On a possibility of forecasting of Bezymianny Volcano eruptions according to seismic data.

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Since its awakening in October 1955 Bezyamianny volcano remains a very active volcano of Kamchatka. During the period from 1957 to 1961 thirteen of its eruptions have been recorded. By force and character the eruptions of this period can be divided into two types.

1. Eruptions of the first type are preceded and followed by a great number of earthquakes with a focus under the Bezymianny. All of them are quite strong. During the eruptions of the first type agglomerate flows are formed, in winter mud flows are streaming down, there are strong explosions in the crater of the volcano directed often at a sharp angle towards the horizon, there are outbursts of a large amount of ash, which falls on a considerable area. Such eruptions have been recorded on February 13-14th and December 27-28th 1958, on March 27-29 and October 28-30, 1959, on April 13-14, 1960 and on March 26-27, 1961.

Eruptions of the first type are, apparently, associated with the growth of a dome in the crater of the volcano and with the forcing out of new portions of magma from the effluent channel.

2. Eruptions of the second type are neither preceded nor followed by earthquakes. In their majority, these are very slight eruptions of ash, associated, apparently, with a slow squeezing out of the dome and its destruction. Being built of an incandenscent material the dome is in a very unstable state. During cooling it gets badly deformed, enormous blocks of incandescent material become split off and cause stone avalanches by rolling down. When the avalanches move down, the material gets split into bits both by impact and as result of an expansion of the gases enclosed in the glowing material. A lot of ash is formed mixed with hot gases. This ash is entrapped by strong convection currents, carried upwards for many

kilometers and dispersed by the wind to great distances. Thus « outbursts » of gas and ash observed during the eruptions of the second type are not a result of magma explosions in the crater of the volcano.

After a gigantic explosion on March 30, 1956 a young dome began to grow in the new crater of Bezymianny volcano. According to the measurements made by G. S. GORSHKOV and O. G. BORISOV during the period from 1957 to 1960 the height of the dome increased by 140 meters. During these years it noticeably widened and became more massive.

Observations of the seismic activity of Kliuchevskaia group volcanoes are carried out by Kliuchi siesmic station beginning with 1947, by Kozyrevsk seismic stations since autumn of 1958 and by the Apokhonchich seismic station - since 1960. The distances of the seismic stations from Bezymianny volcano are correspondingly 42,45 and 16 km. All the stations are equipped with electrodynamic siesmographs with a galvanometric recording on photographic paper. The magnification of the seismographs can change from 500 to 7000.

By the character of recording and by their association with definite phases of eruptions the earthquakes of Bezymianny volcano are divided into three types.

1. Earthquakes preceding and accompanying eruptions of the first type are usually recorded in swarms. Surface waves are predominant in the records of these earthquakes. Body waves are recorded rather weakly and the S wave is not always correctly discernable. All this indicates a shallow location of their foci. Earthquakes of the first type correspond to earthquakes of B type in the classification of Minakami.

2. Earthquakes accompanying the paroxismal phase of the eruptions of the first type. By the character of their record they only slightly differ from the earthquakes of the first type. They are recorded together with strong explosions in the crater of the volcano. These earthquakes correspond to the type of explosive eruptions in the classification of Minakami.

3. A nearly uninterrupted spasmodic volcanic tremor, which is recorded both during the eruptions of the first type and during the eruptions of the second type. Separate trains of this tremor with large amplitudes greatly remind records of surface waves during

the earthquakes of the first and second types. However, body waves are absent. It is possible that these earthquakes are associated with the rollingdown of stone avalanches from the dome during its destruction.

As already mentioned, eruptions of the first type are preceded by a lengthy seismic preparation, the progress of seismic activity in each case being the same. During the lengthy intervals between the eruptions the volcano behaves absolutely quietly. The first earthquake with a focus under Bezymianny volcano takes place 30-50 days before the beginning of the eruption. At first the earthquakes are rare but later their frequency gradually increases. At the moment of a paroxysm in the eruption a great number of shocks is registered up to a hundred a day. But their strength is much less than during the preparation period before the eruption. After the paroxysm of the eruption the frequence sharply drops or the earthquakes stop completely and only a spasmodic volcanic tremor is observed, its intensity gradually decreasing. When the volcano reaches its usual state the volcanic tremor stops.

As a measure of the seismic activity of Bezymianny volcano we have taken the conventional elastic deformation in the area of the foci of volcanic earthquakes, which is determined according to the density of earthquake energy (E) at the seismic station « Kliuchi ». The density of earthquake energy at the seismic station « Kliuchi » is determined according to an empirical formula obtained by us (TOKAREV, 1961).

$$E = 2{,}08 \left(\frac{A}{T}\right)^2_{max} \quad \text{erg } ½/\text{cm} \qquad [1]$$

where A is a maximum amplitude of ground displacement on horizontal components at the seismic station « Kliuchi » expressed in microns and T - the period of maximum displacement in seconds.

An elastic deformation ε in the focus of earthquake at the moment of its preparation is

$$\varepsilon = K \cdot \sqrt{E}$$

The conventional deformation $\sqrt{E}$ is expressed in ergs ½/cm and with a precision up to coefficient K expresses the elastic deformation. In volcanic earthquakes, when their records exactly resemble each other, the foci are localized in a small area and the epicentral distance remains constant, it is possible to assume that coefficient K remains the same for all earthquakes of the same type. In such a case conventional deformations can be summed up. If there have been N earthquakes during a day, the summary conventional deformation in the focus of these earthquakes will come to $\sum_{1}^{N} \sqrt{E_i}$ By summarizing conventional deformations for a certain period, for instance for k days we get an accretion diagram of conventional deformations for this time interval (Benioff diagram).

$$\varepsilon_k = \sum_{0}^{k} \sum_{1}^{N} \sqrt{E_{ij}}, \qquad \text{where } j = 0, 1, 2 \ldots\ldots k; \qquad i = 1, 2 \ldots\ldots N;$$

N = number of earthquakes during the given day;

k = number of days for which the summarizing is done.

Fig. 1 gives accretion diagrams of conventional deformations in earthquake foci of Bezymianny volcano during 1957-1961. In compiling the diagrams all earthquakes of the first and second type were taken into consideration and their energy density has been determined by formula [1]. Each step in the diagram equals an accretion of conventional deformation for three days. It should be noted that in June and December 1958 there have been intervals in the work of the seismic stations. Consequently data on earthquakes during this period are incomplete and the eruptions, which fell on June and December are not taken into consideration.

As shown by diagrams of fig. 1 eruptions of the first type were preceded by a rather lengthy seismic preparation and the rate of elastic deformations accretion in the area of the foci of volcanic earthquakes (in the upper part of the effluent channel and in the mass of the dome) gradually increases. This regularity has been noticed by us already in the summer of 1959, which permitted to foresee the subsequent eruptions approximately a week before their beginning. But at that time we could not forecast yet the date of the beginning of the eruption. During the summer of 1961 we made a detailed analysis of the four cycles of seismic activity of Bezymianny volcano (during January-February 1958, February-March 1959, Mach-April 1960

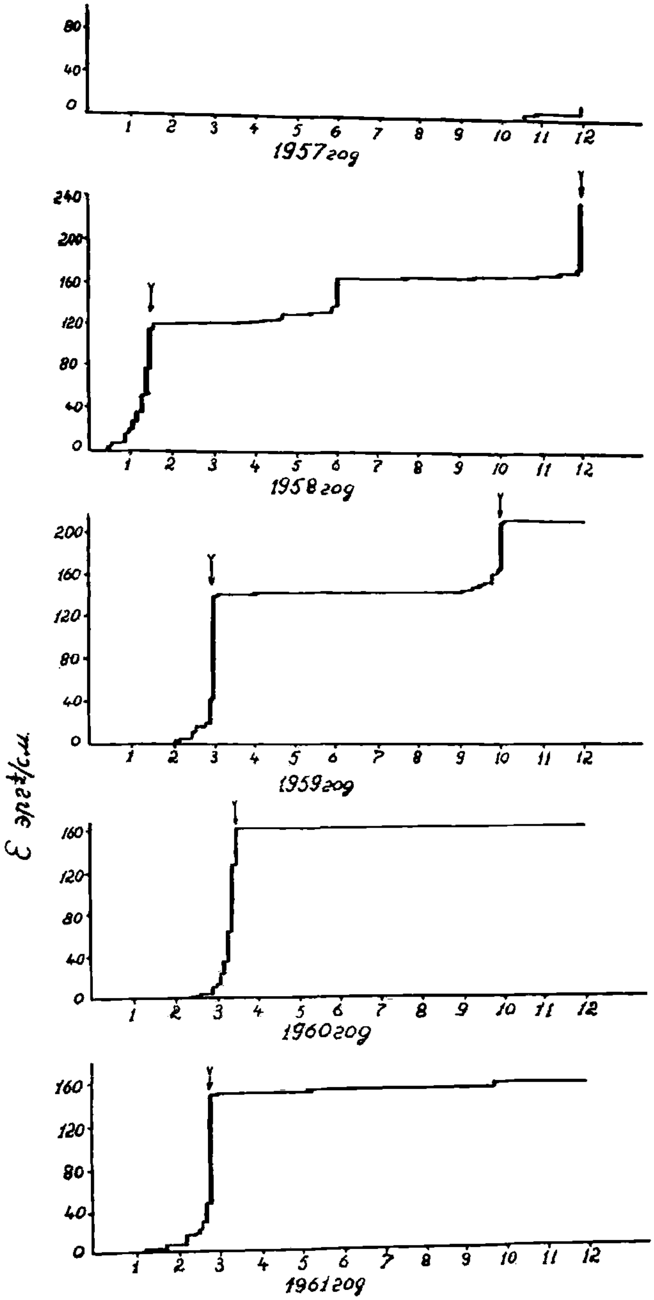

Fig. 1 - Diagram of conventional deformations in the area of earthquake foci of Bezymianny volcano during 1957-1961.

and February-March 1961). It has been established that the elastic deformation grows following the hyperbola

$$\varepsilon_k = \sum_{0}^{k} \sum_{1}^{N} \sqrt{E_{ij}} = a + \frac{b}{T - t_k} \qquad [3]$$

where a and b = are constant coefficients,

k = ordinal number of the day, calculated from the moment t_o,

t_o = time of the first earthquake of the given cycle of seismic activity,

T = crossing moment of the vertical asymptote and the time axis.

One day is taken everywhere as a time unit. Further on all time periods will be counted from the moment t_o.

Knowing the law of conventional deformation accretion by observations over the seismic activity of the volcano before the beginning of the eruption, it is possible to calculate coefficients a and b and to determine the crossing time ($t = T$) of the asymptote with the time axis and, consequently, the time when the eruption begins.

Coefficients a and b have been calculated by the method of least squares according to the mean value of conventional deformations for the abovementioned four cycles of seismic activity. It has been found that coefficient $b = 335$ is the same for all the cycles of seismic activity, i. e. it is a constant value for Bezyamianny volcano, while coefficient a varies in different cycles of activity. Fig. 2 gives a diagram ε_k computed according to formula [3] with $b = 335$ and $a = -5.3$; this diagram shows also mean values of elastic deformation obtained through observations (shown by crosses).

Knowing the law of conventional deformation accretion before the eruption (formula 3) and having an established coefficient b and summary conventional deformation ε_k for a certain time interval obtained by observations, it is possible to determine coefficient a and the time moment ($t = T$) of the crossing betwen the vertical asymptote and the time axis and through this value — the moment of the beginning of the eruption τ, which for Bezyamianny volcano amounts to T-6.

To determine the moment of the beginning of the eruption of Bezymianny volcano the following formula has been obtained:

$$\tau_k = -6 + \frac{t_k}{2} + \sqrt{\left(\frac{t_k}{2}\right)^2 + \frac{335}{\varepsilon_k - \varepsilon_o} \cdot t_k} \qquad [4]$$

where the symbol k near the letter τ means the time interval t_k according to which the moment of the beginning of the eruption τ has been computed. Generally speaking, the computed moment of the beginning of the eruption τ_k somewhat differs from the actual

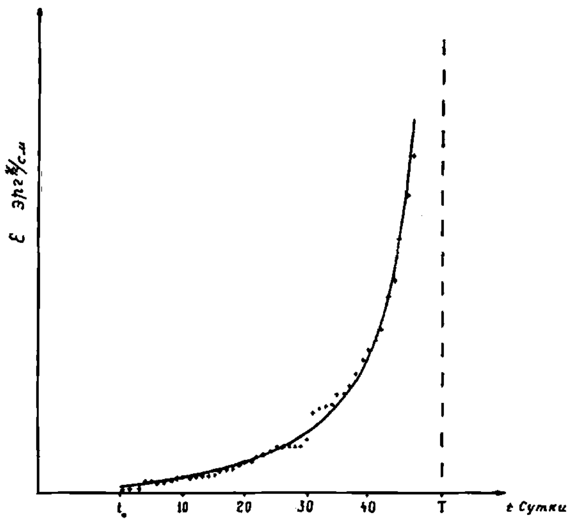

Fig. 2 - Diagram of conventional deformations in the area of earthquake foci before the eruption of Bezymianny volcano computed according to formula (3) (solid line) and mean deformation values obtained by observations (indicated by crosses).

value. This difference is the less the greater the time interval t_k according to which the computation is done. Theoretically, any day of the given cycle of activity can be taken as the beginning of the time count t_o, but, in practice, the earlier the beginning of the count t_o is taken, the longer the time interval t_k according to which the computation can be effected and the greater the precision for the determination of the moment of the beginning of the eruption τ_k.

To forecast the moment when eruptions will take place for Bezymianny volcano it is necessary to keep a constant observation over its seismic activity at all seismic stations to plot daily (continue to plot) a diagram of conventional deformations ε_k, and, beginning with the second day, (or the second earthquake), to compute the time of the beginning of the eruption τ_k and plot a diagram τ_k (t_k).

At first, when t_k values are small (at the beginning of the cycle of seismic activity) points τ_k on the $\tau (t_k)$ diagram are very scattered. With an increase in time t_k (with the approach of the time of eruption) the scattering diminishes and when the summary conventional deformation ε_k exceeds 20-30 ergs ½/cm, the values of τ_k become stable and differ little from its actual value τ. Seven or ten days before the beginning of the eruption τ_k is determined with an error not exceeding three days. Time computations for the beginning of the eruption can be done according to formula [4] and according to observations at other seismic stations if the energy density in the area of these stations equals that at the seismic station Kliuchi.

In conclusion we would like to point out that in forecasting eruptions it is more advisable to use the energy of volcanic earthquakes or a value proportional to it and not the frequence of earthquakes.

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