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Abstract

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GEOPHYSICS

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MECHANISM OF GENERATION OF VOLCANIC TREMORS AND LONG-RANGE FORECASTING OF ERUPTIONS

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Volcanic tremor, preceding and accompanying volcanic eruptions, is a very characteristic and specific phenomenon that characterizes the dynamics of eruptions. However, there is as yet no accepted and analytically substantiated mechanism for the generation of volcanic tremors. In many works, possible sources of volcanic tremor are assumed to be internal eruptions of gases ([1]), movements of magma in the conduit ([2]), motion of gases through a system of fractures ([3]), and others.

Physical and analytical substantiations of the tremor mechanism have been given only in two particular cases ([4,5]).

In Omer' s model ([4]), volcanic tremor arises as a result of fluctuations of hydrostatic pressure in a lava column occupying a volcanic conduit, at the end faces of the layers composing the walls of the conduit. In the analytical treatment of the model, a layer is approximated by an oscillating bar, one end of which is rigidly fixed, while the other end and the lateral sides are free. Braking due to friction and internal damping are not taken into account. The hydrostatic pressure varies according to the Heaviside step function. Oscillations within the bar are described by the equation:

$$\frac{\partial^2 u}{\partial x^2} - \frac{\lambda}{c} \cdot \frac{\partial^2 u}{\partial t^2} = 0, \tag{1}$$

where $u(x,t)$ is the longitudinal displacement of point x during time t, and c is the velocity of propagation of longitudinal waves in the bar. The period and amplitude of oscillations are determined by the relations:

$$p_n = \frac{p_1}{(2n-1)}, \tag{2}$$

$$A_n = \frac{A_1}{(2n-1)^2}, \tag{3}$$

where p_n and p_1, A_n and A_1 are the period and amplitude of the n-th and first harmonics, respectively.

Registration of volcanic tremor at Kilauea showed that $p_1 = 0.43 \div 0.66$ sec, $p_2 = 0.15 \div 0.18$ sec. Accordingly, the calculated length of the bar was $L = 635$–975 m. Geodetic observations established that the width of the zone of nonuniform bending around the Kilauea crater varies from 600 to 1000 m. The rock beds in this zone are thus regarded as "free" bars that are sources of volcanic tremor.

The shortcomings of Omer's model are the following:

1. In subsequent studies at Kilauea, volcanic tremors with $p = 2.5 \div 3.5$ sec were established, which cannot be explained by the proposed model. For the generation of such volcanic tremors

the length of the "free" blocks must be considerably greater than the established width of the zone of heterogeneous bending.

2. On most volcanoes, no distinguished ratio has been found between the periods (2) and amplitudes (3) of the low- and high-frequency components of volcanic tremor.
3. Not all volcanoes exhibit topographic deformations analogous to those observed on Kilauea.
4. The proposed model is applicable only to Hawaiian-type eruptions, accompanied by the outpouring of liquid basic lava. In viscous intermediate and acidic lavas, the hydrostatic pressure cannot vary as a step function. Eruptions of andesitic volcanoes are often not accompanied by lava outpourings at all, but are explosive; nevertheless, volcanic tremor is observed in such cases.

Consequently, the mechanism proposed by Omer explains the generation of only part of the spectrum of volcanic tremors observed on Kilauea, and cannot be regarded as general for other volcanoes.

In the opinion of Simozuru and Berg (5), volcanic tremor is caused by oscillations arising in the conduit as a result of changing pressure. Treating the volcanic conduit as a rod, the period of oscillations can be calculated from the formula

$$p = \lambda \sqrt{\frac{\rho}{E}}, \tag{4}$$

where λ is the wavelength, ρ the density, and E Young's modulus. Taking $\rho = 2.8$ g/cm^3, the effective length of the lava column-rod $\lambda/2 = 500$ m, and assigning values of E for different temperatures, the authors (5) obtained most

Fig. 1. Diagram of the structure of a volcanic apparatus

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of the spectrum of frequencies observed on Niragongo. However, as the authors themselves note, "it is somewhat strange that the observed differences in the periods of volcanic tremor are interpreted only by differences in the magnitude of Young' s modulus, without taking into account possible differences in length, since at present there are no geophysical or geological facts confirming such a characteristic length of the lava column." Having chosen a fundamentally correct path, in the concluding part the authors made an error owing to their desire to obtain the entire frequency spectrum (or its principal range) from a single oscillator. Such a universal oscillator is hardly likely to be found. It is easy to verify that a 500-meter lava column does not ensure generation of the entire frequency range (0.1–1.0 sec.):

1) To obtain long-period oscillations ($p = 0.7$–1.0 sec.), the velocity of longitudinal waves in basalts must lie in the range 1.45–0.92 km/sec.
2) For short-period oscillations ($p \leq 0.1$ sec.), $V \geq 9.2$ km/sec.
3) For the principal range ($p = 0.2$–0.7 sec.), $V = 5$–1.45 km/sec.

Thus, even the principal frequency range cannot be ensured, since the minimum experimentally determined value of the velocity of longitudinal waves in basalt is 3.46 km/sec (6–8). Even if one assumes that at higher temperatures (above 1100–1200°) the indicated velocity value ($V = 1.45$ km/sec) can be reached, the simultaneous generation of high- and low-frequency volcanic tremors by a single source remains unexplained. High-frequency tremors cannot be regarded as higher harmonics, since, first, the amplitude ratio is not maintained, and second, unrealistically high velocity values are required for the generation of low-frequency oscillations. Moreover, with such a formulation and solution of the problem we obtain no information about the structure or state of the volcano, since the estimate of Young' s modulus, and consequently of the temperature in the volcanic conduit, depends on the parameter λ, which is chosen arbitrarily.

In substantiating the proposed mechanism for the generation of volcanic tremors, we proceeded from the facts recorded in the study of tremor, avoiding, as far as possible, committing ourselves to any assumptions.

The volcanic apparatus is a structure of central type, connected by a conduit with a peripheral chamber, which in turn is connected by a conduit with the zone of generation of magmatic melt, located in the upper mantle (Fig. 1). Let us note that the presence of a peripheral chamber is a special case: it may also be absent, and then the model is somewhat simplified.

Fig. 1. Diagram of the structure of a volcanic apparatus

The volcanic conduit and the adjacent zone, having a high temperature, are in effect a waveguide. As Gutenberg noted (12), a considerable part of the energy propagates in a waveguide, especially if the source of oscillations is located in it. The latter condition is fulfilled, since the cause of the oscillations is the displacement of magma along the conduit. In particular, in Hawaii the hypocenters of earthquakes after which many-hour volcanic tremor was observed were located beneath the volcanoes and moved from depth toward the surface, which was associated (13) with the rise of magma.

Oscillations of the natural frequency in such a system have the period:

$$p = \frac{2L}{V}, \tag{5}$$

where V is the velocity of propagation of longitudinal waves in the pipe, and L is the length of the pipe. The causes of the onset of oscillations may be volcanic explosions, the rise of magma along the conduit accompanied by friction against the walls, movements of magma in the chamber, nonstationary release of gases in the feeder conduit, and volcano-tectonic earthquakes.

As can be seen from Fig. 1, the parameter L in our model has a definite geological meaning: it is the depth to the peripheral chamber (L_1) or to the zone of magma generation (L_2). Since approximate values of the velocity of longitudinal waves in basalts at high temperatures are known from experiments (6-8), and the periods of volcanic tremor from seismic observations, formula (5) makes it possible to estimate the value of L and compare it with the results of determining this parameter from independent data.

As an example, we calculated the value of L for Kilauea volcano, for which a complete frequency spectrum of volcanic tremor is available. According to Eaton (9), the magnitude of the long-period oscillations is 2.5-3.5 sec, and the temperature of the liquid lava is 1100-1150°. There are no experimental data on the velocity of seismic waves in basalts at $T > 1070^\circ$. At $T = 1070^\circ$, $V = 3.46$ km/sec (6-8). Assuming that at 1100-1150° the velocity is not less than 2.5-3.0 km/sec, we find that $L = 3.1$–5.2 km. The depth of occurrence of the peripheral magmatic chamber beneath Kilauea volcano, determined from deformations of the Earth' s crust, is 3.5-5.0 km (10, 11).

It should be expected that the rise of magma from the zone of generation into the upper horizons of the Earth' s crust must be accompanied by long-period oscillations corresponding to the natural frequency of the conduit.

Long-period oscillations with periods of tens of seconds in areas of volcanic activity have practically not been studied. An exception is Aso volcano, where such investigations have been conducted since 1957. Several months before the 1958 eruption, there were repeatedly observed···

long-period oscillations (⁀14); however, owing to the novelty of the investigations, there was no certainty that these oscillations were connected with the preparation of the eruption. And only 1.5 months before the eruption, when short-period tremors had already begun, was it established that the regular sinusoidal long-period ($p = 40 \div 55$ sec) oscillations were volcanic tremor. Oscillations with such a period correspond to the natural oscillations of a vent 60–80 km long. According to S. A. Fedotov (⁀15), the probable zone of magma generation beneath the Kurile–Kamchatka and Japanese island arcs lies at a depth of 60–110 km.

It should be noted that the movement of magma from the generation zone into the upper horizons of the Earth's crust may occur not through pipe-like conduits, but along faults and fractures. For the latter case, the natural oscillations of a plate should be considered.

The proposed mechanism for the occurrence of volcanic tremors makes it possible to outline the evolution in the spectrum of volcanic tremors as an eruption approaches. Let us consider it using Avacha Volcano as an example, whose deep structure has been well studied (⁀16). The rise of magma and the transfer of energy from the zone of magma formation to the peripheral chamber will be accompanied by long-period volcanic tremors. The zone of magma formation in the region of Avacha Volcano is located at a depth of ≥ 90 km (⁀17). Accordingly, the period of volcanic tremors caused by the processes of magma ascent from the zone of magma formation will be no less than 35–60 sec. Then volcanic tremors with a period of 4–7 sec will begin to appear, corresponding to the natural oscillations of the conduit connecting the peripheral chamber with the crater. Immediately before and during the eruption, high-frequency ($p = 0.1 \div 1.0$ sec) tremors will be recorded, arising in short conduits—apophyses formed in the frontal part of the lava column, through which lava and pyroclastics reach the surface.

Thus, the study of volcanic tremor over a broad frequency range makes it possible to use seismic observations as a method for the long-term forecasting of eruptions.

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Note: Figure translations are in progress. See original paper for figures.