On Heterogeneities with Reduced Viscosity in the Mantle under the Kamchatka Volcanoes According to Seismological Data *

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Abstract

A seismological study of the upper mantle under the Kamchatka volcanoes using body waves from nearby earthquakes has shown local heterogeneities consisting of materials with reduced elastic properties at depths from 30 to 90 km.

The estimated value of the upper limit of viscosity, η, is about 6×10^{20} pois for the material of the mantle aseismic zone under the Kamchatka volcanoes at depths of $\backsim$70-150 km.

It is suggested that the magmatic chambers are rooted in the mantle heterogeneities filled with substance of reduced elasticity and viscosity.

Introduction

Parameters of the magmatic chambers in the earth's mantle were first studied by G. S. GORSHKOV (1956) who proposed the analysis of body waves from far earthquakes. However, since it is difficult, for such earthquakes, to take into account all the factors affecting the attenuation of the seismic wave energy, it was suggested subsequently the use of near earthquakes as more effective to localize magmatic chambers (FEDOTOV and FARBEROV, 1966).

This work is an attempt to make a further step on the way of using seismic methods for studying local heterogeneities in the mantle under volcanoes.

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An « intrascopy » (1) with P- and S-waves of the volcanoes of the central part of the Kamchatka eastern volcanic belt was carried out (Fig. 1). Earthquakes of energy class K from 7 to 11 having focal depth of 0-120 km and epicentral distances between 20 and 300 km were used. The main data on these earthquakes — which had been recorded in the studied area from 1961 to 1968 — are published in

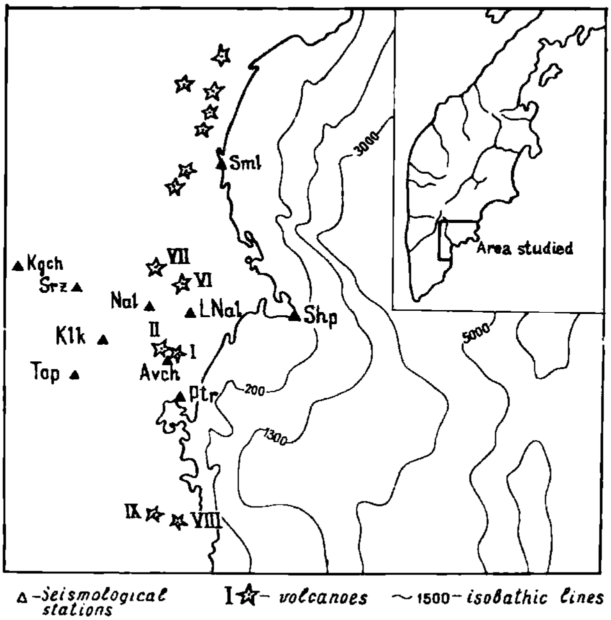


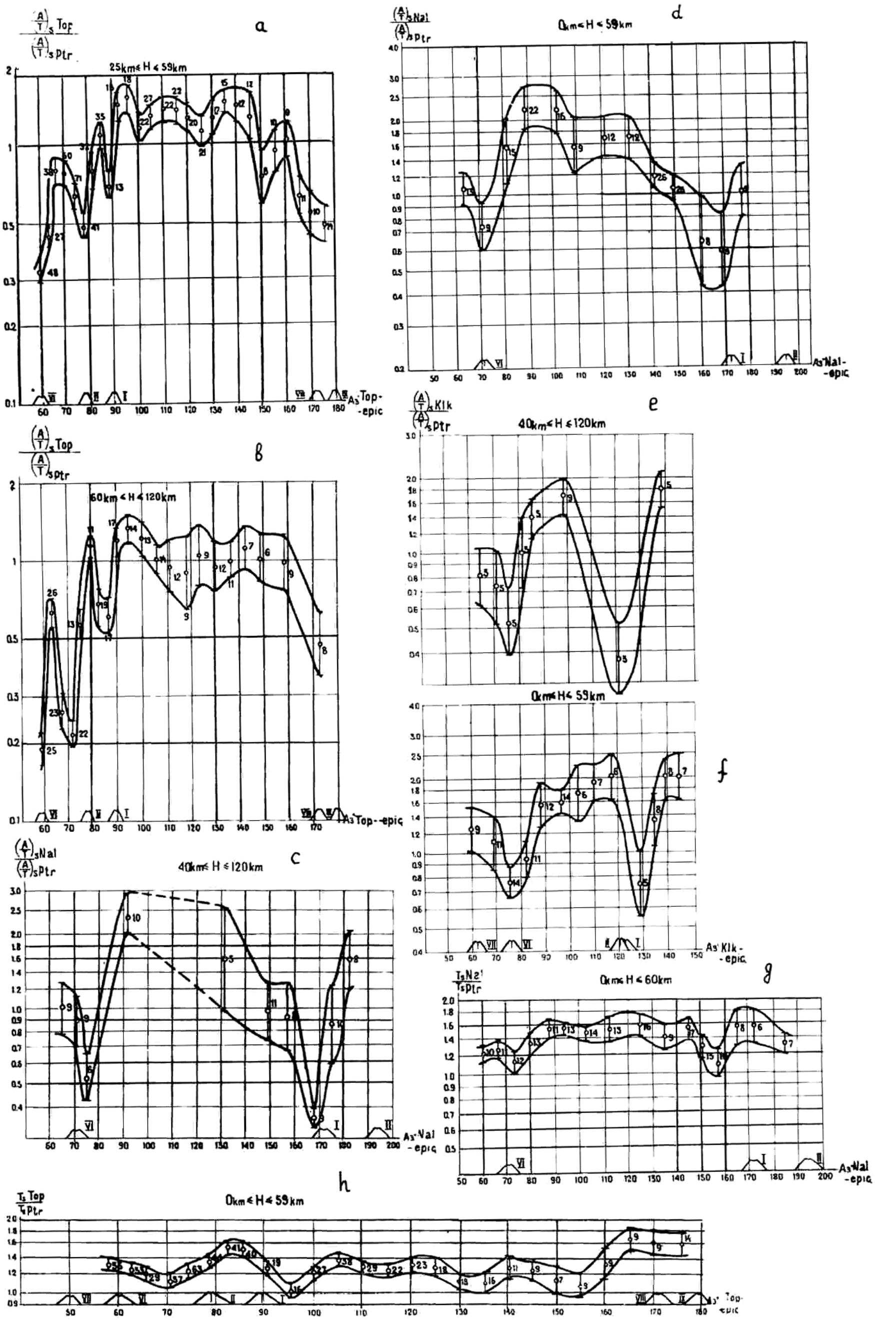
FIG. 1 - Sketch map of the studied portion of the Eastern Kamchatka volcanic belt. Volcanoes: I = Avachinsky; II = Koryaksky; VI = Zhupanovsky; VII = Dzenzursky; VIII = Mutnovsky; IX = Gorely.

the seismological bulletins of the USSR Far East. The seismic stations were equipped with regional type instruments ensuring a rather good reproduction of ground displacements within the frequency range of 1-10 cps.

Methods and Results of the Seismic « Intrascopy »

The Petropavlovsk station (Ptr) was chosen as the standard seismic station because the waves from the foci of most of the

(1) Medium examination by seismic waves.


a
25km ≤ H ≤ 59km
b
60km ≤ H ≤ 120km
c
40km ≤ H ≤ 120km
d
0km ≤ H ≤ 59km
e
40km ≤ H ≤ 120km
f
0km ≤ H ≤ 59km
g
0km ≤ H ≤ 60km
h
0km ≤ H ≤ 59km

observed earthquakes propagated towards this station do not encounter volcanoes. Amplitude of the oscillation velocity A/T and the visible periods of P and S waves recorded at the stations located on the other side of the volcanoes with respect to the epicenters were compared with the same dynamic parameters obtained at the Ptr station.

The maximum amplitude of displacements A was measured on seismograms together with its respective period T in the record interval from arrival to 1.5-2 sec for P waves (vertical component) and 3-5 sec for S waves (both horizontal components). Since the periods of P- and S-waves did not exceed 0.5-0.6 sec and 1.0-1.2 sec respectively, the maximum amplitude, close to the computed, was found as a rule on the third or subsequent oscillations.

To account for differences in epicentral distances for the stations to be compared with the Petropavlovsk station, corrections by the curves $(A/T)_s = f\,(\text{S-P}, \text{H})$ and $(A/T)_p = f\,(\text{S-P}, \text{H})$, constructed for Kamchatka by FEDOTOV (1969), were introduced in the values of $(A/T)_s$ and $(A/T)_p$.

In this work, orientation of planes and directions of movements at the foci of weak earthquakes of the focal zone are assumed to be random. If this assumption is true in each interval of azimuths to epicenter the values of the dynamic parameters for two stations should be considered as mean statistic values. Only those earthquakes whose azimuths for the compared pairs of stations differed by no more than 25° were considered.

Subdivision of the group of experimental points into intervals to obtain gravity centers by which azimuth dependences were constructed (Fig. 2) was made using the method of sliding intervals with overlap of 50 % as a rule. A large overlap is needed because of the « mobility » of points, since the maximum accuracy in determining the epicenter positions was about ± 5 km. For the same reason the intervals were not less than 7-8° wide which corresponds to a section

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FIG. 2 - Oscillatory velocity amplitudes and visible period ratios vs. azimuth to the epicenter.
The two curves show the reliable interval with 0.7 reliability level.
Open circles = interval gravity centers. The figures indicate the number of points in the respective interval.
H = depths of earthquake foci.
Cones = sectors of directions from the receiving stations to the volcanoes. Symbols of volcanoes are the same as in Fig. 1.

15-20 km long since the considered hypocentral distances exceed 100 km. The reliable interval for each of the gravity centers forming the curve was evaluated utilizing the Student law. The position of the gravity center and the dispersion value of a single measurement were therefore considered to be unknown and were evaluated in each case (SMIRNOV and DUNIN-BARKOVSKY, 1969). The reliability level, owing to a strong scattering of experimental data, was assumed to be equal to 0.7.

As it can be seen from Fig. 2, the curves oscillate sharply. Minima on the experimental curves are located within the azimuth intervals corresponding to the S-wave directions of propagation towards the stations, passing under the regions of the Avachinsko-Koryakskaya, Zhupanovsko-Dzenzurskaya and Mutnovsko-Gorelovskaya volcanic groups.

The groups of volcanoes on the whole (and not the single volcanoes) are characterized by a 45-85 % reduction of the relative intesity of the seismic signal at different stations, and there is a tendency towards an intensification of the effect with depth. The probability that the observed oscillations, evaluated by means of « t » acc. to the Student's method, are not of a casual nature is not less than 90 % for all the observed experimental curves.

A general characteristic of the relation between visible periods and position of earthquake epicenters is the presence of local maxima closely followed by minima (Fig. 2).

A reduction of the signal intensity (formation of zones of seismic shadow) and a relative increase of visible periods of S-waves by 15-35 % is observed practically in the same sector of directions. Qualitatively similar results are obtained for P-waves. However, a reduction of the relative intensity of the signal under the Avachinsko-Koryakskaya group of volcanoes for P-waves is $\sim$ 2.5-3 times less than for S-waves.

The Type of Phenomenon

The seismic shadows observed along different directions overlap each other in the area of the studied volcanic groups (Fig. 3), suggesting the presence, in the interval of depths of $\sim$ 30-90 km, of local heterogeneities with mechanical properties different from those of the enclosing medium.

The observed increase of visible periods of oscillations registered in the shadow zone and their decrease in the adjacent « light » zone, corresponds well with the predictions of the diffraction theory (PHINNEY and CATHLES, 1969) and, together with the presence of shadow

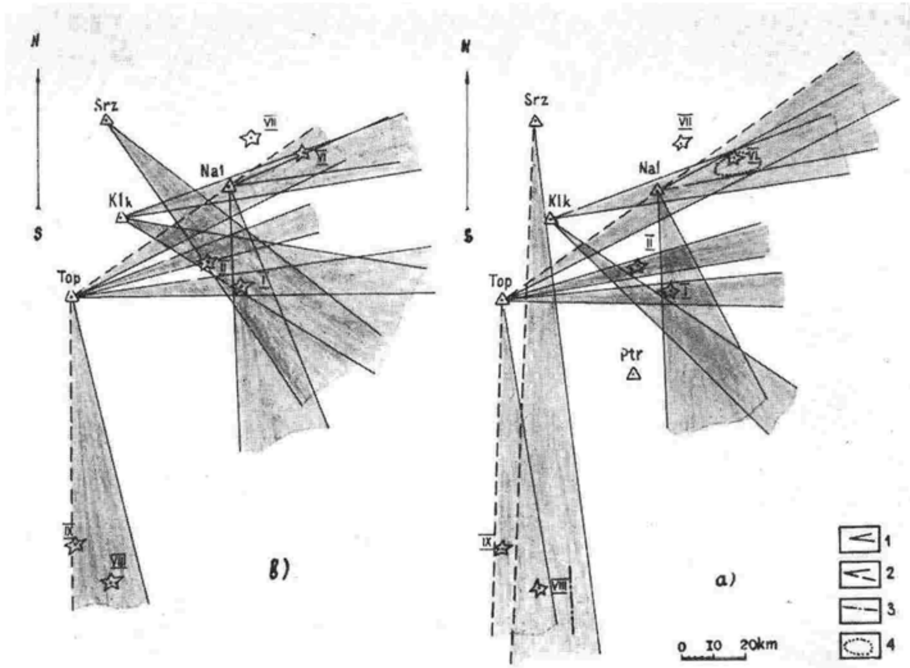

FIG. 3 - Seismic shadows under the observed volcanoes in the depth interval: *a*) ∾ 30-40 km; *b*) ∾ 40-90 km.
Sector of directions: 1 = S-wave strongest attenuation; 2 = cases when the position of one of the shadow boundaries is not exactly defined (« normal level » on the experimental curve is reached only on one side from the minima); 3 = possible position of the eastern boundary of the heterogeneity under Mutnovsky; 4 = possible position of the heterogeneity under Zhupanovsky.
Symbols of volcanoes and seismic stations are the same as in Fig. 1.

zones, indicates that the observed effect is essentially due to diffraction phenomena. This fact and the seismological data on local reduction of longitudinal wave velocities by 0.3-0.5 km/sec in the upper mantle under some volcanic groups of Kamchatka (SLAVINA and FEDOTOV, 1969) made it possible to assume a reduced elasticity for the substance within the observed heterogeneities in comparison with the enclosing medium. Difference in wave resistances between the medium and the diffracting bodies must be not less than 5-10 % (MIKHAILOVSKY and PERVUSHIN, 1968).

The width and the position of the seismic shadows allowed us to determine the location of a diffracting body under the Avachinsko-Koryakskaya group of volcanoes. It must be stressed out that on a number of experimental curves in the middle of the shadow zone, local maxima of the intensity of transversal oscillations were observed opposite to the region located between the Avachinsky and Koryaksky volcanoes (Fig. 2 a-d). The experimental data available did not allow us to establish reliably whether this phenomenon is connected with focusing of rays passing through the heterogeneity with reduced elastic properties, or it is a diffraction effect, arising beyond the opaque (strongly absorbing?) obstacle, or there are two separate heterogeneities under the Avachinsko-Koryakskaya volcanic group.

The boundaries of the geometric shadow and the contours of the corresponding heterogeneities (Fig. 4) have been drawn on the basis of different assumptions on the type of polarization of transversal oscillations relative to the surface of diffracting body.

According to these assumptions the horizontal dimensions of the heterogeneity in the interval of depths of $\sim$ 40-90 km under the Avachinsko-Koryakskaya group of volcanoes vary from about 8×15 km to about 15×40 km (if only one obstacle is present).

The error in determining the area of the heterogeneity cross-section in this interval of depths, caused by the absence of data on the type of polarization of S-waves, is not less than 50 %. Additional errors are caused by the asymmetry of the experimental curves, and by the choice of the azimuth interval where a seismic field may be considered undisturbed. Nevertheless, on the basis of the observations made, it is possible to assume the presence of a volume of anomalous material under the Avachinsko-Koryakskaya volcanic group in the interval of depths of $\sim$ 30-90 km. This volume has the form of a wedge narrowing upwards.

The cross-section of the lower part of the heterogeneity (or heterogeneities) is isometric in shape and is not less than 1.5-2 times greater than the cross-section of the upper part located in the Mohorovicic discontinuity area (depth of $\sim$ 30-40 km) and has the form of a narrow ribbon stretching to the Northwest approximately coinciding with the volcanic group strike.

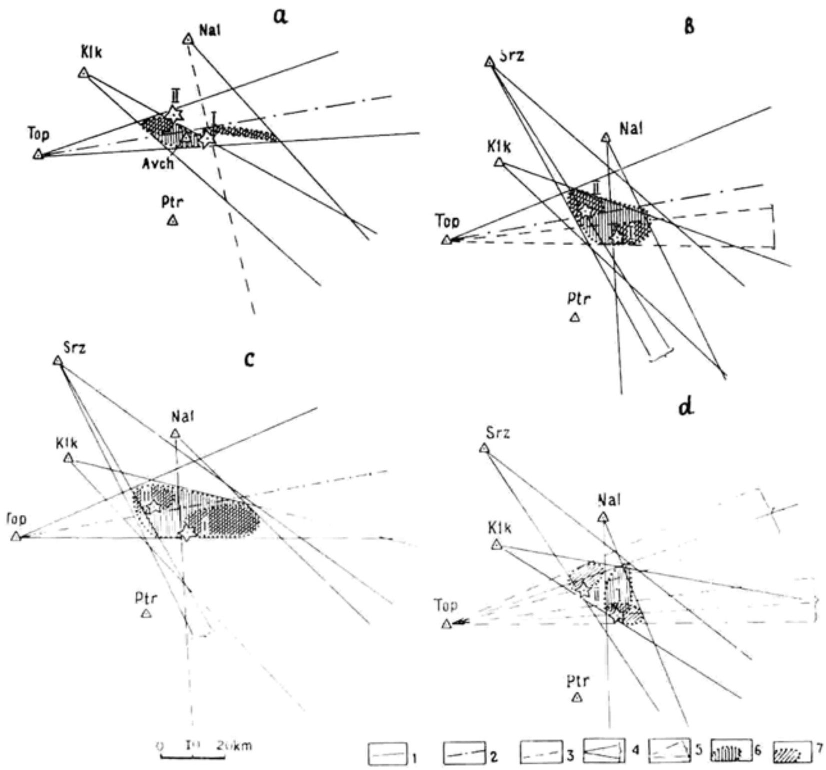

FIG. 4 - Topographic boundaries of the geometric shadow and contours of the heterogeneity under the Avachinsko-Koryaskaya volcanic group acc. to the following assumptions:

a) SH-polarization (shadow boundary shift inside the shadow zone) (SATO, 1968; TENG and RICHARDS, 1969). Depth interval ∾ 30-40 km.

b) No shadow boundary shift relative to the geometrical shadow shift; depth interval ∾ 40-90 km.

c) SH-polarization; depth interval ∾ 40-90 km.

d) The shadow boundary shift relative to the geometrical shadow shift is the same as in the case of P-wave diffraction on a semi-transparent body (MIKHAILOVSKY and PERVUSHIN, 1968). Geometric shadow boundaries are approximated by minimal width of the physical shadow. Depth interval ∾ 40-90 km.

1 = geometrical shadow boundaries; 2 = direction of increased S-wave intensity; 3 = « western » boundary of shadow, evaluated acc. to the minimum width of the physical shadow from Fig. 2d; 4 = possible extreme positions of the « southwestern » boundaries of geometric shadow due to uncertain data from the Srz station; 5 = azimuth interval in which the shadow depth at the Top station comprises 50 % of the « normal level » value of the curve of Fig. 2b; 6 = heterogeneity contours in the hypothesis of only one body present; 7 = same, with two bodies present.

Viscosity of the Heterogeneities

In a previous work (GORELCHIK and FARBEROV, 1969) it was shown that the portions of upper mantle under certain volcanic groups of Kamchatka are characterized not only by an increased attenuation of body waves, but also by aseismicity. In particular, under the Avachinsko-Koryakskaya group of volcanoes an aseismic area with horizontal dimensions $\sim 20 \times 30$ km was found in the interval of depths from the earth's surface to the earthquake focal layer included.

Evidently, reduced viscosity of the material under volcanoes leads to the fact that within the aseismic area an energy sufficient for a discharge by earthquakes of energy class $K \geq 7$ cannot accumulate. Therefore, it seemed interesting to evaluate the viscosity of that part of the area which is within the focal layer.

As it is known, a part of the potential elastic energy accumulated in a medium, E_p, is transformed during an earthquake into seismic energy, E_s, according to the following relation:

$$E_s = E_p \cdot n \cdot c = \frac{\sigma^2}{2G} \cdot V \cdot n \cdot c \qquad [1]$$

where: σ = stress; G = shear modulus;

V = volume of the earthquake focus;

n = coefficient of transformation of the earthquake potential energy into elastic wave energy;

c = coefficient indicating the portion of deformation released during the earthquake.

The material at depths of $\sim$ 70-150 km has properties close to the Maxwell medium (MAGNITSKY, 1965) where stresses increase according to an exponential law if the deformation velocity, $\dot{\varepsilon}_0$, is constant. Then:

$$\frac{\eta^2 \dot{\varepsilon}_0^2}{2G} (1 - e^{-t/\tau})^2 nc = \frac{E_s}{V} \qquad [2]$$

where: τ = time of relaxation;

t = period of preparation of earthquake;

η = viscosity.

In the focal zones during the period of preparation of earthquake t is almost equal to τ (ZUBKOV, 1969). Since only the order of magnitude of viscosity is evaluated, the exponential multiplier in [2] can be assumed to be equal to 1 and viscosity can be computed by:

$$\eta = \frac{1}{\dot{\varepsilon}_0} \sqrt{\frac{2GE_s}{ncV}} \qquad [3]$$

Let us assume that, in the considered area under the volcanoes, earthquakes of the 5th energy class would occur, *i.e.* 2 classes below the smallest earthquakes to be possibly detected in this region, at the mentioned depths, by the present network of stations. For the calculation of η we will utilize the method given by RIZNICHENKO (1960) to evaluate the dimensions of earthquake foci using wave lengths.

For earthquakes with K = 5 the value of the ratio E_s/V is about 85 erg/cm^3. Let us use the typical value $\dot{\varepsilon}_0 = 5 \times 10^{-14}$ sec^{-1} for seismoactive regions (MAGNITSKY, 1965). The average values of n and c are taken as 0.3 (RIZNICHENKO, 1960). The shear modulus is assumed to be equal to 5×10^{11} din/cm^2. With such values of the parameters, η is about 6×10^{20} pois.

As a first approximation this value can be considered the upper possible limit of viscosity in the aseismic portions of the focal layer under the Eastern Kamchatka volcanoes at depths of 70-150 km.

Roots of the Volcanoes

Local heterogeneities under volcanoes are observed from depths of $\sim$ 80-90 km up to the lower horizons of the crust. Aseismic portions in the earthquake focal layer under volcanic groups extend to still greater depths, *i.e.* 150-230 km (GORELCHIK and FARBEROV, 1969).

The mentioned depths correspond to those levels in the upper mantle at which magma generation in the Kurile-Kamchatka volcanic zone is believed to occur by most researchers. This fact and the reduced elasticity and viscosity of the material within the observed heterogeneous zones extending upwards, and their spatial confinement to volcanic groups, make it possible to assume that these structures are magmatic chambers of active volcanoes.

The data obtained during this research do not allow us to evaluate the degree of material liquescency within the observed heterogeneous bodies, but point directly to connecting such structures located under volcanoes with the upper mantle.

Geophysical data indicate the absence of liquid layers extending for tens or hundreds of kilometers under volcanic regions within the mantle block contained between the crust lower part and the earthquake focal layer. But it may be assumed that an area or, rather, certain zones of intensive melting in the upper mantle extend as a comparatively narrow band along the whole East Kamchatka volcanic belt. From them streams of magmatic material originate which get narrower upward. The arrival of these streams at the earth's surface leads to the formation of volcanic centers.

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