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FORMALIZED TECHNIQUE OF BEZYMIANNY VOLCANO (KAMCHATKA) ERUPTION FORECASTING BASED ON THE STATISTICAL ESTIMATION OF SEISMICITY LEVEL

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Abstract. The paper proposes a formalized technique of probabilistic forecast by applying statistical estimation of seismicity level and a number of additional functions that characterize the predictive situation. The possibilities of this method are illustrated by the example of seismic activation before the eruptions of Bezymianny Volcano (Klyuchevskaya group, Kamchatka).

The initial data is the catalog of earthquakes of the Klyuchevskaya group of volcanoes during 1999-2014, compiled by the Kamchatka Branch of the Geophysical Survey, RAS. During this time there were 21 eruptions of Bezymianny Volcano. The precursor is defined as a threshold function associated with the current seismicity level and its characteristic form before the eruption.

The values of parameters characterizing the precursor are given including validity, reliability and efficiency, calculated by two methods. It is shown that the reliability of the precursor decreases with the increase in threshold values, and its validity increases.

The reliability of the method is 0.38–0.95, i.e., from 38 % to 95 % of eruptions had the precursor depending on the threshold level; and the validity is 0.3–0.6, i.e., from 30 % to 60 % of the identified precursors are realized also depending on the threshold level. Values of efficiency confirm the non-random nature of the precursor appearance.

The method includes determination of the probability of the forecast realization. The nomogram for probabilities depending on the duration of the forecast and the values of the prognostic parameter is designed.

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

Introduction

One of the most dangerous volcanic sites of the Russia is Bezymianny volcano from the Klyuchevskaya group of Kamchatka volcanos (Fig. 1, *a*). This volcano is famous for its catastrophic eruption in 1955-1956 culminated with the directed blast on 30.03.1956 that destroyed part of the volcano structure. Besides giant eruptive clouds rose to the height of 35-40 km (see, for example, [*Bogoyavlenskaya and, Kirsanov*, 1981; *Bogoyavlenskaya et al.*, 1991; *Malyshev*, 1997; *Belousov, Voight, and Belousova*, 2007] and others).

From 1977 to 2012, one-two short but strong explosive-effusive eruptions occurred at Bezymianny volcano every year [*Malyshev*, 2000; *Thelen, West, Senyukov,* 2010; *Girina*, 2013; *West*, 2013]. Such eruptions pose a significant danger to the aviation because the height of ash emission reaches 10-15 km and the length of ash trails can be several hundreds of kilometers. From September 2012 to February 2016, Bezymianny volcano displayed steam-gas and fumarolic activity. The pressing of the viscous lava dome that started after the explosion of 1956 continues. By analogy with previous activation periods and estimates of their duration, it is assumed that the modern eruptive cycle of Bezymianny volcano will last at least another 100-200 years [Bogoyavlenskaya and Girina*,* 2006].

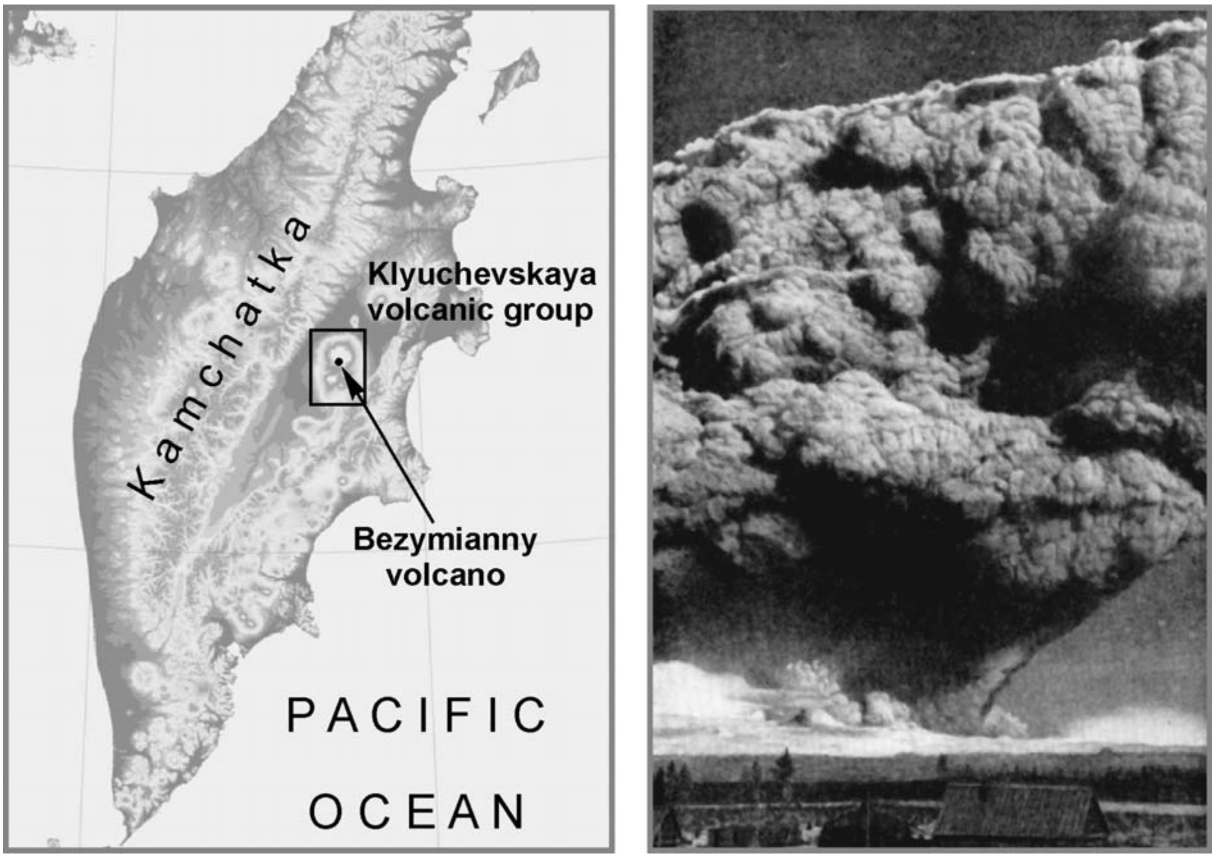


Fig. 1. (*a*) Bezymianny volcano on the Kamchatka peninsula and (*b*) photo of its catastrophic eruption on 30.03.1956 followed by the formation of eruptive cloud 35–40 km high. The author of the photo is I.V. Erov

The most reliable source of information to identify the potentially precursor situation for the volcano is seismicity. Seismicity recorded at Bezymianny volcano is of sporadic character, which is connected with eruptions and their preparations, and is represented by quite weak ($4.0 \le K_S \le 8.8$) shallow ($H<10$ km) seismic events. The network of seismological observations of the Kamchatka Branch of Geophysical Survey of RAS [*Chebrov et al.*, 2013] provides the continuous data on the volcano seismicity that are available for the analysis in real time and do not depend on the possibility of visual observations, weather conditions, atmosphere transparency, satellite availability, etc.

Taking into account the danger of volcano for the aviation and estimated duration of the current cycle of its eruptive activity, the development of forecast methods for Bezymianny volcano eruptions is an urgent problem. Note that presently there is a significant experience in identifying different precursors of eruptions of this volcano and several successful forecasts of its eruptive activity (see, for example, [*Girina*, 2012; *Ivanov*, 2013; *Senyukov,* 2013; *West*, 2013] and others). However, in accordance with modern requirements to the forecast, the method of precursor detecting must be formalized and prognostic parameters should include the precursor effectiveness that allows estimating the probability of the forecast realization.

The paper proposes the formal technique of the probabilistic forecast based on statistical estimation of seismicity level SESL’09 [*Saltykov,* 2011] and a number of auxiliary functions characterizing the precursor situation. The possibilities of the method are illustrated on the example of seismic activations before Bezymianny volcano eruptions (Klyuchevskaya group of volcanoes, Kamchatka) in 1999-2014.

Initial data

The seismicity is traditionally characterized with earthquake catalogues. However, detection of any variations in seismicity requires the choice of the parameter that, on the one hand, characterizes it and, on the other hand, is sensitive to its changes in the energy and time ranges considered in the analysis. In recent years for these purposes, Kamchatka Branch of GS RAS applies the scale of seismic level SESL'09. Its basic parameter is the statistical distribution function, denoted by F, of seismic energy released in a given space-time interval.

The state of seismicity is described by five basic qualitative levels: extremely high, high, background, low, and extremely low. With such ranking, seismicity refers to the background level (F=0.025–0.975) for 95 % of time, the high (F=0.975–0.995) and low (F=0.005–0.025) levels cover each 2 % of time, and the extremely high (F=0.995–1.0) and extremely low (F=0.0–0.005) levels, 0.5 %. To increase the estimation accuracy, the background level is divided into three sublevels: higher background (F=0.85–0.975), intermediate background (F=0.15–0.85), and lower background (F=0.025–0.15). Currently, the SESL'09 method is implemented and is applied in the Kamchatka Branch of GS RAS for monitoring the Kamchatka seismically active zone and its subzones, as well as for annual estimation of seismic level in Russian regions and volcanic areas, in particular, volcanoes of Klyuchevskaya group. Software implementation of the method [*Voropaev, Saltykov*, 2013] significantly increases the efficiency of its application in the studies indicated.

The study exploits the earthquake catalogue of Klyuchevskaya group of volcanoes for 1999-2014 compiled from the data of radiotelemetric seismic stations of the Kamchatka regional network located in the vivinity of this volcanic structure. The catalogue contains data on basic parameters of local tectonic and volcano-tectonic earthquakes with focal depths up to 40 km.

To estimate the seismic level, earthquakes recorded within 6 km from the peak of Bezymianny volcano were selected from the catalogue. Note that sources of almost 98 % of seismic events are concentrated in the depth range up to 5 km. The data set analyzed includes 1226 earthquakes with the maximum class K_S=8.8; the level of reliable registration is K_S=4.0 in accordance with the energy classification of S.A. Fedotov [1972].

Activation of seismicity before eruptions in SESL'09 parameters

To estimate the seismicity state of the region investigated, empirical distribution functions of seismic energy released were constructed in time windows of 5, 7, 15, 30, and 90 days (Fig. 2). Time intervals when the seismic monitoring of Bezymianny volcano was impossible due to the strong volcanic tremor during Klyuchevskoy volcano activations, as well as periods of data missing due to technical reasons were excluded from the analysis of the distribution functions F constructed.

Low, extremely low, and lower background levels of seismicity are not statistically defined for the studied data set.

Intermediate background level can be reasonably considered in time windows longer than 5 days. These constraints of statistical estimates are related with the long time intervals without recorded earthquakes of representative class. Such approach formalizes the concept of "seismic background" for Bezymianny volcano (Table 1). It should be noted that the absence of earthquakes (E = 0 J) at the level of representative class is also a background level for seismicity of Bezymianny volcano.

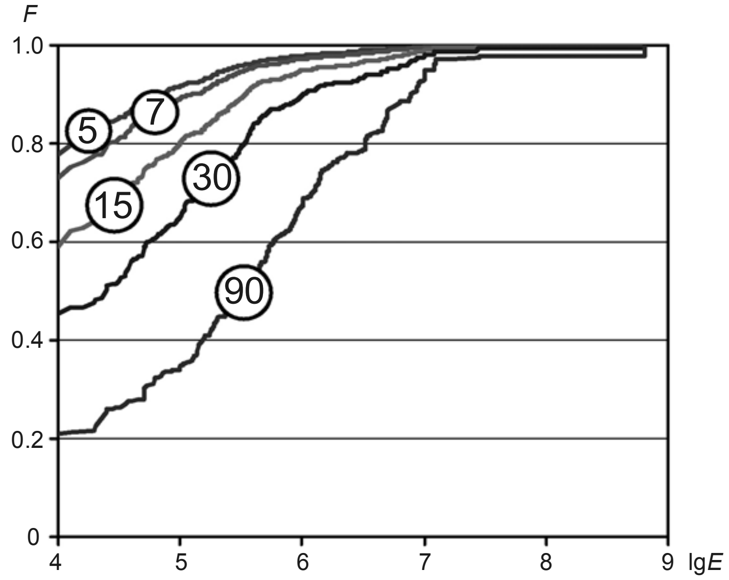


Fig. 2. Distribution functions of seismic energy in time windows of 5, 7, 15, 30, and 90 days for Bezymianny volcano. Window duration is indicated in the circles.

Table 1. Parameters of seismic background for Bezymianny volcano in different time windows

Seismic level	Lg*E*	
	5 days window	30 days window
Background	≤ 5.9	≤ 7.0
Intermediate background	≤ 4.5	≤ 5.7

On the one hand, it is preferable to use short time window to calculate the forecast, which provides the best time reference of the parameter. On the other hand, as it was already mentioned, time windows with the length shorter than 5 days are unacceptable for the studied object and the method used. Therefore, the time variations in seismic level were calculated in the time window of 5 days with the step of 1 day thus simulating the daily monitoring of seismic state.

Twenty one eruptions of Bezymianny volcano occurred in 1999-2014 (Table 2). In two cases (11.05.2007 and 31.05.2010), the seismic monitoring was complicated due to the high level of volcanic tremor associated with the activity of Klyuchevskoy volcano located at a distance of 10 km. So, the catalogue suitable for the statistical analysis contains only 19 eruptions.

Some cells in Table 2 give Δt=0, which means that *U* reaches the threshold level directly on the day of eruption, i.e. it is formally not a precursor and cannot be used in forecasting. The eruption of 31.05.2010, highlighted in gray in Table 2, occurred in conditions of strong volcanic tremor of Klyuchevskoy volcano located at a short distance that made impossible the standard processing of local earthquakes. In frames of forecasting, precursor undetected by such reason should be regarded as "target miss".

Kugaenko and Voropaev [2015] revealed statistically significant changes in seismicity before the majority of Bezymianny volcano eruptions in 2000-2014: from intermediate background level to the higher background, and then to the high (extremely high). Seismic level display no confident variations before only three eruptions (14.10.2007, 13.04.2011, and 08.03.2012) among 19 eruptions considered. Based on the seismic level data for all 19

Table 2. Days before the precursor appearance before eruptions of
Bezymianny volcano in 1999–2014.

№	Date of eruption	Days Δt before the function-indicator U reaches the given level u, days					
		u=1.0	u=1.2	u=1.4	u=1.6	u=1.8	u=2.0
1	24.02.1999	7	5	3			
2	13.03.2000	28	25	24	22	21	19
3	30.10.2000	12	10	8	5	1	
4	06.08.2001	18	15	12	9	6	3
5	15.12.2001	23	18	13	5	2	0
6	25.12.2002	15	9	7	0		
7	26.07.2003	12	3	2	0	0	
8	13.01.2004	4	3	2	1	0	
9	18.06.2004	8	6	4	2	1	1
10	11.01.2005	17	14	12	10	9	7
11	30.11.2005	12	8	6	5	3	1
12	09.05.2006	31	28	26	21	8	6
13	24.12.2006	29	28	26	4	1	
14	11.05.2007	17					
15	14.10.2007	9	0				
16	19.08.2008	41	38	35	11		
17	16.12.2009	14	8	6	5	4	2
18	31.05.2010	Absence of precursor in conditions of strong tremor					
19	13.04.2011	16	4				
20	08.03.2012	10	3				
21	01.09.2012	18	15	8	5	3	2
Average		17	13	12	7	5	5
Standard deviation		±9	±11	±10	±7	±6	±6
Median		16	9	8	5	3	2

eruptions that occurred in 1999-2014 (n=19), the average level SS in time neighborhood of the eruption beginning was calculated according to the formula

$$SS(\Delta t)=\sum_{i=1}^{n} S(t_0^i+\Delta t)/n\,,$$

where Δt is a time relative to the beginning of the i-th eruption t_0^i. The behavior of seismicity level is illustrated in Fig.3.

Function S (…) in the expression above corresponds to the distribution function F recalculated into the linear scale relative to the SESL’09 scale:

$F=0.5$, $S=0$
$F=0.85$, $S=1$ – boundary between the intermediate background and the higher background levels;
$F=0.975$, $S=2$ – boundary between the higher background and the high levels;
$F=0.995$, $S=3$ – boundary between the high and the extremely high levels;
$F=1$, $S=4$.

In the context of the problem solved, formulated as an eruption forecast and precursor determination, the part of SS function that is of interest is limited on the left by $\Delta t=-16$ days (time when SS changes from the intermediate background level to the higher background) and on the right, by $\Delta t=-2$ days (obvious requirement $\Delta t\le -1$ day associated with minimum timeliness of the forecast is worsened by delay of 1 day in the processing of current earthquakes and compilation of the catalogue).

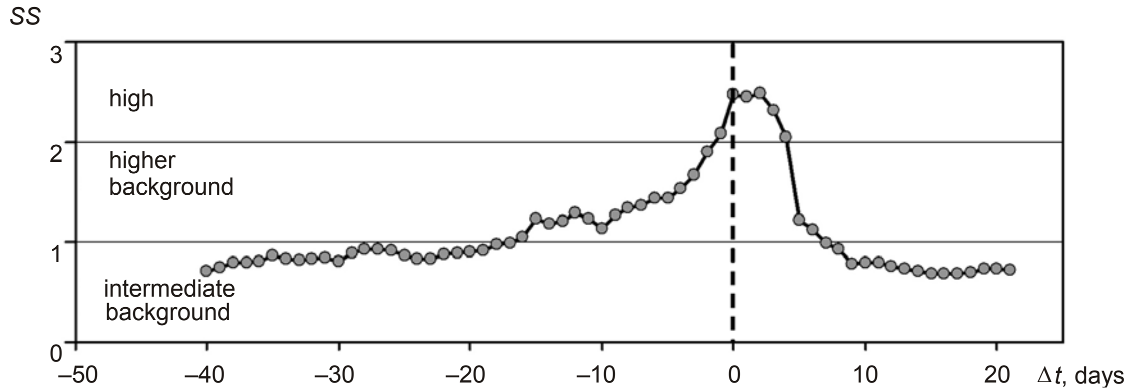


Fig. 3. Behavior of seismic level *SS*(*t*) in the time neighborhood of eruption (Δt=0 is the eruption time). See explanations in the text.

The part of *SS* function in the range $\Delta t = -16\ldots-2$ days was approximated by hyperbola S_{hyp}, which is supposed to be considered as a standard behavior of seismic level before eruption (Fig. 4). The current *S* values should be compared with this behavior to identify the time intervals of eruption preparation.

The comparison involves the following function- indicator

$$U(t) = \frac{1}{15}\sum_{k=-16}^{-2} S(t+k+2)SS(k)$$

that smoothes the seismic level *S*(*t*) in the moving time window 15 days long with the use of the weight function *SS*(Δt). This smoothing procedure is similar to the calculation of correlation, but unlike it is carried out without preliminary centering of *S* and *SS* series. Such transformation allows to obtain *U* series that in certain sense characterize the similarity of behaviors of seismic level *S* and supposed precursor *SS*. Note that such representation allows to conclude the precursor increasing of *U* before the eruptions in 2000-2014 including the ones of 14.10.2007, 13.04.2011, and 08.03.2012 (Fig.5), before which the increase of seismic level itself was not obvious [*Kugaenko and Voropaev*, 2015].

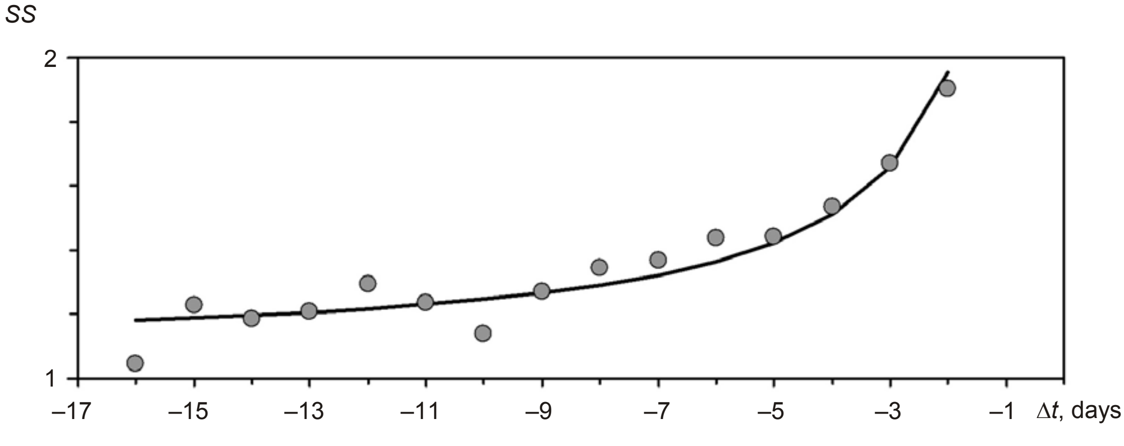


Fig. 4. The part of the plot in Fig.3 accepted as an averaged precursor of Bezymianny volcano eruption. Solid line is a hyperbola approximating data under consideration.

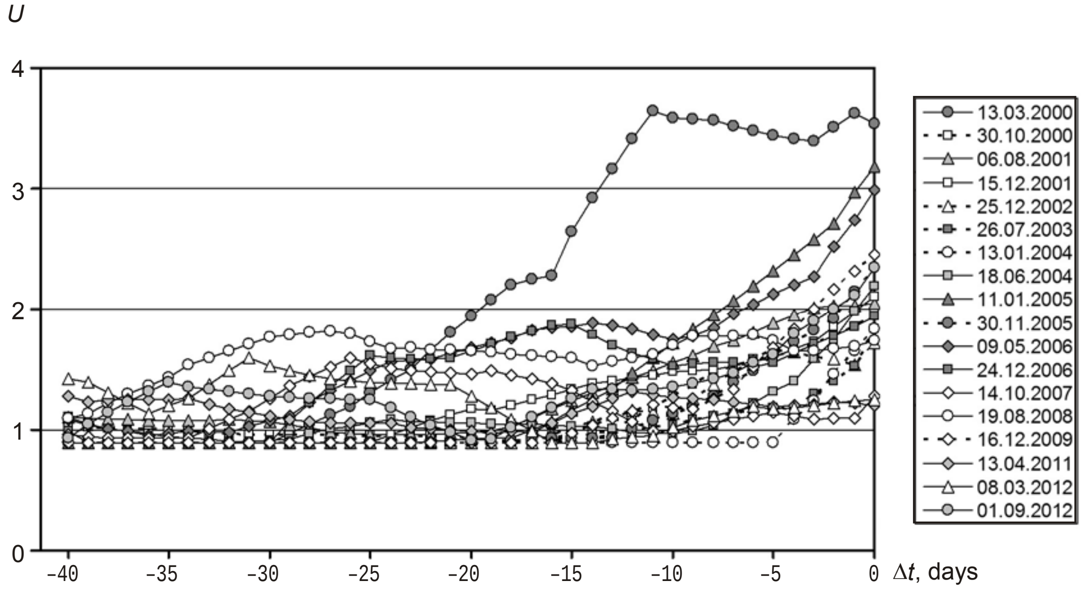


Fig. 5. Examples of time variations of the function-indicator *U* before Bezymianny volcano eruptions that occurred in 2000-2014.

For practical application of the technique proposed for forecasting the volcano eruptions it is necessary to answer the following key questions.

1. What is the criterion for alarm (forecast report)?
2. What is the criterion for alarm cancellation?
3. What is the probability of forecast realization?
4. What is the probability of missing the eruption?
5. What is the validity, reliability, and efficiency of the precursor proposed?

It is proposed to use the threshold criterion: the situation is regarded as precursor if the value of the function-indicator U exceeds the certain threshold value u (further u_{thr}). Taking into account the behavior of function U (Fig. 5), the set of threshold values u_i from 1 to 2 with the step 0.1 is considered below. The preliminary processing involves the determination of time intervals during 1999-2014 where $U \geq u_i$. These intervals form the alarm time T_{alarm}. Three variants of mutual spacing of eruption and alarm interval are possible.

1. If the eruption occurs within the interval where $U \geq u_i$, it is considered that it has a precursor. An important point here is the cancellation of alarm due to the occurred eruption, i.e. the time interval directly after the eruption is excluded from the alarm time, even if $U \geq u_i$.

2. If before the eruption that occurred $U < u_i$, the situation is qualified as “target miss”, i.e. the eruption does not have the precursor that can be identified using the technique proposed and cannot be predicted.

3. The alarm interval is regarded as “false alarm”, if the eruption didn’t occur in this interval.

These variants are considered on the example of two eruptions of Bezymianny volcano (Fig.6).

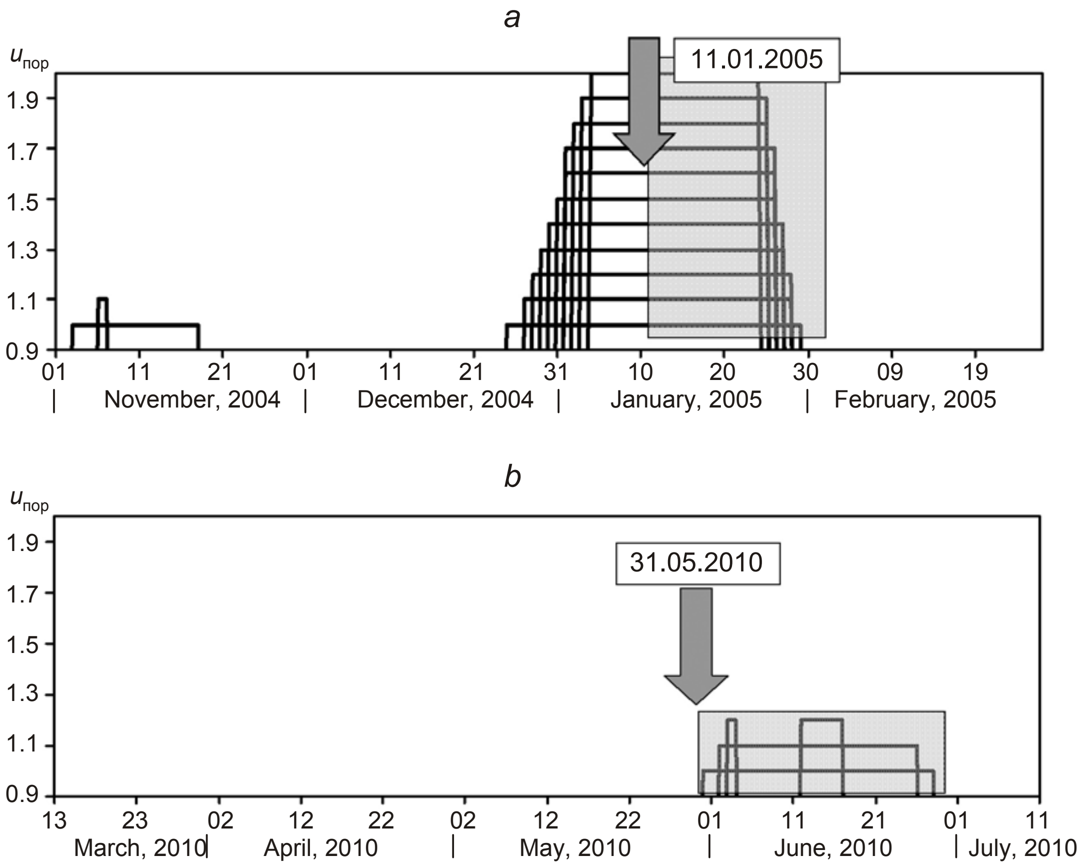


Fig. 6. Schematic representation of behavior of the function-indicator U in the eruption vicinity on the example of Bezymianny volcano eruptions: 11.01.2005 and 31.05.2010. The cases of the realized forecast (11.01.2005), false alarm (3–17.11.2004), and target miss (31.05.2010) are shown. Explanations see in the text.

White rectangles in Fig.6 represent the time intervals where the indicator function U exceeds the given values of u_{thr}; the height of each rectangle corresponds to the value of u_{thr} used. Gray rectangle indicates the cancellation of alarm after the eruption.

Data on times (Δt) before the precursor appearance for all eruptions of Bezymianny volcano in 1999-2014 depending on the values of the used u_{thr} are given in the above Table 2. Table 3 gives the data on the total duration of alarm, number of realized forecasts, and other parameters calculated using the forecast technique. Total monitoring time covering the period from 1.01.1999 to 4.10.2014 is T=5755 days; total number of eruptions during this period is N=21. Alarm time T_{alarm} for each anomaly (exceeding of threshold u_{thr} by the value U) was calculated as time interval between the alarm signal (beginning of the anomaly) and moment of eruption (for the realized precursor) or alarm cancellation (end of anomaly).

Estimation of predictive properties of the precursor

Reliability of the precursor is determined as a ratio of number of eruptions for which the precursor was distinguished (number of successful forecasts N_+) to the number of all eruptions N:

$$R = \frac{N_+}{N} .$$

Table 3. Parameters of forecast technique

Threshold U_{thr}	Alarm time T_{alarm}, d	Number of successful forecasts N_+	Precursor reliability R	Precursor validity V	Efficiency by Gusev J_G±σ	Efficiency by Molchan J_M
1.0	1764	20	0.95	0.32	3.1±0.7	0.65
1.1	992	18	0.86	0.30	5.0±1.2	0.68
1.2	778	18	0.86	0.33	6.3±1.5	0.72
1.3	548	16	0.76	0.34	8±2	0.67
1.4	405	16	0.76	0.44	11±3	0.69
1.5	304	16	0.76	0.59	14±4	0.71
1.6	228	13	0.62	0.48	16±4	0.58
1.7	169	11	0.52	0.42	18±5	0.49
1.8	112	11	0.52	0.55	27±8	0.50
1.9	79	9	0.43	0.60	31±10	0.41
2.0	58	8	0.38	0.58	38±12	0.37

Note. Values of ±σ given for the efficiency by Gusev correspond to standard deviation.

The dependence of reliability R on the threshold u was obtained changing the values of u_{thr} used for precursor identifying and calculating the corresponding values N_+ for it (Table 3, Fig.7, *a*). According to the calculations, the reliability of precursor for low u_{thr} values is considerably bigger than for higher values. This means that before the majority of eruptions (95%), the series of U exceeds the threshold value equal to 1.0, however, the exceeding of higher thresholds becomes rarer with their increase that inevitably leads to the increase in number of target misses. On the average, only before one out of three eruptions U reaches the anomalous value 2.0.

Validity of precursor V (Fig. 7, *b*) is defined as ratio of number of precursor anomalies $N(A_E)$ (in our case, a number of excesses of value u_{thr} by U accompanied by eruption) to the total number of selected anomalies $N(A)$:

$$V = \frac{N(A_E)}{N(A)}.$$

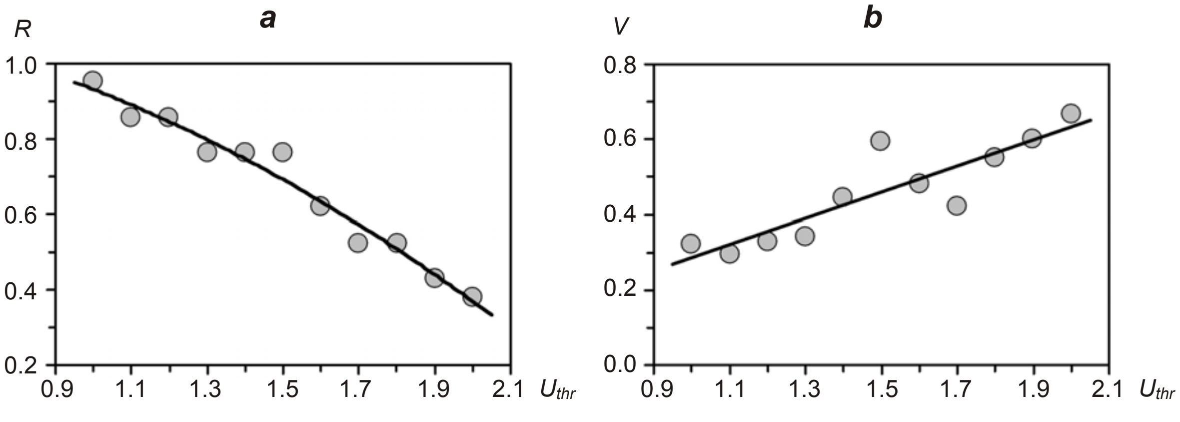


Fig. 7. Dependence of (*a*) reliability and (*b*) validity of the precursor on the value of u_{thr}. Solid lines indicate the general tendency in parameter behavior with the change of threshold value.

According to Table 3 and Fig.7, *b*, two thirds of the most pronounced anomalies (with exceeding the threshold 2.0 by *U*) end with eruption and can be considered as the realized precursor. The validity decreases with the threshold decrease, and, on average, only every third anomaly ends with eruption with the threshold of u=1.0.

To estimate the effectiveness of the precursor considered two approaches were used: approach by A.A. Gusev [1974] and approach by G.M. Molchan [1990] that use the same input data but in different combinations (Fig. 8). Since the choice of combinations is determined by the author's view on the problem solved, they should be regarded independently, without comparing among themselves.

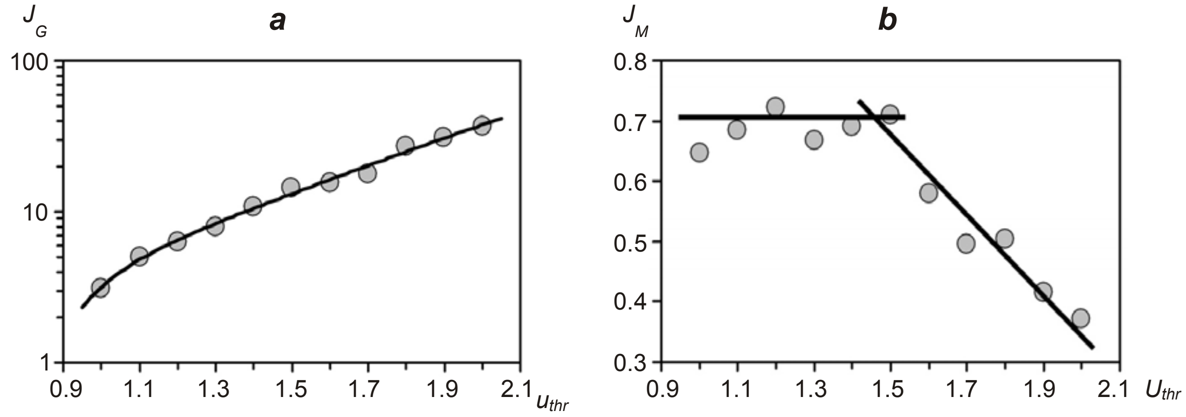


Fig. 8. Dependence of the precursor efficiency calculated using the method (*a*) by A.A. Gusev and (*b*) by G.M. Molchan on the value of u_{thr}. Solid line shows the tendency in behavior of precursor efficiency with the change in u_{thr}

Determination of the precursor efficiency using the method by A.A. Gusev. Efficiency of the regarded method of the precursor detection of eruption J_G is defined for each specific threshold value u according to the formula

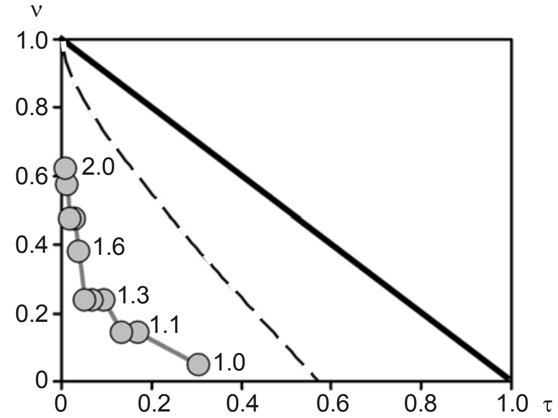
$$J_G = \frac{N_+}{N \cdot \frac{T_{alarm}}{T}} \quad ,$$

where T is the total monitoring time of seismic situation; N_+ is the number of eruptions corresponding to the successful forecast during time T; N is the total number of eruptions during time T; T_{alarm} is a total alarm time (the total duration of all time intervals with the forecast acting according to the method during the total monitoring time). The denominator reflects the average number of eruptions during T_{alarm} in the absence of connection between forecasts and eruptions. Correspondingly, efficiency J_G indicates how much the number of predicted eruptions exceeds the number of eruptions that got in "alarm" time randomly. At random guessing the efficiency J_G is equal to 1.

For the data analyzed, the efficiency J_G changes substantially, by an order, for u_{thr} changes from 1.0 to 2.0 (Fig. 8, *a*, Table 3).

Determination of the precursor efficiency using the method by G.M. Molchan. Figure 9 shows Molchan diagrams for different values of u_{thr}. The abscissa of the point on the diagram is defined as the measure of alarm τ: $\tau = \frac{T_{alarm}}{T}$, and the ordinate, as the part of target misses ν: $\nu = 1 - \frac{N_+}{N}$. The diagram diagonal $\tau + \nu = 1$ connects the points (0; 1) (point of "optimist")

Fig. 9. Molchan diagram for different values of u_{thr}. Explanations see in the text



and (1; 0) (point of "pessimist") and corresponds to the "random" forecast. For this diagonal, the confidence interval can be constructed with the given significance α. In our case, only the lower boundary of this interval, marked by the dashed line (α=0.01) in Fig.9, is of interest.

As seen from Fig.9, the experimental points (τ,ν) lie below the boundary with α=0.01 for all cases that can be interpreted as a high degree of reliability of relation revealed between anomalies (exceeding of the threshold value of *u* by *U*) and eruptions.

The effectiveness of precursor J_M is defined as $J_M = 1 - \nu - \tau$. For "random" forecast J_M=0, and for ideal forecast (without target miss and zero alarm time) – J_M=1. For the values of u_{thr} considered, the efficiency values are given in Table 3 and in Fig.8, *b*. As seen, the efficiency doesn't change significantly for u_{thr} values in the range 1.0-1.5. But with the further increase of u_{thr} up to 2.0, it reduces by half, however, remaining statistically highly significant.

Estimation of probability of precursor realization. To estimate the forecast probability the following algorithm is proposed.

1. Taking into account the Poisson character of eruption distribution the probability of at least one eruption during the given time *t* is estimated by:

$$p(n > 0) = 1 - e^{-\lambda t},$$

where λ is the intensity of the Poisson process. The correspondence of eruption distribution to the Poisson distribution was checked preliminary. All the data in study were verified for the exponential distribution of time intervals between earthquakes, which confirmed that the hypothesis of the Poisson distribution of eruptions could not be excluded.

2. Involving the efficiency parameter J_G determined by the Gusev method (see above), the expected probability of occurrence of at least one eruption within time *t* after the precursor identification will be equal to

$$p_e(n > 0) = 1 - e^{-J_G \lambda t}.$$

The nomogram of probabilities of forecast realization by an earthquake for the precursor "Exceeding of the given threshold value *u* by *U* value" for different alarm times *t* and threshold values *u* is presented in Fig.10.

3. Taking into account that in retrospective analysis it was detected the eruption without the precursor considered (the term "target miss" is used in such cases), the eruption probability can be estimated in the absence of precursor. It is proposed to use the Poisson distribution based on the fact that during the known time of seismic monitoring, the known

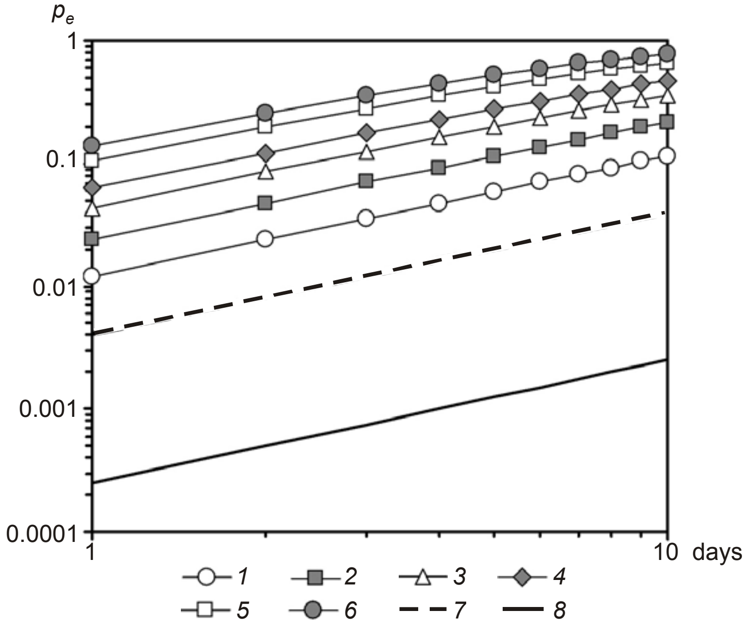


Fig. 10. Nomogram of probabilities of forecast realization p_e depending on the alarm duration t at different values of u_{thr} : *1* - 1.0;
2 - 1.2;
3 - 1.4;
4 - 1.6;
5 - 1.8;
6 - 2.0.
The average long-term eruption probability (*7*) and the probability of eruption in the absence of precursor (*8*) are shown for comparison.

number of eruptions occurred in the absence of precursor (in our case, one eruption approximately in 4000 days). As seen from Fig. 10, the probability of eruption in the absence of precursor is naturally significantly lower than the average long-term probability of eruption occurrence, not to mention the comparison with eruption probability in the presence of precursor.

Characteristics of the forecast technique

This section gives the characteristics of the forecasting technique developed in terms of general prognostics [Prognostica…, 1978]. The method is searching and is aimed at defining possible event location (Bezymianny volcano eruption) in the future. The developed forecast is considered as probabilistic. The object of forecasting is Bezymianny volcano eruption. The forecasting exploits the method of extrapolation, the extension of identified regularities in the forecast object development for the future in assumption that the identified regularity, being the base for forecasting, is preserved in the future.

1. *Precursor*: exceeding by the value of *U* series, calculated from data on the level of seismicity of Bezymianny volcano (within a radius of 6 km from the top) using the SESL'09scale, of a certain threshold value *u* in the absence of the eruption. Continuing during the eruption, excess of *U* over *u* is not a precursor.
2. *Alarm time* (forecast report): moment of the precursor detection.
3. *Parameters of expected event*: Bezymianny volcano eruptions are forecasted.
4. *Forecast anticipation* (period of time, for which forecast is developed): the forecast is given initially for 2 weeks with a possible extension.
5. *Alarm cancellation in the absence of expected eruption* (false alarm): the decrease of the current value of *U* below the threshold value *u*.
6. *Successful (self-fulfilling) forecast*: Bezymianny volcano eruption during the time interval identified as alarm.
7. *Cancellation of alarm after self-fulfilling forecast*: the occurred eruption cancels the alarm state (removes the forecast before time) regardless of seismic level.

8. *Eruption probability*: the forecast is probabilistic and is determined by nomogram in terms of presence/absence of precursor.

Conclusions

In the framework of developing the technology of short-term forecast of natural disasters and on the basis of retrospective analysis of earthquake registration results in 1999-2014 in vicinity of Bezymianny volcano, the predictive method was developed. It is based on monitoring of the calculated parameter *U* associated with seismic level values on the SESL'09 scale.

The formalized eruption precursor was proposed; the procedure of alarm state cancellation was formalized.

The technique includes the estimation of the probability parameter of forecast realization. The nomogram of probability was created depending on the forecast time and value of prognostic parameter.

On the basis of data on seismicity of Bezymianny volcano in 1999-2014 the reliability and validity of the precursor were estimated. It is shown that with the increase of threshold values, the precursor reliability reduces and the validity increases. In eruption forecasting, the reliability is 0.38–0.95, i.e. from 38 % to 95 % of eruptions depending on the given threshold value have the precursor, and the validity is 0.3–0.6, i.e. from 30 % to 60 % of identified precursors were implemented also depending on the used threshold.

The estimation of precursor efficiency was performed in two ways. It is shown that the results of applying the forecast technique statistically significantly differ from random guessing and give the benefit in 3-30 times comparing to it. Presented estimates are obtained according to the data of earthquake catalogue of Kamchatka Branch of Geophysical Survey of RAS from 1999 to 2014; during this time 21 eruptions of Bezymianny volcano occurred.

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