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THE FIRST REAL-TIME APPLICATION OF THE FORMALIZED METOD OF PROBABILISTIC FORECAST: BEZYMIANNY VOLCANO ERUPTIONS

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Abstract. The new episode of the eruptive activity of the Bezymianny Volcano in Kamchatka started in 2016. The article demonstrates the precursor situations identified by increasing the level of seismicity and analyzed in real time before three eruptions in November 2016 – March 2017. The application of the formalized forecasting method developed for the Bezymianny Volcano using seismic data from 1999 to 2014 [*Saltykov*, 2016] allows the formulation of the probabilistic forecast of eruptions in real time.

Keywords: Kamchatka, Bezymianny Volcano, precursor, forecasting, earthquake, eruption.

Introduction

After more than four years of repose the activity of the Bezymianny Volcano increased in Kamchatka in November, 2016. Features and activity chronology of this volcano are described in [*Bogoyavlenskaya et al.*, 1991; *Girina et al.*, 2017; *Girina*, 2013; *West*, 2013] and a number of other works. Another activation period started in the first decade of December 2016; its culmination was an explosive eruption on 09.03.2017, during which clouds of volcanic ash rose to a height of 7-8 km and an ash trail of several thousands of kilometers was formed.

Most of its activations were preceded by the increase in shallow seismicity that made it possible to create a formalized method of probabilistic forecast (MPF) for eruptions of the Bezymianny volcano, described in detail by one of the authors in [*Saltykov*, 2016]. This article is a report on the first application of this method in the real time during the development of eruptive activity of volcano in late 2016 – early 2017.

About the method of probabilistic forecast

According to the authors, the most reliable source of information for identifying a potential precursor situation for the Bezymianny volcano is seismicity, which continuous data is provided by the Kamchatka seismicity monitoring system. These data are available for analysis in real time and do not depend on the possibility of visual observations, weather conditions, atmosphere transparency, availability of satellites, etc. According to the data of 1999–2012, in most cases, eruptions were preceded by a statistically significant increase in seismicity level according to the SESL'09 scale [*Saltykov*, 2011] with advance time of up to 40 days [*Kugaenko, Voropaev*, 2015].

In accordance with modern requirements for the prediction of hazardous natural processes, the method of precursor detecting should be formalized; moreover, to assess the probability of prediction among the parameters that are analyzed in the framework of this method, the assessment of effectiveness of precursor should be presented.

In the mentioned work of *Saltykov* [2016] was proposed a formalized approach to the probabilistic forecast based on the use of statistical assessment of seismicity level of SESL'09 and a number of additional functions characterizing precursor. The indicator-function $U(t)$ and threshold criterion were used to identify the time intervals of eruption preparation and it allowed to formalize the procedure of eruption precursor detecting. Principal component of the method is the estimated probability of forecast realization depending on the duration of the forecast and magnitude of the threshold criterion.

In case of the Bezymianny volcano the seismicity is analyzed at the depths of up to 30 km within the radius of 6 km from its top. Based on the data of 1999–2014, during which 21 eruptions occurred, the reliability and trustworthiness of precursor as well as its effectiveness were evaluated in retrospect. Results of retrospective application of the method of probabilistic forecast are statistically significantly differ from the random guessing and give a gain of 3-30 times compared to it.

Precursor situations in November 2016, January-February and March 2017

Increase in seismicity that started in November 2016 caused the increase in probability of eruption of the Bezymianny volcano. Fig. 1 shows parameters characterizing precursor situations before the eruptions of the Bezymianny volcano in late 2016 – early 2017.

The parameter called contrast (Fig. 1, *a*), shows the increase in probability of the forecasting event with the appearance of the precursor (plot *2*) in comparison with the situation when the precursor is absent (plot *1*). Method is focused on the calculation of the released seismic energy and not on the number of earthquakes registered on the volcano (Fig. 1, *b*). When comparing Fig. 1, *a* and Fig. 1, *b* it can be seen that these values do not always correlate – this is a feature of volcanic areas.

Previously, the method of probabilistic forecast was not tested in real time, so monitoring of the indicator-function in 2016 was performed in experimental "internal" mode. In addition, the long-lasting (since September 2012) absence of eruptions allowed to suggest that the volcano regime has changed and method developed for the events of 1999–2012 may be ineffective. However, the new eruption showed that the proposed approach remains relevant.

According to *KVERT*[1], the eruption began on 05.12.2016 (Fig. 1, *a*) with extrusive phase I, where activated the squeezing of lava dome in the crater, that turned into effusive phase II on 12.12.2016 – a lava flow was poured onto the volcano's slope; on 15.12.2016 was observed an explosive event III – a steam-gas trail with ash was detected [*Girina et al.,* 2017; *Chebrov et al.,* 2017]. An eruption occurred when its probability according to MPF was approximately 10 times higher than the average annual probability and more than 100 times exceeded the probability of eruption in the absence of precursor.

Taking into account the above, the next seismic activation that occurred in January-February 2017 was analyzed in real time. Forecast conclusions on impending eruption were passed to KB REC on 26.01.2017 (ПР1 in Fig. 1, *a*) 03.02.2017 and 10.02.2017. Eruption probability was approximately 7 times higher than the average annual.

Due to the cloudiness that hampered ground and satellite observations, it was impossible to establish the exact date of the start of the eruption – approximately it happened between 7 and 11 of February [*Girina et al.,* 2017]. Starting from 11.02.2017 video cameras of KB FRC UGS RAS[2] recorded a new lava flow on the volcano's slope (Fig. 2, *b*). Thus, the forecast was justified and realized by effusive eruption.

[1] Kamchatka Volcanic Eruption Response Team, http://www.kscnet.ru/ivs/kvert/index.php.
[2] Kamchatka Branch of the Federal Research Center of "United Geophysical Service of the Russian Academy of Sciences"

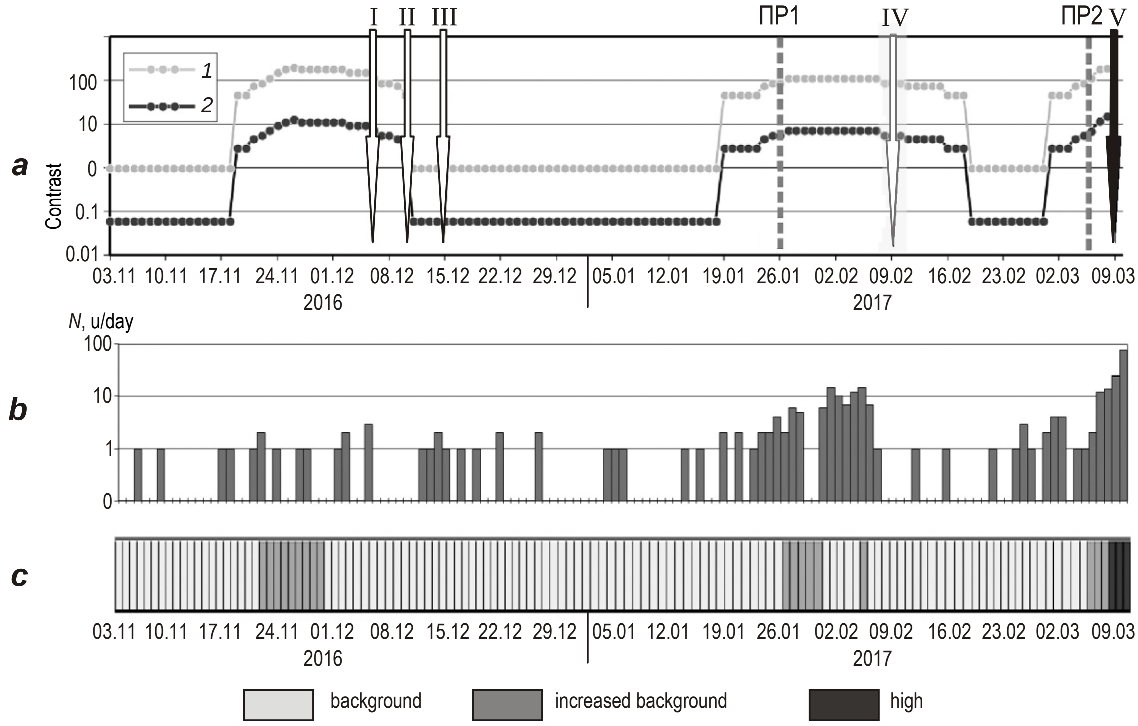

Fig. 1. Precursor situations before the eruptions of the Bezymianny volcano in late 2016- early 2017: *(a)* ratio of eruption probability in the presence of precursor (*1*) to the eruption probability in its absence and (*2*) to the average annual eruption probability; (*b*) number of eruptions recorded within the radius of 6 km from the volcano's top in the depth range up to 30 km; (*c*) time course of seismicity level according to SESL'09 scale in the time window of 5 days (the value is tied to the right edge of the window)

Roman numerals on *a* indicate successive phases of eruption: 2016 – extrusive phase (I), effusive phase (II) and explosive event (III); 2017 – effusive phase (IV) and explosive eruption (V)

Seismic activation in the beginning of March 2017 was also analyzed in real time. Seismicity of volcano (in time window of 5 days) reached the background increased level on 04.03.2017 and on 07.03.2017 moved to the high level (see Fig. 1, *c*). Forecast conclusion made on the basis of the method of probabilistic forecast was passed to KB REC on 06.03.2017 in the moment when the eruption probability exceeded the average annual approximately by 6 times (ПР2 in Fig. 1, *a*).

During 07–08.03.2017 the probability of eruption continued to grow and contrast reached the value of ~16. The forecast was realized by a picturesque explosive eruption on 09.03.2017 (V in Fig. 1, *a*), that was registered by cameras in clear visibility (Fig. 2, *c*). Analysis of satellite images allowed to determine the starting time of eruption – ~01:30 UTC [*Girina et al.,* 2017].

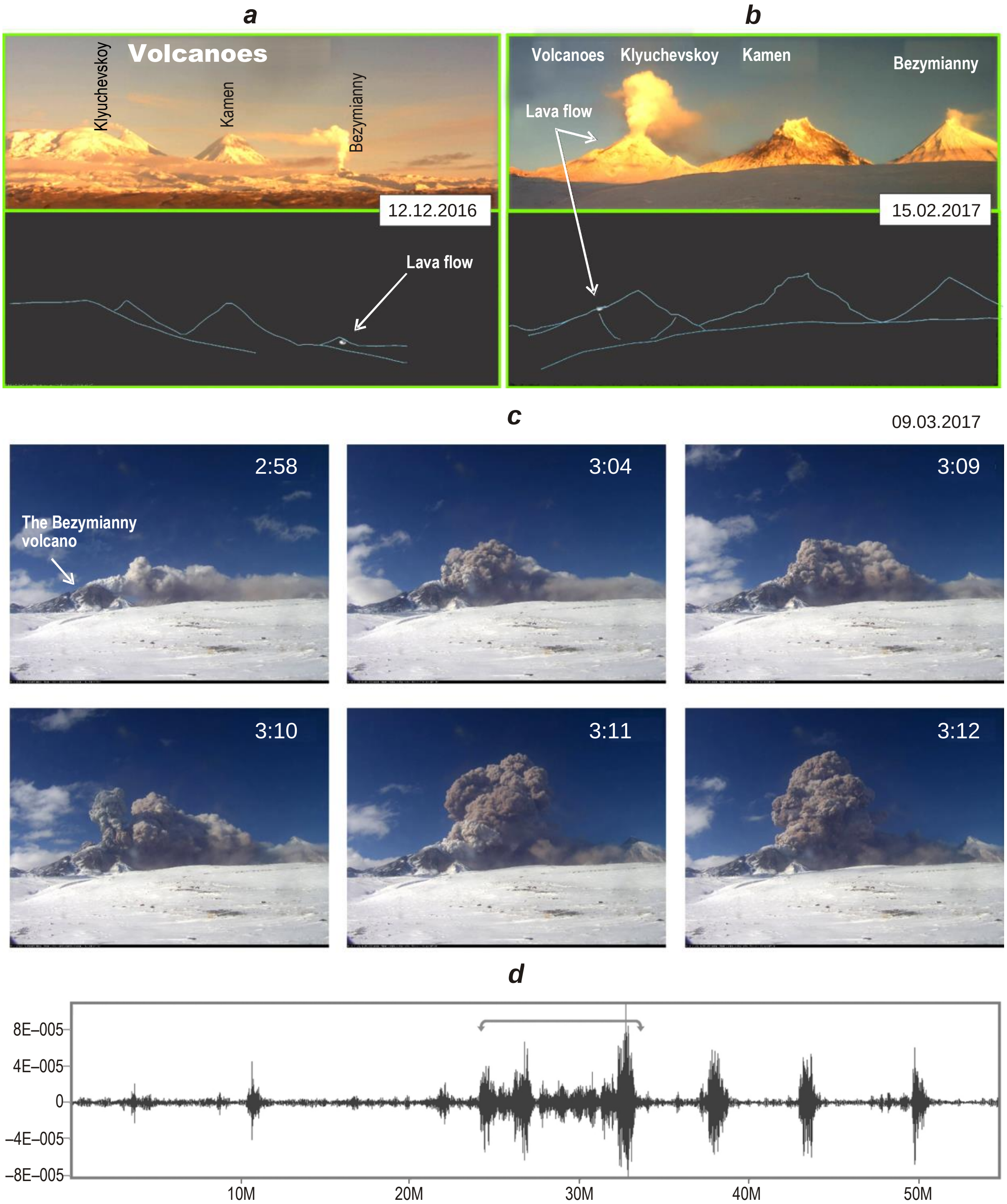

Fig. 2. Eruptions of the Bezymianny volcano in late 2016 – early 2017. (above) Day and (below) night photos of lava flows poured on the volcano's slope (*a*, view from the west) on 12.12.2016 and (*b*, view from the east) on 7–11.02.2017, (*c*) fragments of video filming on 09.03.2017 and (*d*) seismic record of explosive eruption on 09.03.2017. See comments in the text

The five strongest emissions with the rise of ash clouds to a height of up to 7-8 km occurred within about a half an hour that is clearly seen on the seismic record given in Fig. 2, *d*, where this time interval is indicated by a bracket. After the explosions, new portions of lava began to flow on the slope and an intense steam-gas activity continued. Then the Bezymianny volcano went into the state of moderate eruptive activity.

Three eruptions of the Bezymianny volcano that took place on 05–11.12.2016, 08–10.02.2017 and 09.03.2017 and correspond to a single period of its activation in November 2016 – March 2017, confirmed the efficiency of the developed method of the probabilistic forecast using the energy parameters of shallow-focus seismicity, localized within the radius of 6 km from the top of volcano.

The first experience of using the method of probabilistic forecast in real time proved to be successful – forecasts made on its basis and passed to KB REC were admitted as justified.

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