev about the Klyuchevskoy volcano. These two volcanoes have approximately similar eruption products of basaltic composition, large summit craters and many vents on the flanks. Tokarev investigated seismic precursors before Klyuchevskoy eruptions from 1947 to 1986 and concluded that the seismic precursors before the summit and the flank eruption were very different. The main reason is that basaltic magma at 1100–1200 °C is relatively fluid and mobile. This magma rises to the

summit crater via existing vertical conduits without strong resistance and the precursor seismicity is relatively weak. In the case of a flank eruption, the magma must make a new path to a new vent resulting in stronger precursor seismicity. Tokarev (1988) investigated precursor earthquakes before 7 flank eruptions of the Klyuchevskoy volcano and described a general scenario:

- 1) All breakthroughs were preceded by swarms of the shallow (depth <5 km) volcano-tectonic and hybrid earthquakes with  $M_L \geq 2.25$  for 3–13 days;
- 2) The strongest earthquake in a swarm ( $M_L \geq 3.75$ ) occurs during the first or second day, and then the energy and the recurrence rate decrease rapidly; for a few hours before the eruption no more earthquakes with  $M_L \geq 2.25$  occur;
- 3) The average epicenter of an earthquake swarm is located within 1–5 km of the new vent location;
- 4) The swarms are followed by flank eruptions in 87% of cases.

Based on the scenario described above, Tokarev (1983) made a successful short-term forecast of the flank eruption named “Predskazanny” on the Klyuchevskoy volcano on March 08, 1983. At the same time, he could not find any seismic precursor to the summit eruptions before

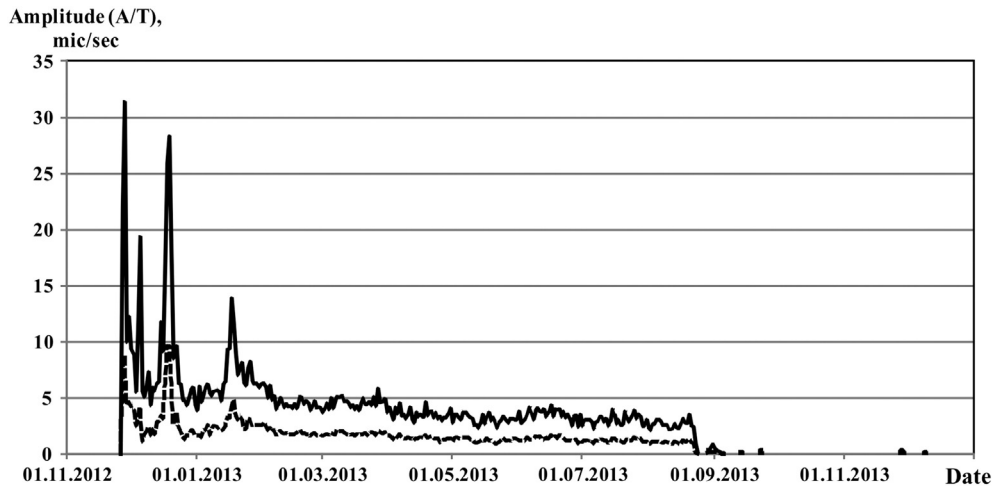


**Fig. 8.** Maps of the earthquake epicenters located during the indicated time periods. Line shows the radial fault along which the centers of eruption were aligned. Stars denote the most powerful eruption centers: the upper eruptive vent (UEV) and the low eruptive vent (LEV).

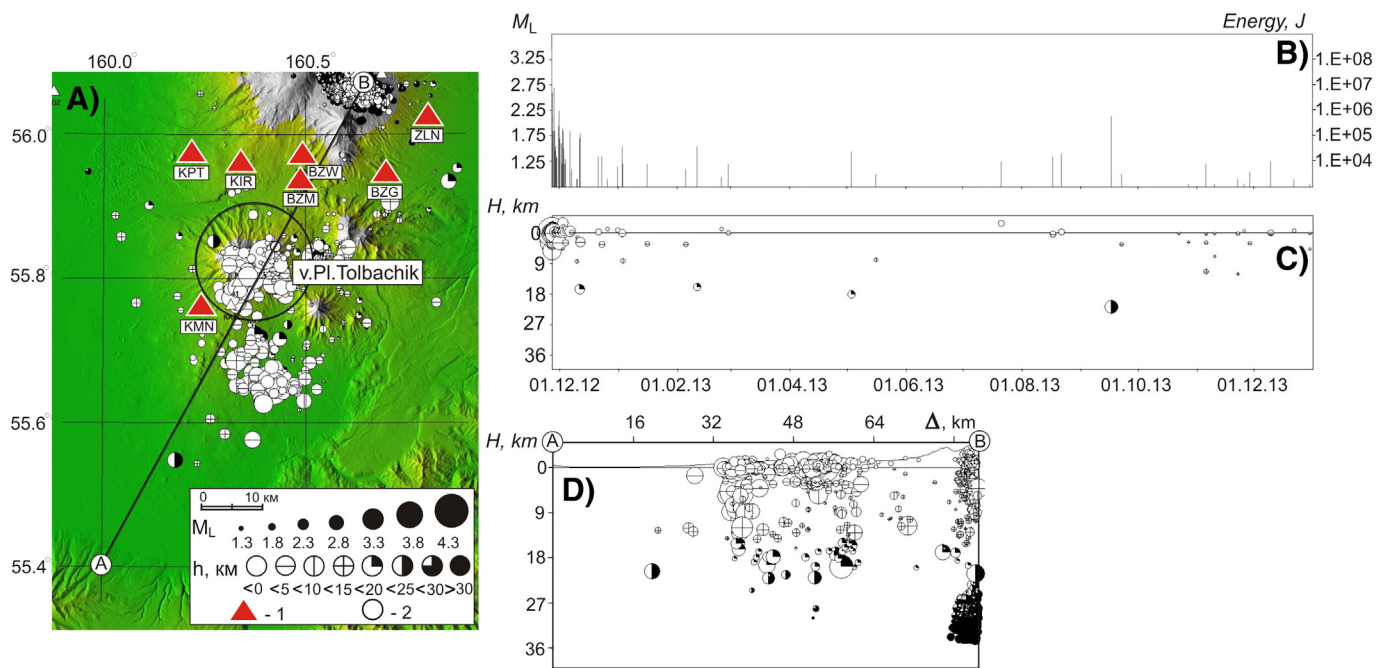
1986 because seismicity was too weak to be recorded on the existing network.

KBGS improved seismic monitoring and the threshold of detection in 1996–1998 due to the installation of new telemetric seismic stations and the implementation of modern digital technologies for data transmission, acquisition and processing (Droznin and Droznina, 2011;

Chebrov, et al., 2013; Gordeev et al., 2013a). This modernization has improved the completeness magnitude primarily. Here it is necessary to clarify that the earthquakes in the Klyuchevskoy volcano group in the period 1971–1996 were processed by the IVS and the KBGS staff in delayed mode and were published on the site of IVS. Earthquakes in 1999 were also processed by KBGS staff in delayed mode, but the earthquakes



**Fig. 9.** Amplitudes of seismic signals of the volcanic tremor at station KMN from November 01, 2012, to December 31, 2013 (solid line—maximum daily amplitude; dashed line—average daily amplitude).



**Fig. 10.** A) Map of epicenters located from November 27, 2012, to December 31, 2013. Indicated in the legend: 1—seismic station, 2—circle with 9 km radius. B) and C) Plots of energies and depths for earthquakes from the cylinder in Fig. 7A (9 km radius, depth range of -3 to +40 km). D) Projection of all hypocenters from Fig. 10A on a vertical plane along line A-B.

from 1997–1998 were not processed in full until recently. Geophysical Survey of the Russian Academy of Science publishes the earthquake catalogs of KBGS in its annual issues: “The earthquakes of Russia” and “The earthquakes of the Northern Eurasia.”

Five summit eruptions occurred at Kluchevskoy between 2000 and 2010. No flank eruptions occurred during this period. We investigated seismic data before the summit eruptions and described a typical seismic “scenario.” This scenario includes a shallowing of located earthquakes and an increase in the number of non-located earthquakes, volcanic tremor and such additional parameters as a thermal anomaly detected from a satellite. This scenario allowed us to predict 3 summit eruptions of 4. All detailed data, variants of the threshold seismicity level for alarms, scenarios, the prediction algorithm and the forecast results for the Kluchevskoy and the Bezymianny volcanoes were published in Senyukov (2013b), and a short description is provided by Senyukov (2013a). For example, the algorithm of the eruption forecast

for the Bezymianny volcano, including the parameters of the individual threshold seismicity levels for alarms and the use of thermal anomalies, helped us to make correct short-term forecasts for 11 of 13 explosive eruptions with only one false alarm. All forecasts were registered by Kamchatka Branch of the Russian Expert Council.

Since the beginning of our observations in 2000, the 2012–2013 eruption Pl. Tolbachik was the first eruptive event at that volcano. We estimated the threshold seismicity levels for the alarm by using our experience for Kluchevskoy and Bezymianny.

The completeness magnitude for this area varied between 1.35 and 1.5 from the ZMAP program (Weimer, 2001), Fig. 11. The completeness magnitude for the period of January 01, 2000, to July 01, 2001, is not determined because there is not enough data. The seismic network in the area of the Kluchevskoy volcano group has not changed in the time period of 2000–2003, so we can assume that the completeness magnitude was also ~1.5 from January 01, 2000, to November 27, 2012.



**Fig. 11.** Graph of completeness magnitude (solid line) and error bars (dotted lines) from January 01, 2000, to November 27, 2012.

The energy of an earthquake in joules can be calculated by using the formulas (1) of Fedotov (1972) and (2) of Gusev (Gusev and Mel'nikova, 1990):

$$E = 10^{Ks}, \quad (1)$$

$$\text{where } Ks = (M_L + 0.75)^2. \quad (2)$$

The energy of an earthquake with a 1.5 completeness magnitude is equal  $1^*E + 4.5$  J using the formulas 1 and 2, right scale in the Fig. 11.

Now we know a place of the last Tolbachik eruption and the location of the precursor earthquake swarm. Therefore, we can extract precursor earthquakes before the last eruption for a retrospective analysis. All of these earthquakes were located within the vertical cylinder shown in Fig. 5A (the circle center is a crater of Pl. Tolbachik (55.822N, 160.374E), the radius is 9 km and the depth range is between  $-5$  and 40 km). The 9-km radius is equal to half the distance between Pl. Tolbachik and Zimina and B. Udina volcanoes. So, we want to try to assess the possibility of the eruption forecast based on earthquakes located within this volume. For this purpose, we investigated a center of seismic energy (CSE) which was calculated from selected earthquakes for the time period 2000–2013 (Fig. 12). This center for a selected day is defined as one equivalent earthquake. Its coordinates are calculated as the arithmetic mean from the coordinates of the earthquakes recorded during the selected day with a weight proportional to the energy of the event. The energy of this equivalent earthquake is the sum of the energies of the selected events. Fig. 12 presents the data of all located earthquakes. CSE was used in Fedotov et al. (1988), Senyukov et al. (2009), Senyukov (2013a), and Senyukov (2013b). The eruption began on November 27, 2012, and the location of the initial outbreak is marked by an arrow in Fig. 12.

The ideal threshold level of seismicity used for the alarm triggering should not produce “false alarms” and should trigger an alarm several days before an eruption for possible adoption of preventive measures. Fig. 12 shows that an energy level of  $1^*E + 4$  J per day is small, would result in many “false alarms” and is incorrect, as there is less than  $1^*E + 4.5$  J (or 1.5 completeness magnitude, Fig. 11). On the other hand, an energy level of  $1^*E + 7$  J per day is too high and would only allow one to fix the alarm on the eve of eruption (on November 26, 2012). We will investigate the levels  $1^*E + 6$  J and  $1^*E + 5$  J per day. The date of registration of these levels is shown in Table 1:

- 1) There were 9 dates when energy was  $\geq(1^*E + 6$  J) between January 01, 2000, and November 01, 2012, and 4 dates in November before the eruption.
- 2) There were 56 dates when energy was  $\geq(1^*E + 5$  J) between January 01, 2000, and November 01, 2012, and 13 dates in November before the eruption.

We conclude that the level of  $1^*E + 5$  J per day will be more useful for the future monitoring of seismic activity of Pl. Tolbachik. In this case, we can offer the following wording for the prediction of the eruption start: “If CSE energy exceeded  $\geq (1^*E + 5$  J) in the 5 cases for a <30-day time period, eruption is likely to start during the following 70 days.” This approach would make a prediction after November 04 without “false alarms.” In this case, the anticipation (or period between the initial prediction and the ensuing eruption) would be 23 days; 70 days in the formulation is selected from those considerations. If we have the minimum statistics (one case), it is better to use the waiting period, which is 3 times greater than the previous period of anticipation.

If, for some reason, we could only locate earthquakes with  $M_L \geq 2.25$  or ( $1^*E + 6$  J) energy (for example, failure nearest stations), we can suggest the following formulation: “If the CSE energy exceeded  $1^*E + 6$  J in the two cases for a <30-day time period, the eruption is likely to start during the following 30 days.” This approach would make a prediction after November 17 without a “false alarm.” In this case, the anticipation would be 10 days.

It should be noted that energy exceeded the level of  $1^*E + 5$  J on 4 dates in the 30-day sliding window only once in September 2012 for the period from 01.01.2000 through October 2012 (Table 1). The energy exceeded the level of  $1^*E + 5$  J on 3 dates in the 30-day sliding window in three cases in February 2011, July 2012 and September 2012. This means that with this approach only after September 28, 2012, and not before was it possible to conclude that such high seismicity in the studied area had not been observed since January 1, 2000.

The paper (Saltykov et al., 2012) presents a retrospective analysis of the statistical estimation of the “seismicity alarm level” of the Pl. Tolbachik area. These authors detected anomalous earthquake energy beginning in September 2012. Daily earthquake counts began to grow one month before September 2012. However, it could be less correct because of different observation conditions for the investigated time.

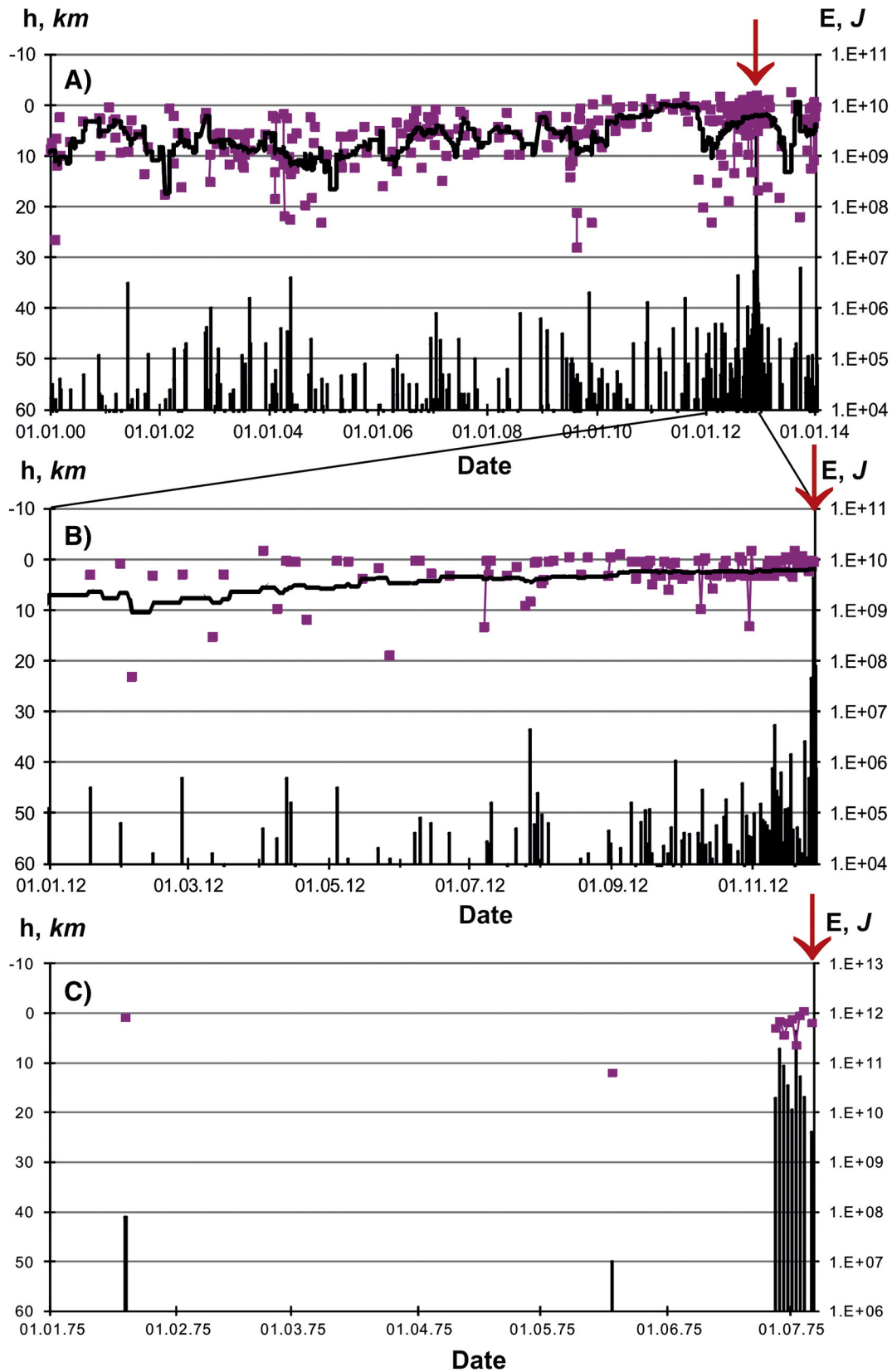
Fig. 12 also shows variations of the average depth of seismicity through time. During the considered period, we can distinguish several episodes of earthquake shallowing. Hypocenters rose to sea level after there were events with a 20–30-km depth. The average depth rose gradually from 7–8-km in November 2011 to 2 km on the eve of eruption. CSE lasted at the 2 km-level until February 2013, and then it dropped to 13 km in May 2013. Later CSE rose once again to the sea level in July 2013, and then began to deepen. The depth of CSE before eruption in 1975 in Fig. 12C also approached the surface. Therefore, the shallowing of the CSE before the eruption can be considered as an additional indicator for forecasting the heightened probability of an eruption.

In summary, we can propose two threshold levels of seismicity for two fissure eruptions that were observed in the Pl. Tolbachik region during the seismic instrumental observation period. The proximal portion of the first fissure (1975 eruption) was located  $\sim 18$  km from the summit of the Pl. Tolbachik; in 2012, the proximal fissure was located  $\sim 1$  km off the summit crater. The precursor earthquake swarms before these eruptions were very different in energy and time distribution (Fig. 12). Therefore, we can discuss two different scenarios. The first scenario was described by Tokarev (1988) for a fissure eruption located more than 18 km away from the summit of Pl. Tolbachik, as it was in 1975. There were no earthquake swarms in the region of the volcano from 01 January 1971 to 27 June 1975 (Fig. 3A), and there were no earthquakes within the 10-km radius from Pl. Tolbachik (Fig. 2A). For the 2012 eruption (and, perhaps, for future fissure eruptions near the summit within a 10-km distance of the summit of Pl. Tolbachik), we can offer the threshold seismicity level for the alarm as described above. Therefore, the location of the new earthquake swarm will determine the choice of one of two possible scenarios and the possible forecast.

#### 4. Conclusion

Based on the real-time analysis of seismicity, a powerful new explosive-effusive 2012–2013 TFE started at  $\sim 05$  h 15 min UTC on November 27, 2012, between the top of the Pl. Tolbachik and the Northern Breakthrough of 1975–1976 GTFE. Before the eruption, seismic events associated with a precursory intrusion were mainly located in the southeast sector of Pl. Tolbachik at 0–5 km depths below sea level. Event rates rose sharply on the eve of the eruption. Despite this fact, because of the bad weather conditions all first conclusions about the beginning and character of the eruption were made using seismological data only. Results from seismological observation were later confirmed by other monitoring methods.

Retrospective analysis of the available seismological observations indicate that the precursor earthquake swarms before two fissure eruptions at Pl. Tolbachik in 1975 and in 2012 were very different in energy and distribution in time. The difference is primarily explained by the location of the eruption. The fissure eruption in 1975 was located  $>18$  km from the top of Pl. Tolbachik and the precursor earthquake swarm was stronger and lasted 9 days. Pavel Tokarev described this



**Fig. 12.** Plots of the depth (squares, left scale) and the energy (vertical bars, right scale) of the “seismic energy center” for periods: A) 01.01.2000–31.12.2013, B) 01.01.2012–27.11.2012, and C) 01.01.1975–06.07.1975. The arrow indicates the beginning of the eruption. Solid black line shows the depth averaged over 100 points (left scale).

scenario in detail (1988). The most recent fissure eruption in 2012 was located closer to the summit (>1 km) and seismicity was relatively weak. We have defined new threshold levels of “daily seismic energy”

for alarms and forecasting the future eruptions at and near the summit of the Pl. Tolbachik volcano. If used in 2012, advance warning could have been issued 10–23 days prior to the eruption onset.

**Table 1**Dates of registration of high seismicity with levels ( $1 * E + 6 J$ ) and ( $E + 1 * 5 J$ ).

Energy, J	Date	Date	Date	Date	Date	Date	Date
$E \geq 1 * E + 6$	28.05.2001	30.11.2002	17.08.2003	19.05.2004	06.11.2009	27.11.2010	09.08.2011
$E \geq 1 * E + 6$	27.07.2012	28.09.2012	10.11.2012	17.11.2012	23.11.2012	26.11.2012	27.11.2012
$E \geq 1 * E + 5$	17.11.2000	28.05.2001	13.10.2001	04.04.2002	11.06.2002	23.06.2002	29.10.2002
$E \geq 1 * E + 5$	02.11.2002	30.11.2002	26.01.2003	27.06.2003	17.08.2003	25.08.2003	08.12.2003
$E \geq 1 * E + 5$	15.03.2004	28.04.2004	19.05.2004	30.09.2004	01.05.2006	14.12.2006	15.12.2006
$E \geq 1 * E + 5$	15.01.2007	14.02.2007	18.06.2007	02.08.2008	13.12.2008	26.01.2009	30.01.2009
$E \geq 1 * E + 5$	13.05.2009	05.06.2009	06.11.2009	25.08.2010	20.11.2010	27.11.2010	16.02.2011
$E \geq 1 * E + 5$	18.02.2011	22.02.2011	25.05.2011	09.08.2011	27.10.2011	31.12.2011	18.01.2012
$E \geq 1 * E + 5$	27.02.2012	12.04.2012	14.04.2012	04.05.2012	10.07.2012	27.07.2012	30.07.2012
$E \geq 1 * E + 5$	09.09.2012	15.09.2012	17.09.2012	28.09.2012	10.10.2012	20.10.2012	27.10.2012
$E \geq 1 * E + 5$	01.11.2012	04.11.2012	09.11.2012	10.11.2012	11.11.2012	12.11.2012	13.11.2012
$E \geq 1 * E + 5$	15.11.2012	16.11.2012	17.11.2012	23.11.2012	25.11.2012	26.11.2012	27.11.2012

The earthquake swarms in the Tolud zone began a few days after the beginning of the lava flow effusion in 1975 and in 2012, perhaps as a part of the compensation process for magma withdrawal.

The installation of new seismic stations near Pl. Tolbachik will significantly improve the seismic monitoring of this area and the ability to accurately forecast future eruptions.

### Acknowledgments

The authors are grateful to the editors of special issue "2012–2013 Tolbachik eruption": Benjamin Edwards, Alexander and Marina Belousov and Anna Volynets for their kind invitation to publish this article. Special and great thank to Christina Neal from the USGS Alaska Volcano Observatory and Nikolay Shapiro from the Institute of Physics of the Earth in Paris (France) for useful suggestions. Two anonymous reviewers significantly improved this manuscript.

### References

- Bliznetsov, V.E., Senyukov, S.L., 2015. ADAP software for automatic detection of ash emission at active volcanoes and calculations of ash plume height using seismological data. *J. Seism. Instrum.* 51 (1), 46–59 (in Russian).
- Chebrov, V.N., Droznina, D.V., Kugaenko, Yu.A., Levina, V.I., Senyukov, S.L., Sergeev, V.A., Schevchenko, Yu.V., Yaschuk, V.V., 2013. The system of detailed seismological observations in Kamchatka in 2011. *J. Volcanol. Seismol.* 7 (1), 16–36. <http://dx.doi.org/10.1134/S0742046313010028>.
- Droznina, D.V., Droznina, S.Ya., 2011. Interactive DIMAS program for processing of seismic signals. *J. Seism. Instrum.* 47 (3), 215–224. <http://dx.doi.org/10.3103/S0747923911030054>.
- Dvigalo, V.N., Chirkov, A.M., Fedotov, S.A., 1984. Changes of crater dimensions before and during eruption. In: Fedotov, S.A. (Ed.), *Great Tolbachik Fissure Eruption, Kamchatka, 1975–1976*. Nauka, Moscow, pp. 81–86 (in Russian).
- Dvigalo, V.N., Fedotov, S.A., Chirkov, A.M., 1991. Plosky Tolbachik. In: Fedotov, S.A., Masurenkov, Yu.P. (Eds.), *Active Volcanoes of Kamchatka vol.1*. Nauka, Moscow, pp. 200–279.
- Dvigalo, V.N., Svirid, I.Yu., Schevchenko, A.V., 2014. The first quantitative estimates of parameters for the Tolbachik fissure eruption of 2012–2013 from aero photogrammetric observations. *J. Volcanol. Seismol.* 8, 261–268. <http://dx.doi.org/10.1134/S0742046314050029>.
- Edwards, B., Belousov, A., Belousova, M., Volynets, A., Melnikov, D., Chirkov, S., Senyukov, S., Gordeev, E., Muravyev, Y.A., Izbekov, P., Demyanchuk, Yu., 2013. Another "Great Tolbachik" eruption? *EOS Trans. Am. Geophys. Union* 94, 189–190. <http://dx.doi.org/10.1002/2013EO210002>.
- Ermakov, V.A., Gontovaya, L.I., Senyukov, S.L., 2014. Tectonics and magma chambers of the recent Tolbachik Fissure Eruption (Kamchatka Peninsula). *Izv. Atmos. Oceanic Phys.* 50 (8), 745–765. <http://dx.doi.org/10.1134/S0001433814080039>.
- Fedotov, S.A., 1972. *Energy Classification of the Kuril-Kamchatka Earthquakes and the Problem of Magnitudes*. Nauka, Moscow (in Russian).
- Fedotov, S.A., Zharinov, N.A., Gorelchik, V.I., 1988. Deformation and the earthquakes of the Klyuchevskoy volcano, model of its activities. *J. Volcanol. Seismol.* 2, 3–42 (in Russian).
- Fedotov, S.A., Zharinov, N.A., Gontovaya, L.I., 2010. The magmatic system of the Klyuchevskaya group of volcanoes inferred from data on its eruptions, earthquakes, deformation, and deep structure. *J. Volcanol. Seismol.* 4 (1), 1–33. <http://dx.doi.org/10.1134/S074204631001001X>.
- Fedotov, S.A., Utkin, I.S., Utkina, L.I., 2011. The peripheral magma chamber of Ploskii Tolbachik, a Kamchatka basaltic volcano: activity, location and depth, dimensions, and their changes based on magma discharge observations. *J. Volcanol. Seismol.* 5, 369–385. <http://dx.doi.org/10.1134/S0742046311060042>.
- Fedotov, S.A., Slavina, L.B., Senyukov, S.L., Kuchay, M.S., 2014. Seismic processes and movement of the magmas, occurring at the 1975–1976 Great Tolbachik Fissure Eruption and the 2012–2013 Tolbachik Fissure Eruption (Kamchatka). *J. Geophys. Process. Biosph.* 13 (3), 5–30 (in Russian).
- Gordeev, E.I., Fedotov, S.A., Chebrov, V.N., 2013a. Detailed seismological investigations in Kamchatka during the 1961–2011 period: main results. *J. Volcanol. Seismol.* 7 (1), 1–15. <http://dx.doi.org/10.1134/S0742046313010041>.
- Gordeev, E.I., Muravyev, Ya.D., Samoylenko, S.B., Volynets, A.O., Melnikov, D.V., Dvigalo, V.N., 2013b. The Tolbachik fissure eruption of 2012–2013: preliminary results. *Dokl. Earth Sci.* 452 (2), 1046–1050 (01).
- Gusev, A.A., Mel'nikova, V.N., 1990. Correlations between world and Kamchatka magnitudes. *J. Volcanol. Seismol.* 6, 55–63 (in Russian).
- Mel'nikov, Yu.Yu., 1990. Program for earthquake location on Kamchatka. *J. Volcanol. Seismol.* 5, 103–112 (in Russian).
- Piip, B.I., 1956. Klyuchevskoy volcano and its eruptions in 1944–45, and before. *Proc. Lab. Volcanol.* 11 (308 pp. (in Russian)).
- Polyak, B.G., Melekestsev, I.V., 1981. Productivity of volcanoes. *J. Volcanol. Seismol.* 5, 22–37 (in Russian).
- Saltykov, V.A., Kugaenko, Yu.A., Voropaev, P.V., 2012. Seismic anomaly preceding New Fissure Tolbachik eruption in 2012. *Vestn. KRAUNZ* 2, 16–19 (in Russian).
- Samoylenko, S.B., Melnikov, D.V., Maguskin, M.A., Ovsyannikov, A.A., 2012. The beginning of new fissure Tolbachik eruption in 2012. *Vestn. KRAUNZ* 2, 20–22 (in Russian).
- Senyukov, S.L., 2013a. Monitoring and prediction of volcanic activity in Kamchatka from seismological data: 2000–2010. *J. Volcanol. Seismol.* 7 (1), 86–97. <http://dx.doi.org/10.1134/S0742046313010077>.
- Senyukov, S.L., 2013b. Forecast of Eruptions for Klyuchevskoy and Bezymianny Volcanoes of Kamchatka. LAP LAMBERTS Academic Publishing, Saarbrücken (13 978-3-659-35224-9 in Russian).
- Senyukov, S.L., Droznina, S.Y., Nuzhdina, I.N., Garbuzova, V.T., Kozhevnikova, T.Y., 2009. Studies in the activity of Klyuchevskoi volcano by remote sensing techniques between January 1, 2001 and July 31, 2005. *J. Volcanol. Seismol.* 3 (3), 191–199. <http://dx.doi.org/10.1134/S0742046309030051>.
- Senyukov, S.L., Droznina, S.Ya., Kozhevnikova, T.Yu., 2013a. Experience of the detection of ash plume and estimation its height using local seismicity for Kamchatkan volcanoes during 2003–2011 (Kamchatka Peninsula, Russia). In: Zobin, V.M. (Ed.), *Complex Monitoring of Volcanic Activity: Methods and Results*. Nova Science Publishers Inc., New York, pp. 35–52.
- Senyukov, S.L., Nuzhdina, I.N., Droznina, S.Ya., Garbuzova, V.T., Kozhevnikova, T.Yu., Sobolevskaya, O.V., Nazarova, Z.A., 2013b. Seismicity of Plosky Tolbachik within 2000–2013. Proc. 4 Conference "Problems of geophysical monitoring of Far East of Russia", Petropavlovsk-Kamchatsky, Russia, September 29–October 05, 2013, pp. 103–107 (in Russian).
- Tokarev, P.I., 1976. Prediction of the place and start time of Great Tolbachik Fissure Eruption in July 1975. *Dokl. Akad. Nauk USSR* 229, 439–442 (in Russian).
- Tokarev, P.I., 1983. Prediction of the of the breakthrough eruption of the Klyuchevskoy volcano in March 1983. *J. Volcanol. Seismol.* 5, 3–8 (in Russian).
- Tokarev, P.I., 1988. Prediction of the breakthrough eruptions of the Klyuchevskoy volcano. *J. Volcanol. Seismol.* 6, 47–61 (in Russian).
- Tokarev, P.I., Fedotov, S.A., Stepanov, V.V., 1984. Prediction of the beginning and development of the eruption. In: Fedotov, S.A. (Ed.), *Great Tolbachik Fissure Eruption, Kamchatka, 1975–1976*. Nauka, Moscow, pp. 373–388 (in Russian).
- Volynets, A.O., Melnikov, D.V., Yakushev, A.I., 2013. First data on composition of the volcanic rocks of the IVS 50th anniversary Fissure Tolbachik eruption (Kamchatka). *Dokl. Earth Sci.* 452, 953–957. <http://dx.doi.org/10.1134/S1028334X13090201>.
- Weimer, S.A., 2001. A software package to analyze seismicity: ZMAP. *J. Seism. Res. Lett.* 72 (2), 374–383.
- Zelenski, M., Malik, N., TaranTaran, Taran, 2014. Emissions of trace elements during the 2012–2013 effusive eruption of Tolbachik volcano, Kamchatka: enrichment factors, partition coefficients and aerosol contribution. *J. Volcanol. Geotherm. Res.* 285, 136–149. <http://dx.doi.org/10.1016/j.jvolgeores.2014.08.007>.
- Zobin, V.M., 2012. *Introduction to Volcanic Seismology*. second edition. Elsevier, London.