# MONITORING OF THE KLUCHEVSKAYA VOLCANIC GROUP USING TECHNICS OF STATISTICAL ESTIMATE OF SEISMICITY LEVEL (SESL'09)

**Voropaev[1], P., Saltykov[1], V., Kugaenko[1], Yu.**
[1]*Kamchatkan Branch of Geophysical Survey of RAS, Petropavlovsk-Kamchatsky, Russia*

We study the seismicity of Kluchevskaya Volcanic Group (KVG) using the method of Statistical Estimate of Seismicity Level (SESL'09) (Saltykov, 2011). Monitoring is carried out for 8 seismically active areas, including volcanoes Klyuchevskoy, Bezymianny, Tolbachik, Udina, Zimina (Fig. 1). For each seismically active region, with a given periodicity, the distribution functions of the seismic energy released in different time windows are calculated for construction of the SESL'09 nomograms. Then, the current level of seismicity is determined.

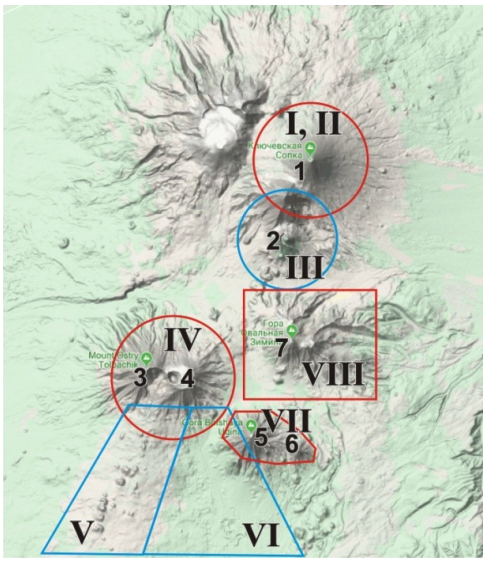


*Fig. 1. KVG Seismically active areas in which seismicity is monitored by the method (SESL'09).*
*Volcanoes:*
*1- Klyuchevskoy;*
*2 - Bezymianny;*
*3 - Ostry Tolbachik;*
*4 - Plosky Tolbachik;*
*5 - Bolshaya Udina;*
*6 - Malaya Udina;*
*7 - Zimina volcanic massif.*
*Monitored areas:*
*I, II - shallow and intermediate magma chamber of the Klyuchevskoy volcano (cylinder with a radius R = 7 km from the top of the volcano);*
*III - Bezymianny volcano (cylinder, R = 6 km);*
*IV - Tolbachik volcano (cylinder, R = 8 km);*
*V - Tolbachinsky dol (polygon);*
*VI - Tolud zone (polygon);*
*VII - Udina volcano (polygon);*
*VIII - Zimina volcano (polygon).*

**Data sets**

We use the 2000-2017 catalog of the KVG, obtained from the data of the Kamchatka regional network. The catalog contains information about the main parameters of local tectonic and volcanic-tectonic earthquakes up to a depth of 40 km. For each studied region (*I-VIII*) the earthquake catalog is analyzed. Main parameters of data sets for regions (*I-VIII*) are presented in Table 1.

Table 1. Parameters of studied data sets (01.01.2000 - 31.12.2017).

| Seismically active areas | *Kc* | *N* | *Nc* | lg *E* (*J*) | *Kmax.* | *Year* |
|---|---|---|---|---|---|---|
| Shallow magmatic chamber of the Klyuchevskoy volcano, I | 4.5 | 19 602 | 10 813 | 9.83 | 7.9 | 2012 |
| Intermediate magmatic chamber of the Klyuchevskoy volcano. II | 5.0 | 46 421 | 11 746 | 9.57 | 7.9 | 2012 |
| Bezymianny volcano. III | 4.0 | 3797 | 1485 | 8.93 | 8.8 | 2013 |
| Tolbachik volcano. IV | 4.5 | 1356 | 442 | 9.7 | 9.4 | 2013 |
| Tolbachinsky dol. V | 5.0 | 382 | 123 | 9.2 | 8.7 | 2013 |
| Tolud zone. VI | 5.0 | 1640 | 497 | 11.4 | 11.3 | 2013 |
| Udina volcano. VII | 4.2 | 171 | 84 | 7.4 | 6.6 | 2017 |
| Zimina volcano. VIII | 5.0 | 325 | 117 | 8.9 | 8.9 | 2013 |

*Kc* – completeness class (magnitude); *N* - total number of earthquakes; *Nc* - number of earthquakes of completeness class; *E* is the total seismic energy; *Kmax* - the maximum class of earthquakes; *Year* - year of monitoring start.

**SESL'09 Method**

The SESL'09 method developed by Saltykov (2011) is designed to represent relative seismicity characteristics using the released seismic energy rate for arbitrary periods. The empirical distribution function of the total released seismic energy $E$: $F(K) = P(\log E \le K)$, where $P$ indicates the probability. The defined threshold values of the distribution function $F$ (0.005, 0.025, 0.15, 0.85, 0.975, 0.995) make a scale

that contains seven seismicity levels: *extremely high* $0.995 \le F$; *high* $0.975 \le F < 0.995$ *lower background* $0.025 < F \le 0.15$; *intermediate background* $0.15 < F < 0.85$; *higher background* $0.85 \le F < 0.975$; *low* $0.005 < F \le 0.025$; *extremely low* $F \le 0.005$. Comparing the energy over a certain time interval, using this scale, you can determine the level of seismicity.

**Examples of current monitoring**

*Bezymianny volcano (zone III)*. Analysis of the dynamics of the level of seismicity of the Bezymianny volcano before the eruptions of 1999-2012 revealed the characteristic features of seismic behavior, which have a predictive nature. A method for probabilistic forecasting of the eruptions of the Bezymianny volcano was developed on the basis of SESL'09 (Saltykov, 2016). Activity of the Bezymianny volcano resumed in 2016 after a long (since September 2012) absence of eruptions. The probabilistic forecasting was applied practically in 2017. Variations in the seismicity level of the Bezymianny volcano are present on fig. 2.

Forecasts of four episodes of Bezymianny activation in 2017 are recognized in the Kamchatka Branch of the Russian Expert Council on Earthquake Prediction (KB REC) as successful (table 2).

Table 2. Application of the methodology of the probabilistic forecasting in practice for the Bezymianny volcano

| Seismicity level | Assessment of probability* | Forecast date | Eruption date | Comments |
|---|---|---|---|---|
| Higher background | 210 | - | 05.12.2016 | Retrospective study |
| Higher background | 120 | 02.02.1017 | 11.02.2017 | Successful forecast |
| High | 120 | 06.03.2017 | 09.03.2017 | Successful forecast |
| Extremely high | 370 | 16.06.2017 | 16.06.2017 | Successful forecast |
| Extremely high | 370 | 18.12.2017 | 20.12.2017 | Successful forecast |

* The ratio of the probability of the Bezymianny volcano eruption with the presence of a precursor to the probability of an eruption without a precursor

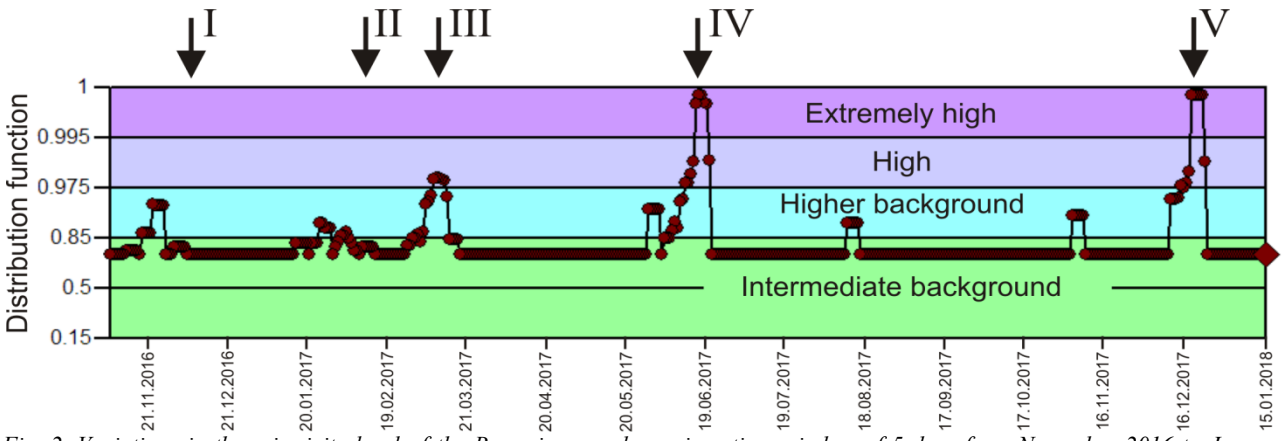


*Fig. 2. Variations in the seismicity level of the Bezymianny volcano in a time window of 5 days from November 2016 to January 2018. The arrows indicate the eruptions of the Bezymianny volcano: I – 05.12.2016; II – 11.02.2017; III – 09.03.2017; IV – 16.06.2017; V – 20.12.2017.*

*Udina volcano (zone VII)*. Volcanoes Bolshaya and Malaya Udina are extinct. From early 2000 to September 2017, weak seismic activity was recorded in this area. Since October 2017, seismic activization has been observed in the region of Udina. From 01.10.2017 to 28.02.2018, 250 earthquakes were recorded. The seismic energy released in this time interval was $4.45 \cdot 10^7$ J.

In October 2017, seismic growth was recorded with reaching a *high* level with the subsequent achievement of an *extremely high* level in November. At the end of February 2018, the seismicity in the Udina volcano region was *extremely high* at the time windows of 15, 30, 90 days (Fig. 3). At the time of writing, the seismic activity continues. Calculations of the level of seismicity for this zone are conducted daily.

Seismic activation on the Udina volcano is revealed. This activation has no analogues in the practice of seismological observations of this volcano: the level of seismicity lasts for ~ 5 months at a *high* - *extremely high* level (October 2017 - February 2018).

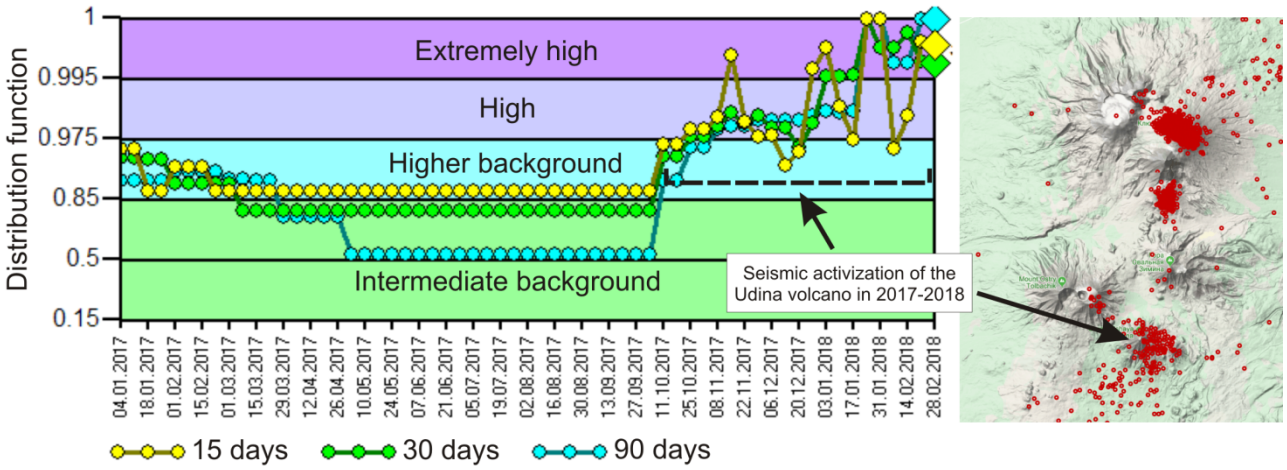


*Fig. 3. Variations of the seismic level of the Udina volcano region from January 2017 to February 2018 in the time windows of 15, 30, 90 days and KVG earthquakes epicenters of compliciteness class that occurred during a given time interval.*

*Tolbachik volcano (zone IV).* The seismic activation preceded the Fissure Tolbachinsky eruption 2012-2013. It was most manifested in August-November 2012. There was an increase in seismicity to a *high - extremely high* level (fig. 4). There has been a significant increase in the number of recorded earthquakes, the growth of their released energy and the acceleration of the seismic flow (Kugaenko et al., 2015).

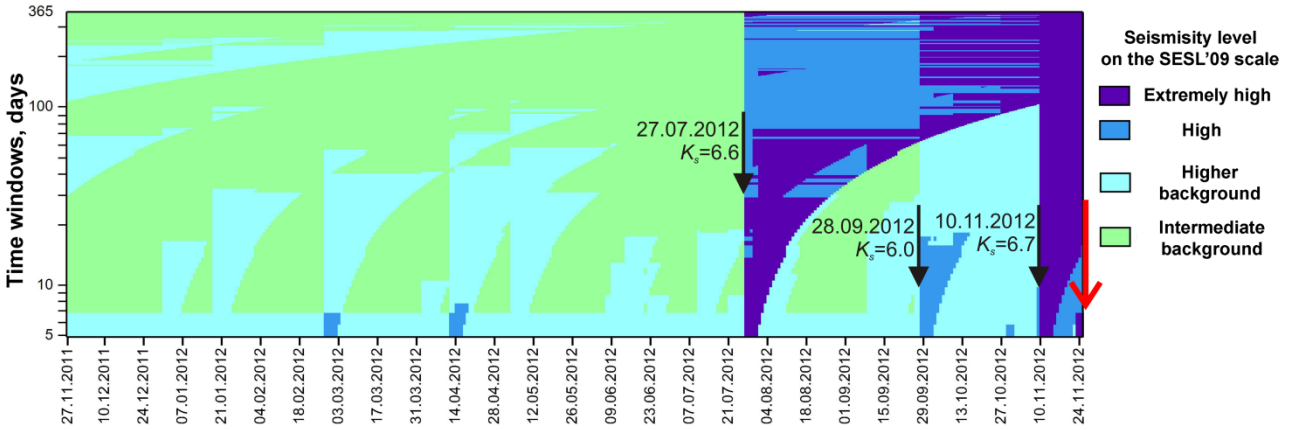


*Fig. 4. Seismicity levels on the SESL'09 scale of Tolbachik volcano from November 2011 to November 2012 in time windows 5-365 days. Black arrows show earthquakes that caused seismicity to a high and extremely high level. Red arrow indicates the beginning of the Fissure Tolbachinsky volcano eruption on November 27, 2012.*

## Conclusion

The level of seismicity of the volcanoes of the KVG is being monitored according to the method of SESL'09. The SESL'09 allows us to provide a statistically valid estimate of the current seismic situation. Results of seismic monitoring are sent weekly to the KB REC. Most important episodes in the 2016-2017 monitoring practice are paroxysmal eruptions of Bezymianny volcano and unusual seismic activization on the Udina volcanic massif.

## References

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