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On some theoretical problems of volcanology

(With 2 plates)

One of the main problems in present-day volcanology is the question of the depth of magmatic reservoirs. A correct solution of this problem determines ways of solving many other related questions of volcanology, structural geology, theory of ore deposition, tectonics and physics of the Earth.

It is for a long time already that volcanological literature is dominated by the idea of a shallow occurrence of magmatic reservoirs. However this point of view, which became a tradition, is based on various more or less arbitrary premises and is not substantiated by any geophysical observations. The author tried to determine the depth of the magmatic reservoir of the Kliuchevsky volcano, taking advantage of the discovered screening effect of transverse seismic waves (1).

During seismic observations, which had started in autumn of 1948, seismographs of the Kamchatka volcanological station (village Kliuchi) had registered many hundreds of local and distant earthquakes. Local earthquakes did not vary much from similar earthquakes of other regions; the presence with shallow hypocenters of arrivals of $\overline{P}$, P^* and P waves, as well as $\overline{S}$, S^* and S waves proved that the structure of the crust in the region of Kamchatka does not differ from the structure of the crust in other continental areas, i.e. there are here granitic and basaltic layers of a considerable thickness.

In recording the majority of distant earthquakes a distinct arrival of P and S phases was observed, which indicated the absence of a continuous layer of liquid magma under the crust, which, possessing a sufficient thickness, would inevitably screen off all transverse waves. An exception in this respect was only a certain part of Japanese earthquakes. Earthquakes from the region of the islands Hokkaido and Northern Honsyo were still recorded sufficiently fully; on the other hand, earthquakes with epicenters in southern parts of Japan, over twenty of which have been recorded, had on seismograms of the station « Kliuchi » only records for longitudinal waves (P, PP, etc), while direct transverse waves S were absent. Earthquakes located on the same azimuth as Japan but from more distant regions (Philippine islands, Celebes) again have on their seismograms distinct arrival of phase S.

A possible reason for the absence of S waves on seismograms could be the unfavorable position of the station in respect to the forces in the hypocenter. However, as demonstrated by latest studies (2-4), the majority of earthquakes within the area of island arcs is determined by shifts in a direction approximately perpendicular to the margin of the continent, i.e. in a direction most favorable for recording a transverse wave on the station « Kliuchi ». On records of the station « Petropavlovsk », located approximately on the same azimuth from the Japanese islands as the station « Kliuchi », a distinct phase S is present. It is quite obvious that this suggested reason proves to be invalid.

A possible case of a sharp decrease of the energy wave on a corresponding epicentral distance has not been analysed by us in detail, because earthquakes from other regions with the same epicentral distance as Japan (Alaska, for instance) display a distinct S phase. The station « Magadan », situated at the same distance from Japanese epicenters as the station « Kliuchi », contrary to the latter, registers a distinct arrival of S waves. Apparently, the question is not in the epicentral distance and this second suggested reason for the absence of S waves on seismograms of the station « Kliuchi » for South-Japanese earthquakes is also unacceptable.

Fig. 1 illustrates the above-said.

It is obvious that the absence of transverse waves on records is determined by a purely local reason - the existence in the vicinity of the station of a peculiar « screen ». Epicenters of earthquakes, the records of which have no phase S, are at a distance from 24 to 48-50° along azimuth 213-230° from the station « Kliuchi ». The said direction passes through the Kliuchevskaia group of volcanoes. The most natural and plausible explanation seems to be that the reason for a seismic shadow for direct transverse waves is their screening off by a liquid magmatic reservoir.

Knowing the distance to the summit of the volcano, i.e. up to the volcanic chimney connecting the magmatic reservoir with the surface, and, having determined the emergence angle of the screened waves, it is easy to calculate the depth of the « screen » - the magmatic reservoir. Angles of emergence for P waves of different epicentral distances are given in many textbooks; to make calculations easier it is accepted that longitudinal and transverse waves travel along the same path. However, a priori it is possible to say that this is not true, because their velocities are different, which means that at a given epicentral distance the angles of emergence for longitudinal and transverse waves will be different. Thus we can not use tables and charts of emergence angles for P waves but must determine the angle of emergence for S waves.

This angle can be determined by differentiating the hodograph:

$$\operatorname{Cos} e = \frac{dT}{d\Theta} \, Vs \qquad [1]$$

where e - angle of emergence, T - travel time of the wave along the epicentral distance Θ, Vs - velocity of the transverse wave near the surface of the earth.

The value of the derivative of the hodograph function T (Θ), given at equal intervals of argument h, is determined according to the formula (5):

$$\left.\frac{dT}{d\Theta}\right|_{\Theta = \Theta_0} = \frac{1}{h}\left\{ \frac{\Delta^1_{\frac{1}{2}} + \Delta^1_{-\frac{1}{2}}}{2} - \frac{1}{6}\,\frac{\Delta^3_{\frac{1}{2}} + \Delta^3_{-\frac{1}{2}}}{2} + \right.$$

$$\left. + \frac{1}{30}\,\frac{\Delta^5_{\frac{1}{2}} + \Delta^5_{-\frac{1}{2}}}{2} \cdots \right\} \qquad [2]$$

where $\Delta^k_{-\frac{1}{2}}$ and $\Delta^k_{\frac{1}{2}}$ (k = 1, 2, . . .) — successive differences of the K order; the process by which they are being compiled is shown by the following table:

Θ	T				
$\Theta_o - 2h$	T_{-2}				
		$\Delta^1_{-\frac{3}{2}}$			
$\Theta_o - h$	T_{-1}		Δ^2_{-1}		
		$\Delta^1_{-\frac{1}{2}}$		$\Delta^3_{-\frac{1}{2}}$	
Θ_o	T_o		Δ^2_0		Δ^4_0
		$\Delta^1_{\frac{1}{2}}$		$\Delta^3_{\frac{1}{2}}$	
$\Theta_o + h$	T_{+1}		Δ^2_1		
		$\Delta^1_{\frac{3}{2}}$			
$\Theta_o + 2h$	T_{+2}				

Values Δ^k in each column of this table are differences between values standing in the two corresponding lines of the preceeding column. Thus

$$\Delta^1_{-\frac{1}{2}} = T_o - T_{-1}\,;\ \Delta^1_{\frac{1}{2}} = T_1 - T_o\,;$$

$$\Delta^2_{-1} = \Delta^1_{-\frac{1}{2}} - \Delta^1_{-\frac{3}{2}}$$

etc.

Fig. 2 in graphic form gives results of computations for the emergence angle of S waves, as well as a chart for the emergence angle of P waves. As we see there is a very marked difference between the angles for emergence for the waves P and S for each epicentral distance.

It should be added that a numerical differentiation of experimental curves, as for instance the hodograph, does not provide absolutely precise results; a quite sufficient precision, for our purposes, could be obtained by a much simpler method in replacing the derivative by a ratio of finite increments. If we replace then in formula [1] Vs by its numerical value $= 3.5$ km/sec we will get:

$$\text{Cos e} = 3.5 \frac{\delta T}{\delta \theta} \qquad [3]$$

or translating kilometers into degrees:

$$\text{Cos e} = 0.031 \frac{\delta T}{\delta \theta} \qquad [4]$$

The screening off of transverse waves at the station « Kliuchi » happens at epicentral distances from 24 to 48-50°. According to fig. 2 these epicentral distances correspond to angles of emergence for S waves from 57½° up to 64½°.

The depth of the « screen » - H in horizontal projection to its location in 1 is equal to:

$$H = 1 \text{ tge} \qquad [5]$$

With the distance from the station to the Kliuchevsky volcano being 33 kms, the depth of the magmatic reservoir is determined to lie at an interval between 50 and 70 km, i.e. virtually on the boundary between the Earth's crust and the mantle. It should be remembered that in recent researches in the extreme East of Asia an increased thickness of the earth's crust has been established - up to 60 km.

Investigating the boundaries of the « seismic shadow », it is possible to have some idea of the shape and size of the magmatic reservoir. The « seismic shadow » has the shape of an elliptic cone sinking under the surface at an angle of about 60°. The angle between the generants in a vertical section (α) is 7° and in a projection to a horizontal plane 15-17°.

This permits us to represent the shape of the reservoir as a convex lens or maybe a triaxial ellipsoid elongated in a latitudinal direction and flattened in a meridional direction. The extension of the reservoir and its thickness can be estimated at 25-35 km. Its volume - approximately 10-20 th. km^3.

II.

Records of many Japanese earthquakes after 8-14 seconds after the calculated by the hodograph but absent arrival S show a distinct arrival of a secondary wave (i_2 on fig. 1). We consider this wave composite, refracted by the magmatic reservoir (along the type of SKS waves) and designate it SRS. Apparently of the same nature are distinct arrivals which follow sometimes at intervals of 14-19 sec. after the arrival of diffracted waves P: (PRP) (i_1 in fig. 1).

By the difference in the time of arrival of direct and composite waves it is possible to determine the velocity of the composite wave in the magmatic reservoir. It is easy to calculate that:

$$V_R = \frac{VH}{H + V\Delta t}, \qquad [6]$$

where V_R - velocity of the composite wave in the magmatic reservoir, V - velocity of the direct wave near the margin of the magmatic reservoir, H - length of travel line of the composite wave in the magmatic reservoir, Δt - difference in time of arrival of the direct and composite wave. H = 30-35 km, Vp = 7.8 km/sec, Vs = 4.6 km/sec, Δt for S = 12-14 sec, for P = 18-19 sec.

According to these data V_R is determined in the interval of 1.6-1.8 km/sec, which approaches the velocity of longitudinal waves in water or loose rocks (under normal pressure).

Considering that the rigidity μ of a substance in a magmatic reservoir is equal or close to zero, we have:

$$V_R = \sqrt{\frac{k}{\rho}} \qquad [7]$$

where K — bulk modulus of a substance and ρ — density of a substance in a magmatic reservoir (3.4 g/cm^3), i.e.

$$K = \rho V^2 \qquad [8]$$

which means that $K = 1 \times 10^{11}$ dynes per cm^2 or 1×10^5 bars.

The inverse quantity - compressibility (β) is determined as 10×10^{-6} bars^{-1}. The obtained value of compressibility is an average between its values for a typically solid body and a typical liquid and is not absurd (for the Earth's mantle $\beta = 0.8 \times 10^{-6}$ bars^{-1}; for the water $\beta = 48.9 \times 10^{-6}$ bars^{-1}).

In such a way the study of seismograms gives also some idea regarding elastic constants of a substance in a magmatic reservoir.

III.

The described solution of the question of depth and shape of a magmatic reservoir and elastic constants of its substance should be regarded as definitely preliminary. However, the above cited considerations should suffice to serve as a basis for a short discussion of some general questions of volcanology:

1. The occurrence of magmatic reservoir on the boundary between the Earth's crust and mantle or, which is more probable, in the upper parts of the mantle is by far not accidental. It is at these depths (80 km) that GUTENBERG (6) had recently discovered lower velocities of seismic waves, and, consequently, a decrease of the elastic constant. The most probable reason for this phenomenon is a transition from a crystalline state into an amorphous condition. On the other hand, H. A. LIUBIMOVA * (7) has calculated that in the upper parts of the mantle there is a certain interval of depths where the curve of temperature practically coincides with the curve of fusion. In such a way in the upper parts of the mantle conditions are predominant which are especially favorable for a transition of substances into a liquid state under a change of thermodynamic conditions. Great tectonic dislocations accompanied by local drops of pressure or rise of temperature must inevitably lead to the formation of magmatic reservoirs.

This quite naturally leads us to appreciating the relations

* Also report at XI General Assembly of IUGG.

between present-day volcanism mainly with the zone of Alpine orogenic movements.

2. In some cases liquid magma which has been formed will be squeezed upward but will not reach the surface of the earth and will consolidâte in basic intrusions. In places where the crust of the earth will be split by superdeep fractures (up to 60-80 km), liquid magma will appear on the surface of the earth in some form of effusive volcanicity. That is why volcanoes are always connected with deep fractures of the Earth's crust. And it does not make any difference in principle whether these fractures will coincide with the zone of recent orogenesis or whether they will split an already consolidated platform or ancient mountain region. As long as a deep fracture is formed (60-80 km), volcanoes would appear in any case. A convincing evidence is provided by present-day volcanoes of Manchuria, Tibet and Eastern Africa, as well as by very young volcanoes of North-Eastern Asia.

Deep fractures are determined only by rows of closely spaced volcanoes and, as a rule, are not accompanied by disjunctive dislocations. On the contrary, apparent faults and shifts are caused by shallow fractures and usually are not associated with volcanism.

3. The occurrence of magmatic reservoirs at a considerable depth where there is no great difference in the chemical composition of the substance, very simply explains the striking similarity in the character of magmas in large regions. With the presence of shallow reservoirs it is impossible to explain the uniformity in the character of lavas on a distance of many thousand kilometers in the geosyncline zone along the periphery of the Pacific ocean. At the same time the difference in lava chemism in a direction perpendicular to the margins of the continents implies a marked difference in the composition of the upper part of the mantle or the lower parts of the crust depending upon the oceanic, geosyncline or continental character of the Earth's crust or, in the end, upon the degree of development of the main geological process — the formation and growth of geosynclines. That

is why lavas of continental volcanoes of Uiun-Holdonga in Manchuria are alike lavas of volcanoes inside the continent of remote East Africa and sharply differ from adjoining lavas of geosyncline volcanoes in Japan.

4. A big role in theoretical ideas of volcanology belongs to the hypothesis of peripheral magmatic reservoirs. Put forward by A. Kircher (8) as early as the XVII century, this theory was reborne on the brink of our century by A. Stübel (9). At the present time Stübel's postulations on the laws governing the development of volcanoes are abandoned, but the idea of peripheral reservoirs continues to dominate many brains.

We are not going to discuss this theory in details. We will only point out that during earthquakes in the regions of Southern Kamchatka and Northern Kurile Islands the waves pass through the Kliuchevskaia group of volcanoes at a depth of about 30 km but no anomalies have been discovered, which means that there could be no accumulation of liquid magma of any substantial volume at this depth.

Local shorth-period earthquakes with epicenters at different small depths (3-20 km) in the region of the Kliuchevsky volcano also do not display any anomalies. Local earthquakes have a period of S waves of 0.2-0.4 sec. These waves would be screened off already by the thickness of a liquid layer of 500-1000 m. Consequently seismic data reject the possibility of a peripheral reservoir existing at shallow depths. Exceptions from this rule are encountered extremely rarely and can be associated only with a metasomatic replacement of carbonate masses, as it is apparently taking place on Vesuvius.

5. When eruptions are taking place with intervals during the first dozens or hundreds of years, there is usually a sharp differentiation in the composition of lavas: the eruptions begin in acid pumices and end with basic lavas (Krakatau, Hekla). The total volume of ejecta of one eruptive cycle rarely exceeds several cubic kilometers. The volume of the volcanic vent 60 km deep is at least 60-80 km^3. It is quite obvious that such an interparoxysmal differentiation so rapid in time and so marked in its chemism is determined by processes in the volcanic chimney.

A slower and less expressed differentiation in the magmatic reservoir determines a gradual change of chemism towards an increase of alcalinity during thousands and dozens of thousands years. A brilliant example of both types of differentiation was illustrated by A. N. ZAVARITZKY on the rocks of Vesuvius (10).

6. Eruptions of different volcanoes in the same volcanic zone which take place at different times are determined by processes in the volcanic chimney. Such eruptions either happen hazardously, or each volcano might have its own rhythm, not depending on the rhythm of neighbouring volcanoes. These eruptions are accompanied by earthquakes with small hypocenters, usually at a depth of 3-5 km.

7. Simultaneous, conjugated eruptions of many volcanoes of one or several volcanic regions are determined by causes of a deeper origin maybe regional and sometimes even planetary which influence simultaneously a group of magmatic reservoirs (Andes, 1932; Kamchatka and the Kuriles 1945-1946). These causes are not quite established yet; they are apparently associated with the activization of tectonic movements. This seems to be indicated by intermediary earthquakes with a depth of 60-100 km, often preceding conjugated eruptions of several volcanoes.

The birth of new volcanoes (Paricutin) or reawakening of extinct (Bezymiannaia sopka on Kamchatka) are also associated with the activization of processes taking place in the reservoir and are also accompanied by earthquakes which are intermediary by their depth.

8. The location of the magmatic reservoir at a considerable depth and the absence of peripheral reservoirs limit the solution of a number of individual problems in the theory of volcanism. For instance, it becomes obvious from this point of view that the formation of calderas can not take place as a result of roof collapse in the magmatic reservoir. It becomes necessary to admit that ESCHER's old idea (11) is correct and that calderas are being formed as a result of

collapse of the walls of a chimney cleared by previous powerful explosions.

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The examples given in the paper show that it is possible to create a general theory of volcanology, which could work out a number of general and individual laws governing the eruptive manifestations on the basis of magmatic reservoirs occurrences at great depths.

It would be most desirable to check our conclusions on other volcanoes. First of all such work could be carried out at the Hawaiian volcanological Observatory and in Japan.

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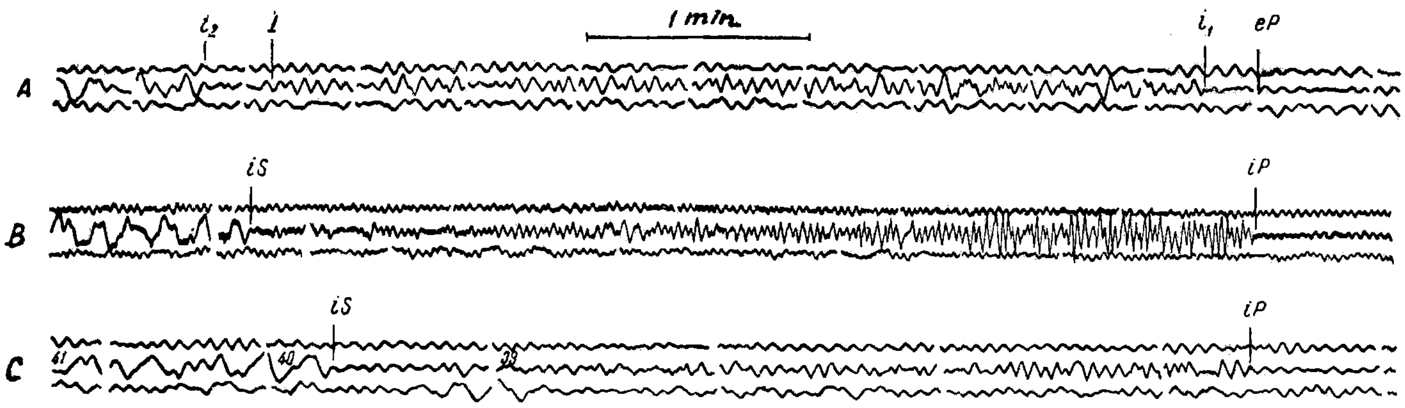

Fig. 1. - Seismograms of the Japanese earthquake on November 27, 1953 at 11 h. 30 m. 08±2 sec. Component N-S.

A - station « Kliuchi », Δ 25°,6;
eP - 11 h. 35 m. 36 sec; i_1 - 11 h. 35 m. 50 sec.;
I - calculated according to hodograph arrival time of absent phase S - 11 h. 39 m. 59 sec.
i_2 - 11 h. 40 m. 17 sec.;
B - station « Magadan », Δ 26°,1;
iP - 11 h. 35 m. 39 sec.; iS - 11 h. 40 m. 06 sec.;
C - station « Petropavlovsk », Δ 22°,2;
iP - 11 h. 35 m. 04 sec.; iS - 11 h. 39 m. 10 sec.

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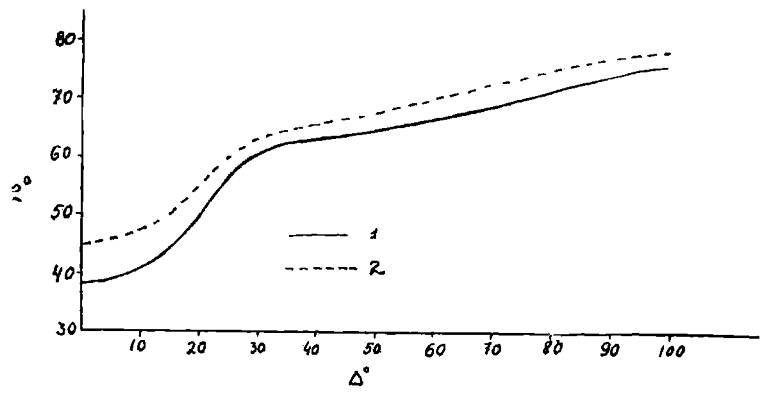

Фиг 2

Fig. 2 - Dependence of the emergence angle of seismic waves upon the epicentral distance.

1 - emergence angles of transverse waves,

2 - emergence angles of longitudinal waves,

e - value of emergence angles,

Δ - epicentral distances.