Anomalous Seismic Effect under Volcanoes and Some Features of Deep-seated Structure of Volcanic Areas *

A. I. FARBEROV and V. I. GORELCHIK
Institute of Volcanology, Siberian Branch of the USSR
Academy of Sciences

Abstract

This paper considers the focal distribution of subcrustal earthquakes and the dynamic features of seismic wave propagation under some volcanic areas of Kamchatka. Under active volcanoes there are aseismic areas of anomalous attenuation of seismic waves. These features suggest the presence of low viscosity zones under volcanoes, in which there are no concentration of sufficient stresses to generate earthquakes. These zones extend down to the focal layer.

Introduction

The presence of the focal layer zone, in which intense fracturing movements are taking place at the ocean-continent boundary, is a typical feature of volcanic belts fringing the Pacific Ocean. It has been noted many times that this zone of earthquakes with intermediate focal depth are directly under the belt of active volcanoes (WADATI and IWAI, 1954, 1956, MAGNITSKY, 1965; FEDOTOV, 1963; TOBIN and SYKES, 1966; OCOLA, 1966; HAMILTON and GALE, 1968). In SHIMOZURU's opinion (1963) all the data directly indicate the depth of magma formation under the active volcanoes.

AKI (1966), DICKINSON and HATHERTON (1967) and TARAKANOV and LEVIY (1967) consider that magma formation can occur in the intersection of the asthenospherical layer at 100-150 km depths with the focal zone descending under the continent.

* Paper presented at the Symposium « Volcanoes and Their Roots », Oxford, England, Sept. 1969.

The study of earthquake focal mechanisms showed that the focal zone is a compressional zone (BALAKINA, 1962), which is probably impermeable for magma. It was therefore assumed that magma uplift takes place directly from the magma formation zone by vertical movement (FEDOTOV, 1966).

Detection of magma uplift areas has been recently done in Kamchatka. The presence of a zone apparently enriched with magmatic material (FEDOTOV and FARBEROV, 1966) was determined by means of S wave-seismic ray attenuation (GORSHKOV, 1956, 1958) under the Avacha-Koryakskaya volcanic group at 20-80 km depths.

High attenuation of S waves was also marked under the Kliuchevskya group volcano at 40-140 km depths (ZOBIN, 1969; FIRSTOV and SHIROKOV, 1969).

In this paper the AA. make an attempt to localize the area which caused the high attenuation of S waves under the Avacha-Koryakskaya group volcanoes. Dynamic features of seismic wave propagation and the distribution of earthquake foci were examined in detail in this area. The spatial distribution of subcrustal earthquake foci was compared with the position of some active volcanoes of Kamchatka.

The data on Kamchatka seismicity for 1961-1968, published in the seismological bulletins of the USSR Far East, were taken as initial material. In addition, data were used on the location of weak earthquake foci with energy $E \geqslant 10^6$ joule for the region of the Avacha-Koryakskaya and Zhupanovo-Dzenzurskaya volcanic groups for the period 1964-1967 (GORELCHIK, 1969).

Phenomena of Anomalous Attenuation of S-waves

Phenomena of anomalous attenuation of S waves under the Avacha-Koryakskaya group volcanoes was done from the seismograms of earthquakes with focal depth H = 25-120 km and epicentral distances Δ = 80-300 km. The records were from the stationary stations Petropavlovsk (Ptr) and Topolovo (Top) and from the temporary stations 1, 2 and 3 which operated in 1966-67.

All the stations were equipped with regional type apparatus with flat frequency response in the 1 to 5 c/s range and magnification from 7,000 to 10,000.

The maximum amplitude of displacement A and the corresponding period T of direct transverse waves were measured on the seismograms. On the record these waves are dominant in the considered interval of epicentral distances. From the measurement data of both horizontal components, the absolute values of the complete vector for the transverse waves, polarized in the horizontal plane, were calculated — $(\bar{A}/T)_{SH}$. All the measurements were made on the record interval which has a 3-5 sec duration from the moment of S wave arrival. About 400 earthquakes were studied.

The problem was to determine what part of the S wave dynamic characteristics was conditioned by the presence of obstacles on the propagation paths of seismic waves to the Topolovo, and 1, 2, 3 stations. These stations are situated on the opposite side of volcanoes with respect to the considered earthquakes. The Petropavlovsk station was chosen as a reference standard because the waves form the foci of the examined earthquakes were propagating to it avoiding the volcanic areas.

The relationship of the ratio values

$$|(\bar{A}/T)_{SH}|_{Top\ 1,\,2,\,3}/|(\bar{A}/T)_{SH}|_{Ptr}$$

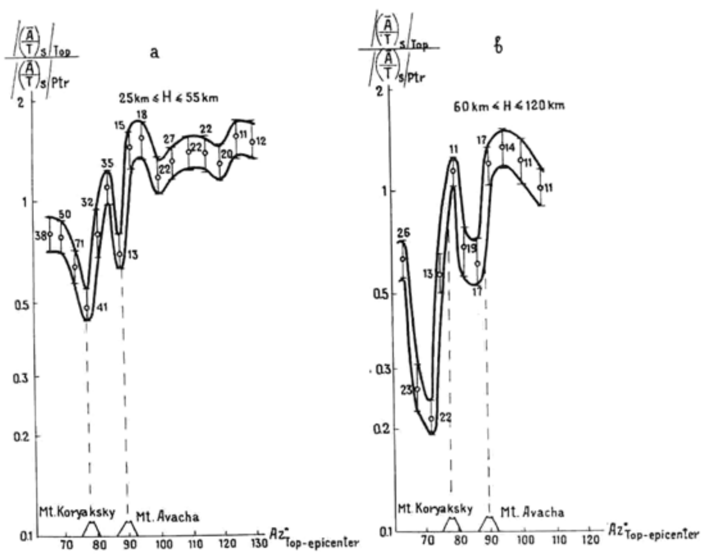

FIG. 1 - Diagram of $\frac{|(\bar{A}/T)_{SH}|_{Top}}{|(\bar{A}/T)_{SH}|_{Ptr}}$ versus azimuths from stations to earthquake epicenters: *a* - earthquakes with $H = 25$-55 km; *b* - earthquakes with $H = 60$-120 km. The gravity centers are indicated by light little circles; the figures above them indicate number of data points which form a corresponding gravity center; the confidence of the gravity centers are shown by thin vertical lines; confidence limits at level 0.7 are shown by solid thick lines.

was studied with respect to the azimuth to the earthquakes epicenter. To eliminate the influence of S wave attenuation depending on distance, the values $(\bar{A}/T)_{SH}$ for each pair of the comparable stations were reduced to the single epicentral distance. For this reason, corresponding corrections were introduced into the values $|(\bar{A}/T_{SH}|_{Top\ 1,2,3}$ according to the curves $\bar{A}/T = f(\Delta, H)$, calculated for Kamchatka by S.A. Fedotov, with allowance for the difference in epicentral distances Δ Top-Δ Ptr, Δ 1-Δ Ptr, Δ 2-Δ Ptr.

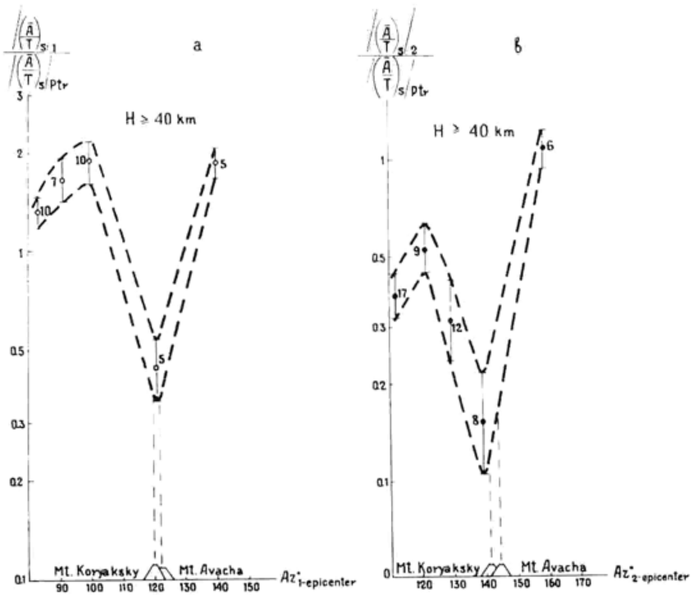

FIG. 2 - Diagram of a: $\frac{|(\bar{A}/T)_{SH}|_1}{|(\bar{A}/T)_{SH}|_{Ptr}}$, b: $\frac{|(\bar{A}/T)_{SH}|_2}{|(\bar{A}/T)_{SH}|_{Ptr}}$ versus azimuth from station to the epicenter for the earthquakes with $H \geqslant 40$ km; the confidence limits at level 0.7 are indicated by the dotted lines. The other designations are the same as in Fig. 1.

To remove the direction factor effect of seismic energy radiation from the focus, the AA. considered only those earthquakes with azimuths to hypocenters which differed not more than 25° for comparable pair of stations.

It was assumed that ground-geological conditions under the stations equally affect the value $(\bar{A}/T)_{SH}$ irrespective of the azimuth of seismic wave arrivals.

For example, the results of experimental data evaluation for the stations Top-Ptr are shown in Fig. 1. In this case the earthquakes were divided into two groups according to their depth of foci $H = 25$-55 km (Fig. 1*a*) and $H = 60$-120 km (Fig. 1*b*). The results of the experimental data evaluation for earthquakes with focal depth $H \geqslant 40$ km are shown in Fig. 2 for the stations 1-Ptr and 2-Ptr [1].

The general feature of all drawn curves is the presence of minimums situated in azimuths corresponding to the direction from the seismic station to the Avacha-Koryakskaya group volcanoes. The values of the confidence intervals of the average centers are considerably less than the oscillation amplitude of the observed curves, which supports the significance of the minimums. The estimations calculated for all curves indicate that the probability of the observed differences being random chance are only about 10 %.

Thus the presence of seismic shadow zones is determined with good certainty at the stations surrounding the volcanic group. The seismic shadow shows a possible position of an obstacle within the limits of some area. The shadow boundaries do not coincide with the boundaries of the geometric shadow because of wave diffraction (Hänl, 1964). The physical shadow width behind the obstacles slightly depends upon the physical parameters of the material in it (Duwalo and Jacobs, 1959; Rubinov and Keller, 1961; Knopoff and Gilbert, 1961; Nussenzveig, 1965; Pervushin, 1967), and it is mainly determined by distances (source-obstacle expressed by X_0, and obstacle-receiver expressed by X), and by the ratio between wave length λ and cross dimensions of the obstacle, expressed by d (Fridlender, 1962; Nussenzveig, 1965; Pervushin, 1967).

Minimum dimensions of the obstacle can roughly be calculated from the size of the seismic shadow zone [2]. The calculations were made for two possible positions of the examined obstacle center — under the Avacha or the Koryaksky volcanoes. On the basis of the

---

(1) In drawing the curves, the division of experimental points into intervals for the calculation of the position of average centers was done by the method of sliding intervals with 50 % intersection. The confidence level of error calculation of the point center was taken to be 0.7. The confidence limits are shown in Fig. 1 and 2 by solid or dotted lines depending on the number of experimental points which form the average center.

(2) This was calculated by the formulas for determination of zone length of the physical shadow behind the obstacle in the form of a disk (Primakoff, 1947), a smooth convex cylinder (Rubinow and Keller, 1961), and an arbitrary form inclusion (Sokolov, 1961).

data of the Topolovo and 1, 2, 3 stations, the minimum cross dimensions of the obstacle are approximately 8-30 km.

As the length of the considered transverse waves is $\lambda \backsimeq 1.8$-4.5 km, then, in our case, is apparently possible to take $d/\lambda \geqslant 4.5$; distance $X_0 \backsimeq 5$-$130\,\lambda$, and $X \backsimeq 10$-$70\,\lambda$.

The estimations of the values X_0/λ, X/λ, d/λ allowed us to delineate the obstacle by the method worked out for geoacoustical sounding of ore bodies in mines (PERVUSHIN, 1967), taking into account the theoretical calculations of diffracted S wave fields (SHOLTE, 1956; NAGASE, 1956; DUWALO and JACOBS, 1959; SATO, 1968; TENG and RICHARDS, 1968*a*, *b*) and the results of ultrasonic modelling of S wave scattering by obstacles of finite dimensions (KNOPOFF and GILBERT, 1961; TENG and WU, 1968).

The sharp peak of the curves in the center of the « seismic shadow » zone (Fig. 1*a* and *b*) can be explained by ray focussing, diffracted from the lateral surfaces of the obstacle, *i.e.* by the « Poisson spot » effect. The peak can also be explained by the presence of two separate obstacles. In our case it is difficult to calculate a coefficient of the resolving capacity of the S wave ray attenuation method for two closely situated obstacles (PERVUSHIN, 1967) because of the asymmetry of the experimental curves.

The maximum value of the peaks of both curves is 70 % higher than the value $|(\bar{A}/T)_{SH}|_{Top} / |(\bar{A}/T)_{SH}|_{Pir}$ for the « normal level » ([3]). In our case X/λ Top $\leqslant 60$, the 70 % value indicates a possible presence of two obstacles (PERVUSHIN, 1967), but still this problem is uncertain because there are no theoretical and model investigations of this problem for S waves.

According to the paths of S wave propagation from the foci of the considered earthquakes to the receiving stations, the examined obstacle or obstacles are situated at $\backsim$ 30-100 km depth interval. Contours of the obstacle or obstacles at $\backsim$ 30-40 km and $\backsim$ 45-100 km depth intervals are shown in Fig. 3*a* and *b*. Estimated relative error of the position determination of the boundaries is within 50 % (PERVUSHIN, 1967).

The position offset in the plan of contours at different depths shows an inclination of the detected obstacle, its lower part being displaced to NW with respect to the upper part.

([3]) The mean of the first diffracted peak.

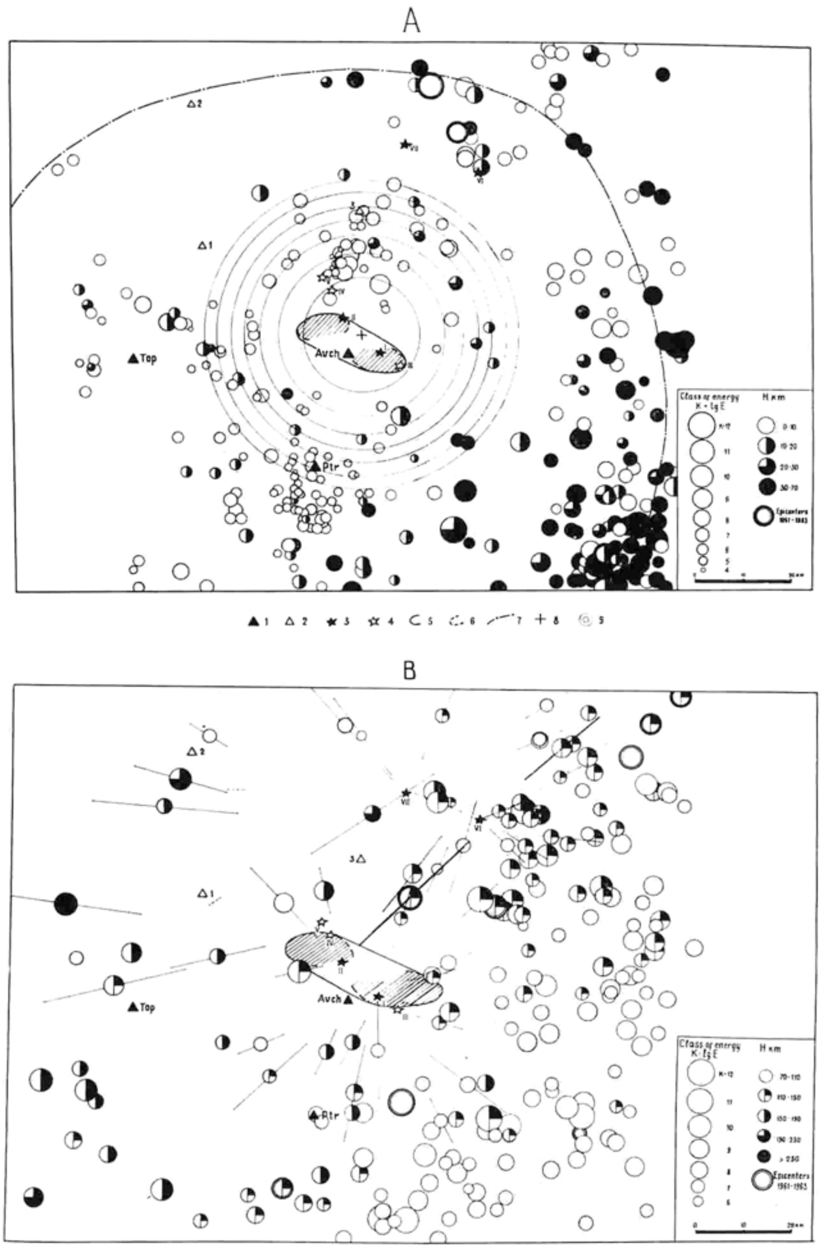

FIG. 3 - Map of earthquake epicenters. *a*: with normal focal depth (0-70 km); *b*: with intermediate depth of the focus (70-250 km) for the region of the Avacha-Koryakskaya group volcanoes for the period 1961-1968: 1 - stationary seismic stations; 2 - temporary seismic stations; 3 - active volcanoes (I - Mt. Avacha; II - Mt. Koryaksky; VI - Mt. Zhupanovsk; VII - Mt. Dzenzursky); 4 - extinct volcanoes (III - Mt. Kozelsky; IV - Mt. Aric; V - Mt. Aag); 5 and 6 - contours of the revealed seismic obstacle or obstacles; 7 - limit of the area where earthquakes with $E \geqslant 10^6$ joule are located; 8 - the conditional center; 9 - the equal volume concentric layers.

The method of observations and the location of the earthquake foci in the region did not allow us to detect the revealed obstacle to greater depths into the mantle or to shallower depths within the earth's crust.

Earthquake Foci Distribution under Some Volcanic Groups of Kamchatka

The maps of the earthquake epicenter distribution with focal depth 0-70 km and 70-250 km are shown in Fig. 3*a* and *b* for the region of the Avacha-Koryakskaya group volcanoes for the period 1961 to 1968 (⁴).

From both maps one can see that crustal earthquake foci with $E \geqslant 10^6$ joule are situated not nearer than 10 km from the craters

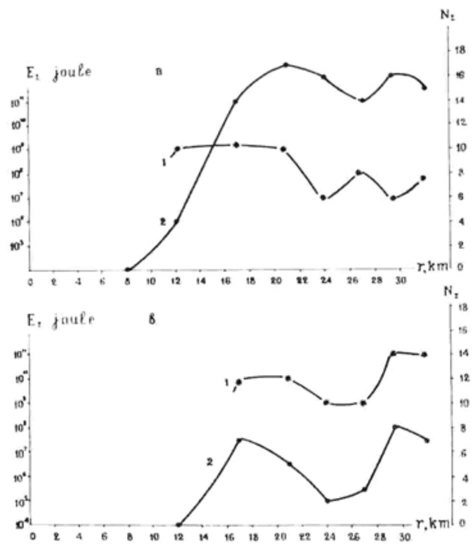

FIG. 4 - The plot of seismic energy and number of earthquakes in the equal volume concentric layers versus distance from the Avacha-Koryakskaya group volcanoes. *a*: for depth interval 0-30 km; *b*: for depth interval 70-170 km; 1 - energy of earthquakes, E_Σ; 2 - number of earthquakes, N_Σ.

(⁴) Coordinates of the foci are determined by depth and epicenter with an error not more than ± 15 km. Location error of the possible position of earthquake epicenters nearest the active volcanoes are shown by thin lines in Fig. 3*b*.

of the Avacha and Koryaksky volcanoes. Subcrustal earthquake foci at 30-100 km depths are displaced away from the volcanoes to a distance of ∾ 30-50 km, and then at 100-170 km depths they return again to about 10 km distance. It should be noted that seismicity at 30-70 km depths is negligible for the whole volcanic belt of Kamchatka.

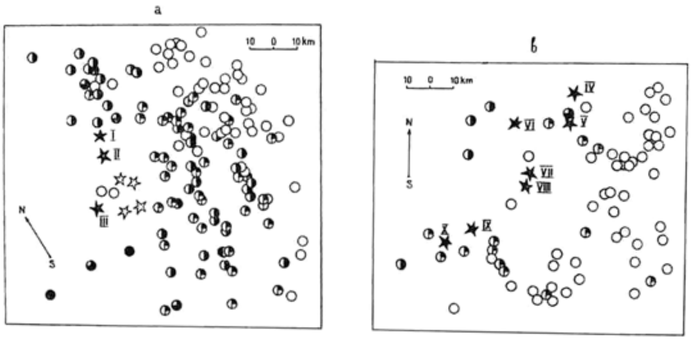

FIG. 5 - Map of the earthquake epicenters with intermediate depth of focus (70-250 km) for the period 1961-1968. *a*: the region of the Kliuchevskaya group volcanoes (I - Mt. Kliuchevskiy; II - Mt. Bezymyanny; III - Mt. Plosky Tolbachik); *b*: the region of the central part of the Eastern volcanic belt of Kamchatka (IV - Mt. Krasheninnikova; V - Mt. Kikhpinych; VI - Mt. Uzon; VII, VIII - Mt. Bolshoy Semyachic; IX - Mt. Maly Semyachic; X - Mt. Karymsky. The other designations are the same as in Fig. 3*b*.

Estimations of seismic energy and earthquake number in equal volume concentric layers under the Avacha-Koryakskaya group volcanoes are given in the form of diagram in Fig. 4. A conditional center, situated midway between the volcanoes, was taken for the zero of the coordinates. The calculations were made for the two depth intervals: 0-30 km and 70-170 km. The maximum distance was not extended beyond 30 km from the chosen center because Zhupanovsky, Dzenzursky and other volcanoes affect apparently the seismic field character at greater distances.

Analysis of the earthquake hypocenter distribution (Fig. 3 and 4) shows that under the Avacha-Koryakskaya group volcanoes there is an aseismic area with dimensions ∾ 30 × 20 km, elongate in a N-W direction and descending into the focal layer at ∾ 150-170 km depths.

A study of the earthquake distributions with intermediate depth of foci was also made for other volcanic regions of Kamchatka. The observation period was also 1961-1968.

An aseismic area, the boundaries of which are fixed by earthquakes with foci 110-230 km below the surface, is revealed under the Kliuchevskaya group volcanoes (Fig. 5*a*). In the central part of the Eastern volcanic belt of Kamchatka there is also an area of absence of intermediate earthquakes on the periphery of which are situated Uzon, Kikhpinych and Bolshoy Semyachik volcanoes (Fig. 5*b*).

The presence of such aseismic zones under volcanoes is also reported for Japanese volcanoes — Mt. Asama, Mt. Fuji, Mt. Aso (WADATI and TAKAHASHI, 1965). SUGIMURA (1966) noted the complementary distribution of volcanoes and epicenters of mantle earthquakes in Japan.

Conclusions

The distribution of subscrustal earthquake foci under active volcanoes was compared with the upper mantle features in the same areas, detected by the method of S wave ray attenuation.

The boundaries of the aseismic area in the region of the Avacha-Koryakskaya group volcanoes coincide rather well with the contours of the obstacle which causes the formation of a seismic shadow.

The same phenomenon is observed in the region of the Kliuchevskaya group volcanoes, where an anomalous attenuation of seismic waves is noted at $\sim$40-140 km depth interval.

The observed coincidence of the general location of the aseismic zones and the upper mantle heterogeneities which cause high attenuation of seismic waves, allows us to assume the same reason of the observed phenomena. As one of many possibilities, we suggest the presence of low viscosity zones under the volcanoes, in which there is no concentration of stresses sufficient to generate earthquakes. These zones descend into the focal layer. The presence of the vertically elongated local heterogeneities in the upper mantle under Kamchatka volcanic belt contradicts Shimozuru's ideas (1963) on magmatic zones as oblated spheroids.

The minimum depth of the lower boundary of the heterogeneities can be estimated by the depths of earthquake foci surrounding the aseismic areas under the volcanoes: 120-230 km depth for the Kliuchevskaya group volcanoes; 100-160 km depth for the Avacha-Koryakskaya group volcanoes; 70-130 km depth for Uzon, Kikhpinych and Bolshoy Semyachic volcanoes. It is noted that more shallow intermediate earthquakes surround the aseismic zones under the volcanoes which erupt more acid lavas (Uzon); and more deep-seated earthquakes surround the aseismic zones under the volcanoes which are more basic (Kliuchevsky).

It is possible that the heterogeneities descend more deeply through the focal layer zone and that they exist without connection wit processes which are taking place in the focal layer zone. However, the elucidation of this problem is beyond the scope of the present investigation.

The authors realize that the above conclusions are based on a short period of observations (∾ 7.5 years), and should be considered as preliminary ones.

Acknowledgements

The authors are deeply grateful to Drs. Z. B. Slavina, S. A. Fedotov, A. A. Tarakanovskiy, S. T. Balesta, P. I. Tokarev for their keen interest, advice and stimulating criticism during the course of this work.

References

AKI, K., 1966, *Earthquake generating stress in Japan for the years 1961 to 1963 obtained by smoothing the first motion radiation patterns.* Bull. Earthq. Res. Inst., Vol. 44, No. 2.

BALAKINA, Z. M., 1962, *General regularities in the directions of the main stresses in the earthquake foci of the Pacific ocean seismic belt.* Izvestia, AN USSR, ser. geophys. No. 11, 1471-1483 (in Russian).

DICKINSON, W. R. and HATHERTON, T., 1967, *Andesitic volcanism and seismicity around Pacific.* Science, 157, p. 801-803.

DUWALO, G. and JACOBS, J. A., 1959, *Effects of a liquid core on the propagation of seismic waves.* Can. Journ. Phys., 37, p. 109-128.

FEDOTOV, S. A., 1966, *Deep structure, upper mantle properties and volcanic activity of the Kurile-Kamchatka island arc according to seismological data from 1964,* in « *Volcanism and deep structure of the Earth* », Vol. 3, Moscow (in Russian).

————, BAGDASAROVA, A. M., KUZIN, I. P., TARAKANOV, R.Z., 1963, *On Seismicity and deep-seated structure of the southern part of the Kurile island arc.* DAN USSR, Vol. 129, No. 4, p. 785-788 (in Russian).

———— and FARBEROV, A. I., 1966, *On screening of transverse seismic waves and magmatic chamber in the upper mantle of the Avacha group volcanoes region,* in « *Volcanism and deep structure of the Earth* ». Vol. 3, Moscow (in Russian).

FIRSTOV, P. P., SHIROKOV, V. A., 1969, *Root localization of the Kliuchevskaya group volcanoes according to the seismic data.* In « *Volcanism, hydroterms and depths of the Earth* ». Petropovlovsk-Kamchatsky (in Russian).

FRIDLENDER, F., 1962, *Sound impulses.* Moscow (in Russian).

GORELCHIK, V. I., (in press), *Distribution of earthquake foci in the region of the Avacha-Korykskaya and Zhupanovskaya group volcanoes in 1964-1967.* Bull. Volcanol. St. No. 46, ed. « Nauka » (in Russian).

GORSHKOV, G. S., 1956, *On the depth of the magmatic chamber of the Kliuchevskiy volcano.* DAN USSR, Vol. 106, No. 4, p. 703-705 (in Russian).

————, 1958, *Some problems of theoretical volcanology.* Izvestia AN USSR, ser. geol., 1958, No. 11 (in Russian).

HAMILTON, R. M. and GALE, A. W., 1968, *Seismicity and structure of North Island, New Zeland.* Journ. of Geophys. Res., Vol. 73, No. 12, p. 3859.

HÄNL, H., MAUE, A., VESTPHAL, R., 1964, *Diffraction Theorie.* Moscow.

KNOPOFF, L. and GILBERT, F., 1961, *Diffraction of elastic waves by the core of the Earth.* Bull. Seismol. Soc. Am., 51, No. 1.

MAGNITSKIY, V. A., 1965, *Internal structure and physics of the Earth* (in Russian).

NAGASE, H., 1956, *Diffraction of elastic waves by a spherical surface.* Journ. Phys. Soc. Japan, 11, p. 279-301.

NUSSENZVEIG, H. M., 1965, *High-frequency scatterring by an impenetrable sphere.* Annals of Physics 34, p. 23-95.

OCOLA, L., 1966, *Earthquake activity in Peru* in « *The Earth beneath Continents* ». Geophys. Monograph 10, p. 509-528.

PERVUSHIN, V. N., 1967, *Examination of sound-ranging methods of ore macrodefectoscopy.* Thesis, Lvov (in Russian).

PRIMAKOFF, H., KLEIN, M. J., KELLER, J. B., CARTENSEN, E. L., 1947, *Diffraction of Sound around a circular disk.* Journ. Acoust. Soc. Amer., 19, p. 132. 515.

RUBINOW, S. I. and KELLER, J. B., 1961, *Shift of the shadow boundary and scattering cross section of an opaque object.* Journ. of Applied physics, Vol. 32, No. 5, p. 814.

SATO, R., 1968, *Body wave amplitude near shadow boundary -SH-Waves.* Journal of Physics of the Earth, Vol. 16, No. 2.

SHIMOZURU, D., 1963, *Geophysical evidences for suggesting the existence of molten pockets in the Earth upper mantle.* Bull. Volcanol., Vol. 26.

SHOLTE, J. G., 1956, *On seismic waves in a spherical earth.* Konikl. Ned. Meteorol. Inst. Publ., 65.

SUGIMURA, A., 1966, *Complementary distributions of epicenters of mantle earthquakes and of foci of volcanoes in island arcs.* Zisin, Vol. 19, No. 2, p. 96-107.

TARAKANOV, R. Z. and LEVIY, N. V., 1967, *Poliasthenospheric model of the Earths upper mantle according to seismological data.* DAN USSR, 176, No. 3, p. 571-574 (in Russian).

TENG, T. L. and RICHARDS, P. G., 1968*a*, *Frequency shift of P and S shadow boundaries.* Trans. Amer. Geophys. Union 49, p. 285.

———— and ————, 1968*b*, *Diffracted SH and SV.* Nature, Vol. 218, No. 5147, p. 1154.

———— and WU, F. T., 1968, *A two-dimensional ultrasonic model study of compressional and shear wave diffraction patterns produced by a circular cavity.* Bull. Seismol. Soc. of Am., Vol. 58, No. 1, p. 171-178.

TOBIN, D. G. and SYKES, L. R., 1966, *Relationship of hypocenters of earthquakes to the geology of Alaska.* Journ. Geophys. Res., 71, No. 6, p. 1659-1667.

WADATI, K. and IWAI, J., 1954, *The minute investigation of seismicity in Japan, 1.* Geophys. Magaz., 25, p. 167.

——— and ———, 1956, *The minute investigation of seismicity in Japan, 2.* Geophys. Magaz. 27, p. 11.

——— and TAKAHASHI M., 1965, *Seismic activity under volcanic areas.* Japan Acad. Proc. Vol. 41, No. 10, p. 938-942.

ZOBIN, V. M., 1969, *Some features of tansverse seismic waves in the region of the Kliuchevskaya group volcanoes.* Trans. of the 1st City meeting of Young Scientists and Specialists, Petropavlovsk-Kamchatsky (in Russian).

Manuscript received Dec., 1969