Forecasting Volcanic Eruptions from Seismic Data

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Abstract

An increase in cumulative seismic strain release from volcanic earthquakes prior to eruptions of Bezymyanniy Volcano in 1955-1961 and Sheveluch Volcano in 1964 in Kamchatka, and of Tokachi-dake Volcano on Hokkaido Island in 1962 occurred in accordance with a hyperbolic law. The relationship obtained may be universal for andesite volcanoes. Knowing the law of the increase of cumulative seismic strain and carrying out continuous observations of the seismic regime of andesite volcanoes makes it possible to predict time and energy of eruptions. By observation of volcanic earthquakes it is also possible to predict the place and time of the occurrence of lateral craters.

Many years of observations show that eruptions of andesitic and dacitic volcanoes and also outbursts of adventive craters at the foot of basaltic and andesitic volcanoes are always preceded by swarms of volcanic earthquakes. Thus, there are some objective data for the forecasting of the above mentioned volcanic eruptions. The problem is to discover the regularities of seismic phenomena related to volcanic eruptions, the application of which will allow us to predict place, time and energy of eruptions.

Studying the relationship of preceding phenomena with the eruption of Asama volcano, MINAKAMI (1960) used the number of volcanic earthquakes. But in our investigations of the eruptions of the Bezymianniy volcano in 1958-1961, it was determined that a sharp change in earthquake number takes place only 1-2 days before the beginning of the eruption and that this phenomenon did not allow us to predict the eruption time opportunely. Earthquake energy is a more reliable characteristic of seismic activity and does not depend on distance of seismic stations fron a volcano or on the equipment sensitivity.

As a characteristic of volcano-seismic activity we make use of cumulative seismic strain diagrams (Benioff diagrams)

$$\varepsilon_k = \sum_0^k \sum_1^N \sqrt{E_{ij}} \qquad [1]$$

where E is earthquake energy expressed in ergs; $j = 0, 1, 2 \ldots k$; $i = 1, 2 \ldots N$; N is number of earthquakes per day, and k is number of days for which the summarizing is done.

As $E \sim (A/T)^2$, where A and T are amplitude and period of maximum displacement of shear waves, $\varepsilon = \beta (A/T)$ and $\varepsilon_k = \sum_0^k \sum_1^N \beta_{ij} (A/T)_{ij}$.

As the registration of volcanic earthquakes at one and the same station involves only a small change in hypocentral distance, the coefficient remains nearly the same for all earthquakes of the same type, *i.e.* $\varepsilon_k = \beta \sum_0^k \sum_1^N (A/T)_{ij}$. Thus, plotting of the seismic strain is a simple summarizing of values (A/T).

Five types of volcanic earthquakes have been distinguished at the volcanic eruptions in Kamchatka (TOKAREV, 1966). Earthquakes of the type I have foci at 10-30 km depth and are not connected with eruptions. Earthquakes of types II and III precede the eruptions of andesitic and dacitic volcanoes and outbursts of adventive craters. These types have foci at depths of not more than 10 km beneath the vent of the volcano. Only types II and III earthquakes can be used for forecasting the place, time and energy of eruptions. Earthquakes of type IV are explosive earthquakes, and earthquakes of type V are volcanic tremors, and they characterize the eruption dynamics.

In studies of the Bezymianniy Volcano eruptions in 1958-1961, connected with the extrusion of a dome in the crater, it was determined that a release of seismic strain before the eruption took place according to a hyperbolic law (TOKAREV, 1963). Some time later, it was determined that an analogous phenomenon took place before the Tokachi-dake Volcano eruption of June 29, 1962 and the Sheveluch Volcano eruption on Nov. 12, 1964 (TOKAREV, 1967).

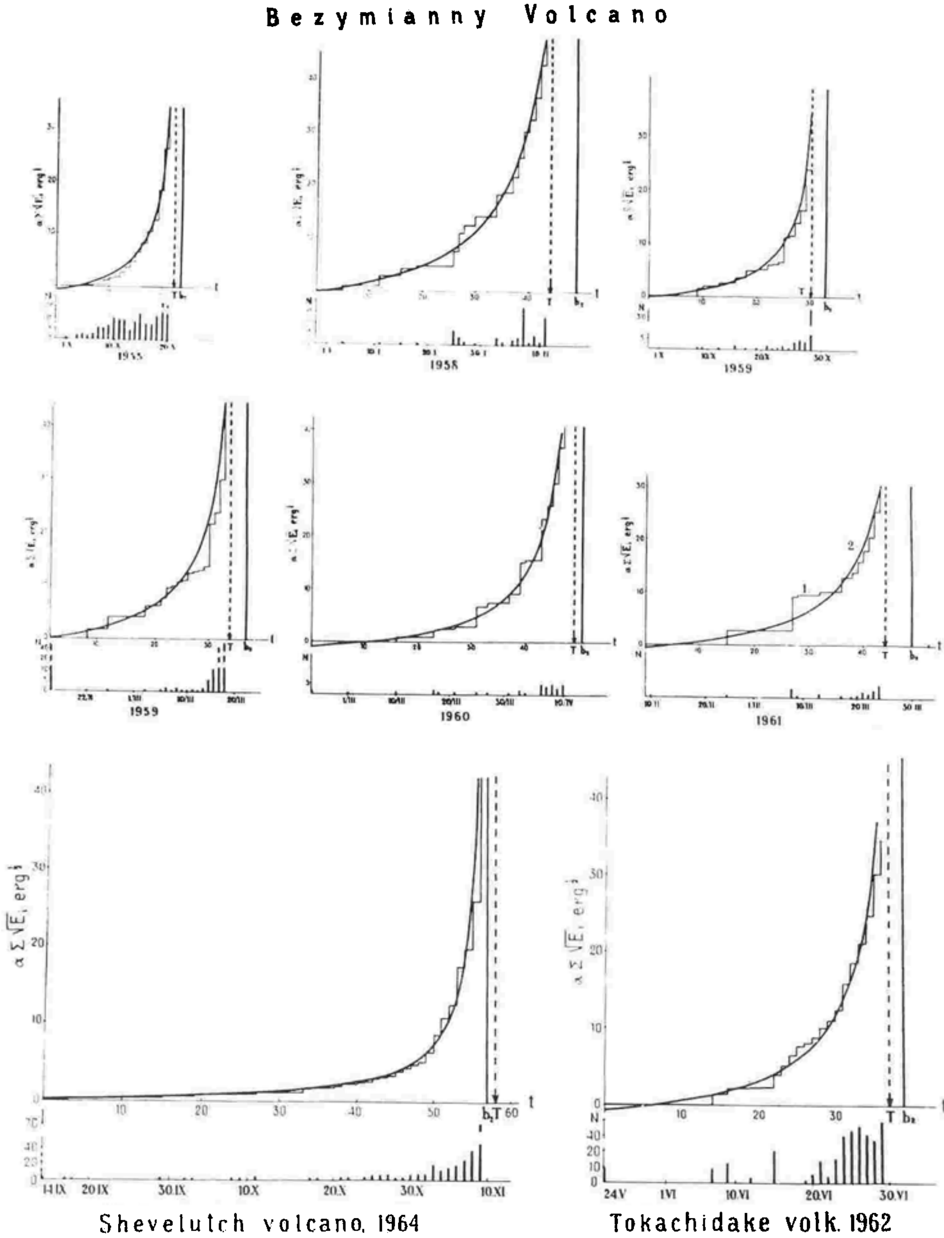

FIG. 1 - Growth diagram of cumulative seismic strain release before andesitic volcanic eruptions.
1 - curve from experimental data; 2 - curve calculated by eq. [1]; N - number of earthquakes per day.

Diagrams of cumulative seismic strain release

$$\varepsilon_k = \alpha \sum_{0}^{k} \sum_{1}^{N} \sqrt{E_{ij}} \ \mathrm{erg}^{1/2}$$

and approximate hyperbolas of the type $\varepsilon_k = a_1 t_k + b_i/t_k + b_2$ before volcanic eruptions of Bezymianniy, Sheveluch and Tokachi-dake are shown in Fig. 1. Coefficient values a_1, b_1, b_2, beginning time of readings t_o and eruption time T, the quantity of eruptive juvenile material m, and scale coefficients α are given in Table 1.

TABLE 1

Volcano, and Date of Eruption	Date t_o	T in 24h	α	$\alpha\ a_1$ erg$^{1/2}$	$\alpha\ b_1$ erg$^{1/2}$	b_2 in 24h	m ton
Bezymianniy							
22.10.1955	29.09	23	7.7×10^{-10}	−4.3	14.5	−23.4	3×10^9
12.02.1958	30.12	44	1.6×10^{-10}	−7.5	12.4	−48.9	6×10^7
28.03.1959	22.02	34	1.6×10^{-10}	−5.3	−2.0	−37.0	4×10^7
29.10.1959	29.09	30	1.6×10^{-10}	−3.3	4.7	−32.8	4×10^7
12.04.1960	23.02	49	1.6×10^{-10}	−4.5	44.3	−50.5	6×10^7
25.03.1961	9.02	44	1.6×10^{-10}	−4.7	20.6	−48.8	6×10^7
Sheveluch							
11.11.1964	14.09	59	2×10^{-9}	−0.7	−14.6	−56.9	1.6×10^9
Tokachi-dake							
29.06.1962	24.05	36	3.1×10^{-8}	−4.3	25.8	−38.8	10^8

As seen in Fig. 1, in all cases the diagrams of cumulative seismic strain are well approximated by equilateral hyperbolas. The eruption takes place in the time interval $t = b_2 - c$, where $0 < c < 5$ days.

The general relationship in all the cases considered is a regular growth of cumulative seismic strain beginning 30-50 days before the eruption. In the most cases a regular growth begins from the onset of an earthquake swarm. But in some cases it is preceded by an irregular release of seismic strain.

Knowing these relationships and carrying out constant observations of the seismic regime of a volcano, it is possible to calculate the coefficients a_1, b_1 and b_2 and to forecast the eruption time with an error of not more than 5 days. An additional feature of an oncoming eruption is a sharp increase in the number of earthquakes and onset of earthquakes of type III, the foci of which are at a depth of not more than 1-2 km from the bottom of the active crater. This allows a more exact prediction of the eruption time.

Calculation of cumulative seismic strain allows prediction not only of eruption time but also of its energy. On the basis of analysis of the above mentioned eruptions, the following empirical formula of mass of juvenile eruptive material to the value of cumulative seismic strain was obtained:

$$m = 0.044 \ (-b_2 - t_k) \cdot \left(\frac{-b_2 - 5 + \frac{b_1}{a_1}}{t_k + \frac{b_1}{a_1}} \right) \cdot \varepsilon_k \qquad [2]$$

where m = mass of eruptive material in metric tons; a_1, b_1 and b_2 = coefficients of eq. [1]; ε_k = cumulative strain for time t_k expressed in $erg^{1/2}$. Calculation accuracy of mass according to eq. [2] is in the range of calculation accuracy of observed material mass from eruptions. It is also possible to estimate a total thermal energy of an expected eruption owing to mass m.

The given forecasting method of time and energy of andesitic volcanic eruptions requires continuous observations of the seismic regime of a volcano with at least one seismic station, and continuous construction of diagrams of cumulative seismic strain from the recorded earthquakes. As soon as a regular increase in seismic strain release begins, it is necessary to make daily calculations of coefficients a_1, b_1 and b_2 and eruption energy. Seven to ten days before the eruption, the time of eruption ($T = -b_2 - 5$) and the mass of eruptive material can be estimated. The stability of values b_2 and m indicate the proximity of an eruption. If a regular growth of cumulative seismic strain takes place from the beginning of an earthquake swarm, coefficient b_1 may be taken as equal to 0 and it is possible to make a calculation according to the simplified formula

$$\varepsilon = \frac{a_1 t}{t + b_2} \qquad [3]$$

For calculation of only the eruption time, it is possible instead of $\varepsilon_k = \sum_0^k \sum_1^N \sqrt{E_{ij}}$ to take $\varepsilon'_k = \sum_0^k \sum_1^N (A/T)_{ij}$ from the data of the same station.

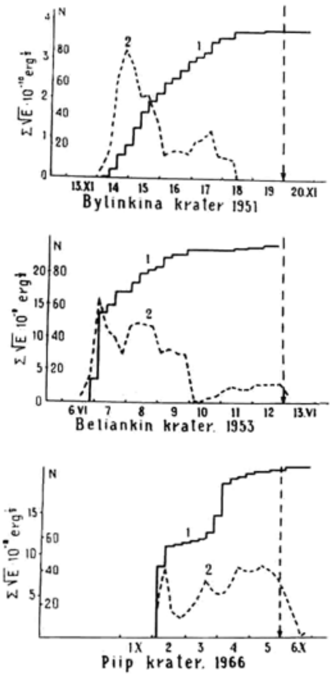

FIG. 2 - Growth diagram of cumulative seismic strain release [1] before outbursts of Kliuchevsky Volcano adventive craters.
N - number of earthquakes [2] per 6 hours.

In the eruption of adventive craters, magma moves to the earth's suface along fissures in solid rocks. On its way it destroys rocks and generates earthquakes. Fig. 2 shows diagrams of cumulative seismic strain and a number of volcanic earthquakes of types II and III which preceded the eruption of adventive craters of Kliuchevsky Volcano. As seen in the diagrams, volcanic earthquakes appear 3-7 days before the ourburst of adventive craters. A characteristic feature is that the strongest earthquakes take place in the first few days, and earthquakes stop before the outburst of the adventive crater (TOKAREV, 1966; TOKAREV *et al.*, 1968). Thus a sharp decrease in cumulative seismic strain indicates that shortly after (1-3 days) an outburst from an adventive crater will take place. The outburst location is related to the position of earthquake epicenters. There is no method for energy calculation of adventive eruptions.

Conclusions

1. Eruptions of andesitic volcanoes are preceded by volcanic earthquakes of types II and III. Growth of cumulative seismic strain release before volcanic eruptions of Bezymianniy, Tokachi-dake and Sheveluch took place according to a hyperbolic law. It is possible to draw the conclusion that this may be a general relationship for andesitic volcanoes.

2. Knowledge of the growth law of cumulative seismic strain release of volcanic earthquakes prior to eruptions, allows prediction of the time and energy of expected eruptions.

3. Eruptions of adventive craters are also preceded by volcanic earthquakes of types II and III. Growth of cumulative seismic strain at the beginning of these earthquake swarms takes place very quickly. Before the eruption, the seismic strain sharply decreases and this allows an estimate of the eruption time. It is also possible to predict the eruption location of adventive craters from the position of the earthquake foci.

References

BENIOFF, H., 1951, *Earthquakes and rock creep - Part I.* Bull. Seis. Soc. America, v. 41, p. 31-62.

MINAKAMI, T., 1960, *Fundamental research for predicting volcanic eruptions (Part. I).* Bull. Earth. Res. Inst., vol. 38, part 4, Tokyo.

TOKAREV, P. I., 1963, *On a possibility of forecasting Bezymianniy volcano eruptions according to seismic data.* Bull. Volcan., T. XXVI, p. 379-386.

TOKAREV, P. I., 1966, *Eruptions and seismic regimes of Kliuchevsky Volcano group.* Nauka (in Russian).

————, 1967, *A gigantic eruption of Sheveluch volcano on Nov. 12, 1964 and its forerunning phenomena.* Izvestiya Ac. Sc. of the USSR, ser. Earth Phys., N. 9, Nauka (in Russian).

————, SHIROKOV, V. A. and ZOBIN, V. M., 1968, *Seismic phenomena connected with Piip adventive crater eruption in Oct.-Dec., 1966.* Bull. volcanological Stations, N. 44, Nauka (in Russian).

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