Estimation of Klyuchevskoy Volcano Activity in 2023 based on the SESL'09 technique

V. A. Saltykov[1] and *A. A.* Shakirova[1*]

[1]Kamchatka Branch of the Geophysical Survey of Russian Academy of Sciences, Piipa Street, 9, Petropavlovsk-Kamchatsky, 683006, Russia

Abstract. In October 2023, Klyuchevskoy volcano (Kamchatka, Russia) erupted, when the height of the ash column reached ~15 km. The eruption was preceded by seismic activity. The dynamics of seismicity in the four most seismically active volumes of the subsoil beneath Klyuchevskoy volcano in the depth range of 4 km above sea level and up to 34 km was analyzed using the "Statistical Estimate of Seismicity Level" methodology – SESL'09. The most pronounced increase in seismicity with an exit to high and extremely high levels was manifested at a depth of 5–8 km 1–3 months before the appearance of lava in the crater of the volcano. The precursor effect detected 1–3 months before the eruption was caused by the redistribution of stresses in the medium containing the feeding magmatic system, the pressure in which varies depending on the conditions of accumulation or supply of magma. After the culmination phase of the eruption, seismic activity at depths of more than 20 km reached an extremely high level. This may be related to the end of the eruption.

1 Introduction

Klyuchevskoy Volcano (Russia, Kamchatka Peninsula) is the highest active volcano in Eurasia, its absolute height changes during eruptions and is 4800 m ± 50 m above sea level (Figure 1). It belongs to the Northern Group of Volcanoes, consisting of 14 volcanoes (Figure 1d). This group is one of the most active volcanic groups in the world in the subduction zone. The age of Klyuchevskoy Volcano is ~ 7000 years, it is in the initial stage of its development. Under Klyuchevskoy Volcano, there is one of the most intense world sources of deep long-period earthquakes (DLPE), corresponding to the crust-mantle boundary at depths of 20-35 km [1, 2]. This is the only cluster of DLPEs in Kamchatka.

Klyuchevskoy Volcano has been in a state of almost continuous eruption since 2003. It is characterized by both eruptions in the summit crater (Figure 1c) and eruptions on the slopes. Sufficiently complete information on the eruptions of Klyuchevskoy Volcano has been available since 1920 [3]. However, it has not yet been possible to identify any time cycles of volcanic activity.

At present, the existing network of seismic stations of the Kamchatka Branch of the Geophysical Survey of Russian Academy of Sciences (KB GS RAS) (Figure 1d) allows for detailed seismic monitoring of Klyuchevskoy Volcano [4], localizing earthquakes in the

* Corresponding author: shaki@emsd.ru

area of the volcano with a minimum energy class Ks=1.8 [5]. Ks = lgE, where E is the earthquake energy (J) determined from S-wave) [6].

The paper considers one of the strongest eruptions of Klyuchevskoy Volcano, which occurred in 2023. The eruption was preceded and accompanied by high seismic activity with earthquake focal depths of up to 36 km. Glow was observed since June 22 in the crater of Klyuchevskoy Volcano (http://www.emsd.ru/~ssl/monitoring/main.htm), a lava began to flow from ~21–26 July. The peak of the culmination phase of the eruption was recorded on October 16 and October 28–November 1, when ash clouds rose to a height of 10–15 km.

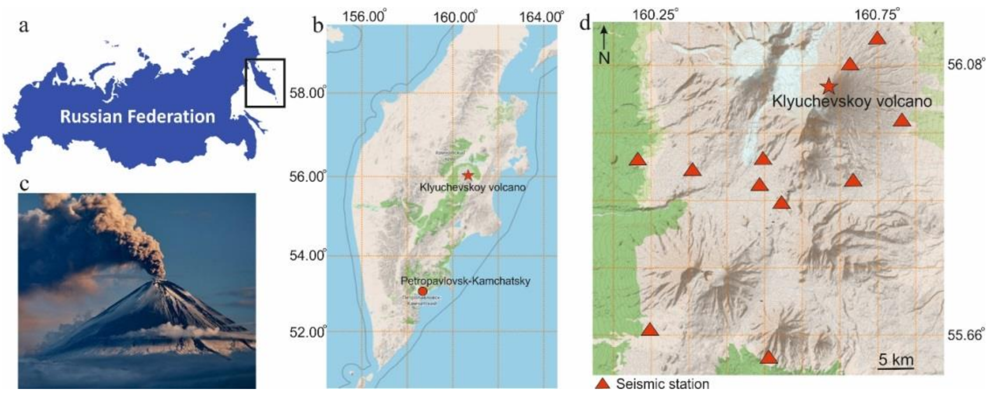

Fig. 1. The Kamchatka Peninsula on the map of the Russian Federation (a), the location of the Klyuchevskoy Volcano on the Kamchatka Peninsula (b) and its eruption (c) (photo by Nikolay Ushakov), seismic stations in the area of the Klyuchevskoy group of volcanoes.

The seismicity levels of the Klyuchevskoy Volcano area in 2023 are estimated in this paper. The levels are tied to the statistical distribution function of seismic energy, taking into account the statistical nature of the basic parameter, the method is called "Statistical Estimate of Seismicity Level" (SESL'09) [7]. Variations in seismicity levels in the four most seismically active volumes of the subsoil beneath the Klyuchevskoy volcano are compared with episodes of recorded volcanic activity.

2 Initial data and methodology

We use the earthquake catalog of the KB GS RAS in the Klyuchevskoy Volcano area for 2023. The features of seismicity behavior beneath Klyuchevskoy Volcano and the elements of its magmatic feeding system were taken into account when selecting the analyzed seismically active volumes. The dynamics of seismicity was analyzed in four volumes of the subsoil, identified by the earthquake density maxima (Figure 2b): surface ($-4 \leq H \leq 2$ km), near-surface ($4 \leq H \leq 8$ km), intermediate in the crust-mantle layer ($20 \leq H \leq 25$ km) and deep ($26 \leq H \leq 34$ km). For convenience, we designate them, respectively, H1, H2, H3, H4. The final sample of earthquakes for the given ellipses and depths H1–H4 is shown in Figure 2a.

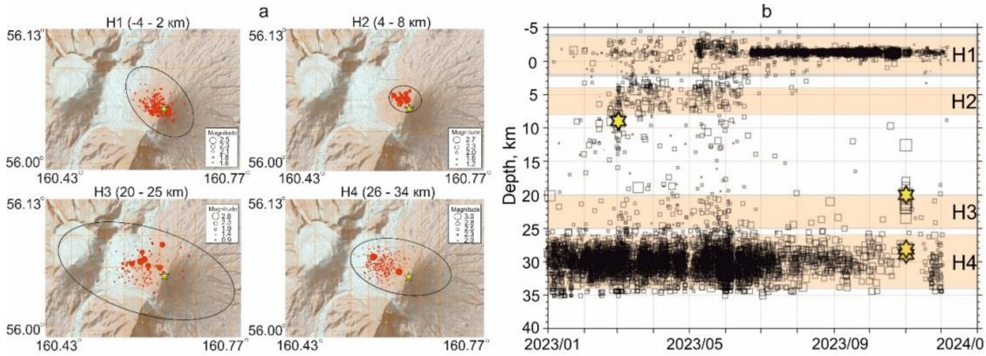

Fig. 2. The final sample of earthquakes from the KF GS RAS catalog for 2023 for a given ellipse and depth -4–2 km, 4–8 km, 20–25 km, 26–34 km, the summit of Klyuchevskoy Volcano is marked with an asterisk (a). The depth of the hypocenters of earthquakes recorded in the area of Klyuchevskoy Volcano in 2023, and the depths of the four most seismically active volumes of the environment selected for analysis (H1–H4), earthquakes with Ks≥7.3 are marked with asterisks (b).

In each sample, the representative magnitude K_C was determined. K_C was calculated using the modified Pisarenko method [8], where the representativeness is determined through the threshold estimate Kc, above which the distribution of the number of earthquakes N by energy class K can be considered exponential for a given level of statistical significance a.

A scale tied to the statistical distribution function of seismic energy [7] as a parameter characterizing the level of seismicity of a given spatial object in a certain time interval developed and implemented in KB GS RAS to describe the level of seismicity:

$$F(K)=P(\lg E \leq K),$$

where E is the seismic energy released over a certain time interval; $P(\lg E \leq K)$ is the relative frequency of time intervals with equivalent magnitude $\lg E$.

The energy distribution function is constructed based on the seismic energy values in a sliding time window of a certain length. The intervals between the quantiles of the released seismic energy distribution form a scale that includes seven seismicity levels: extremely high $0.995 \leq F(\lg E)$; high $0.975 \leq F(\lg E) < 0.995$; background elevated $0.85 \leq F(\lg E) < 0.975$; background average $0.15 < F(\lg E) < 0.85$; background reduced $0.025 < F(\lg E) \leq 0.15$; low $0.005 < F(\lg E) \leq 0.025$; extremely low $0.005 \leq F(\lg E)$.

Nomograms of the level of seismic activity were constructed for the selected seismically active volumes H1 – H4. It make possible to determine the corresponding level of seismicity based on the value of the released seismic energy over a specific time (Figure 3).

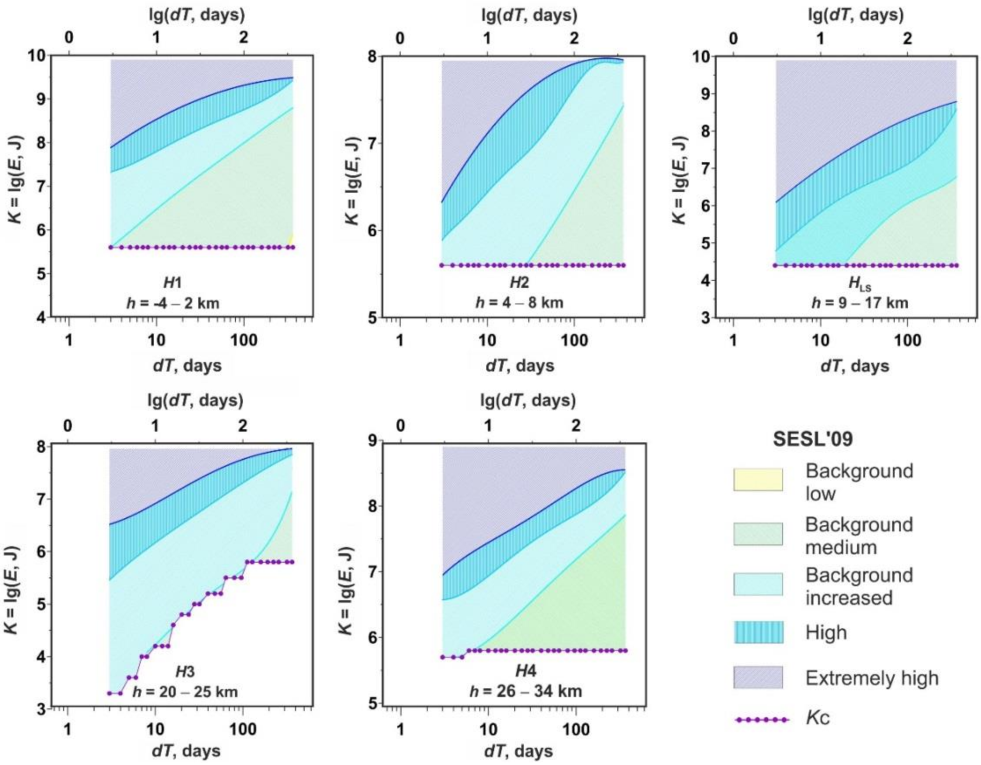

Fig. 3. The nomograms of the seismic activity level for the Klyuchevskoy Volcano in five volumes of the environment.

Currently, the SESL'09 methodology is used in the KB GS RAS for monitoring the Kamchatka seismically active zone and its subzones, as well as for the annual assessment of the seismicity level of the regions of Russia. The software implementation of the SESL'09 methodology [9] in the form of a computer program executed in the MS Windows allows its prompt application in this study. Recently, the application of the SESL'09 has been expanded to solving the problems of predicting volcanic eruptions on the Kamchatka Peninsula. The developed formalized methodology for predicting the eruption of Bezymyanny Volcano (Kamchatka Peninsula) based on the SESL'09 has proven its operability in real time. The preparation of all eruptions of Bezymyanny Volcano in 2015-2020 was identified [10].

3 Results

An analysis of the time course of the seismicity level of Klyuchevskoy Volcano in 2023 shows that the eruption that began in the second half of June 2023 (Figure 4, yellow stripe) was preceded by a statistically significant increase in seismic activity.

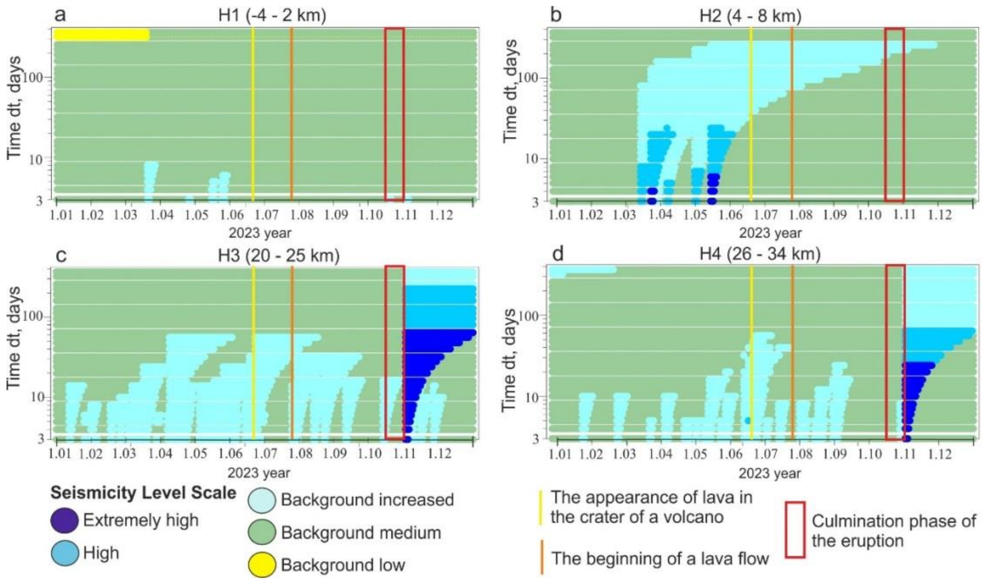

Fig. 4. The SESL diagrams for Klyuchevskoy Volcano for 2023 for seismically active volumes H1–H4.

The most pronounced increase in seismicity with an exit to high and extremely high levels was manifested in the volume of H2 1–3 months before the appearance of lava in the crater of the volcano (Figure 4b). A high level was obtained in the windows of 2–12 days, and an extremely high level in the windows of 2–6 days. The high level of seismicity in H1 in the windows of 2–5 days corresponded to the period of a strong explosive phase of the eruption at the end of October (Figure 4a). The culmination phase of the eruption occurred on October 31 – November 1, when ash clouds rose to a height of 10–15 km (KVERT, http://www.kscnet.ru/ivs/kvert/). After the culmination phase, seismic activity in H1 decreased, and in H3 and H4 it reached an extremely high level in the windows of 2–70 days and 2–30 days, respectively (Figure 4c, d). Which may be associated with the redistribution of stresses in the vicinity of the volcano's feeding system.

The precursor effect was manifested in the volume of the medium at a depth of 5–8 km. Although most of earthquakes beneath Klyuchevskoy Volcano occur at depths of -4 to 5 km and 20 to 40 km, and the energy classes of earthquakes are higher in these volumes of the medium. Earthquakes in the 5–8 km layer, occurring as rare isolated events, are classified as volcano-tectonic [11]. Most likely, the precursor effect detected 1–3 months before the eruption was caused by the redistribution of stresses in the medium containing the feeding magmatic system, the pressure in which varies depending on the conditions of accumulation or supply of magma. Also, at the present stage of the study, it is possible to propose a hypothesis that an extremely high or high level of seismicity at great depths (in H3 and H4) after the culmination phase of the eruption may indicate the end of the eruption.

4 Conclusion

The analysis of variations in the seismicity level of Klyuchevskoy Volcano in 2023 was carried out. The estimates were made based on the distribution functions of seismic energy released in different time windows in several depth ranges in the area of the volcano, according to the catalog of the Klyuchevskoy group of volcanoes of the KB GS RAS.

Seismic energy distribution functions and seismicity level nomograms were constructed. The obtained variations in the seismicity level in 2023 can index episodes of recorded volcanic activity of Klyuchevskoy Volcano: the process of eruption preparation and its end. The precursor effect manifested itself in the volume of the environment at a depth of 5–8 km 1–3 months before the appearance of lava in the crater of the volcano. Extremely high or high levels of seismicity at great depths (in H3 and H4) after the climactic phase of the eruption may indicate the end of the eruption. Retrospective analysis of previous eruptions of Klyuchevskoy Volcano will make it possible to clarify the identified features of seismicity behavior before and after the eruption and assess the prospects for using the SESL'09 methodology in monitoring the state of Klyuchevskoy Volcano.

The study was supported by a grant from the Russian Science Foundation № 24-17-20019, https://rscf.ru/project/24-17-20019/, the Ministry of Education and Science of Russia (within the framework of state assignment № 075-01271-23) and using data obtained at UNU (https://ckp-rf.ru/usu/507436/, http://www.gsras.ru/unu/).

References

1. V. I. Gorelchik, V. T. Garbuzova, A. V. Storcheus, J. Volcanol. Seismol. **6**, 21–34 (2004) DOI: https://doi.org/10.1134/S1069351320060026
2. N. M. Shapiro, D. V. Droznin, S. Y. Droznina, et al., Nature Geoscience **10(6)**, 442-445 (2017)
3. I. T. Kirsanov, G. P. Ponomarev, G. S. Htejnberg, Byulleten' Vulkanologicheskih Stancij **49**, 93-98 (1973)
4. V. N. Chebrov, D. V. Droznin, Y. A. Kugaenko, et al., Journal of Volcanology and Seismology **7**, 16-36 (2013) DOI: https://doi.org/10.1134/S0742046313010028
5. A. Yu. Chebrova, A. S. Chemarev, E. A. Matveenko, D. V. Chebrov, Geophysical Research **21(3)**, 66 – 91 (2020) DOI: https://doi.org/10.21455/gr2020.3-5
6. S. A. Fedotov, Energeticheskaya klassifikatsiya Kurilo-Kamchatskikh zemletryaseniy i problema magnitude (Nauka, Moscow, 1972)
7. V. A. Saltykov, Journal of Volcanology and Seismology **5(2)**, 123-128 (2011) DOI: https://doi.org/10.11.34/S0742046311020060
8. V. A. Saltykov, O. G. Volovich, *O probleme ocenki prostranstvenno-vremennyh osobennostej predstavitel'nosti kataloga zemletryasenij Kamchatki*, Sovremennye metody obrabotki i interpretacii sejsmologicheskih dannyh, in Proceedings of the XIII Mezhdunarodnoj sejsmologicheskoj shkoly, pp. 237-242 (2018)
9. P. V. Voropaev*, Programmnaya realizatsiya otsenok urovnya seysmichnosti po metodike SOUS'09*, in Proceedings of the X regional'noy molodezhnoy nauchnoy konferentsii. Petropavlovsk-Kamchatskiy, IViS DVO RAN, pp. 101–113 (2012)
10. V. A. Saltykov, Journal of Volcanology and Seismology **16(6)**, 462-471 (2022)
11. D. C. Roman, K. V. Cashman, Geology **34(6)**, 457-460 (2006) DOI: https://doi.org/10.1130/G22269.1