Elastic Properties of Kamchatka Rocks at Pressures up to 30 kb in Connection with Problems of Deep-seated Structures of Volcanic Areas - Preliminary results *

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Abstract

In this paper compressional and shear wave velocities at quasihydrostatic pressures up to 20-30 kb are reported for rocks of the Kamchatka peninsula. Discussions of the results are made in terms of possible interpretation of the seismic wave velocity distribution in the upper mantle under Kamchatka, which was established by seismological methods. A number of assumptions are made about the composition and the physical conditions of the upper mantle under Kamchatka.

The upper mantle under volcanic areas is characterized by abnormal low values of the seismic wave velocities (FEDOTOV and SLAVINA, 1968). This fact is usually interpreted in terms of specific composition and of specific physical characteristics of the upper mantle under volcanic areas (GORSHKOV, 1967).

Most of the laboratory studies on the velocities of both P and S waves for rocks have been made at pressures not exceeding 10 kb (ca. 35 km of depth) (BIRCH, 1960; SIMMONS, 1964; CHRISTENSEN, 1965, 1966, 1968; KANAMORI and MIZUTANI, 1965). In these investigations rocks from volcanic areas have not been studied sistematically.

Ultrasonic determinations of velocities at pressures of 20-40 kb have been made mainly on the samples from Baltic shield area

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(Volarovich and Levykin, 1965). In the present study, determinations of P- and S-wave velocities of various Kamchatka rocks at pressures of 20-30 kb have been made.

Description of Specimens

There are still great uncertainties about the possible composition of the deep crust and of the upper mantle under the volcanic areas. Therefore, the authors have selected various rock specimens which may be important constituents of the earth crust and of the upper mantle according to the present-day hypotheses.

Effusive rocks (from andesite-dacites to basalts), intrusive rocks (pyroxenite), metamorphic rocks (amphibolites) and ultramafic xenoliths have been studied. Samples of the first group are represented by lavas of Late Quaternary and Recent eruptions of some Kamchatka volcanoes. Late Cretaceous-Paleogenic pyroxenites were from two localities of the ultrabasic belts of Kamchatka. Such belts, according to recent hypotheses (Sheinmann, 1964; Boyd and MacGregor, 1964), would correspond in composition to the residual ultramafic zone of the highest part of the upper mantle which may be present under the volcanic areas after segregation of basaltic melts.

As to amphibolites, these rocks are considered to be one of the possible sources of basaltic magmas (Wagner, 1928; Poldervaart, 1957; Yoder and Tilley, 1962). Some authors have supposed the presence of amphibolites not only in the crust, but also in the upper mantle (Oxburgh, 1964; Ringwood, 1962).

Ultramafic xenoliths are usually considered as erratic masses of upper mantle material (Green and Ringwood, 1968). These rocks are commonly found in the lavas and pyroclastic depostits of the Kamchatka volcanoes (Masurenkov *et al.*, 1969).

The list of the samples is given in Table 1. In this Table the SiO_2 contents in the effusive rocks are also quoted.

Measurement Methods and Results

The method of measurements of P- and S-wave velocities under quasi-hydrostatic pressures was the same as it was described by Volarovich and Levykin (1965). The natural frequency of the transducers was 1 Mc/sec.

Anisotropy of wave velocities for three mutually perpendicular directions has been determined at atmospheric pressure in cube-shaped rock specimens. The cubes were subsequently ground to right circular cylinders of 18 mm in diameter and 20 mm long. The axes of the cylinders have been chosed to be parallel to the direction of maximum velocity in the specimen.

The P- and S-wave velocity measurements were made on the same specimen, and the results of these measurements are shown in Figures 1-5.

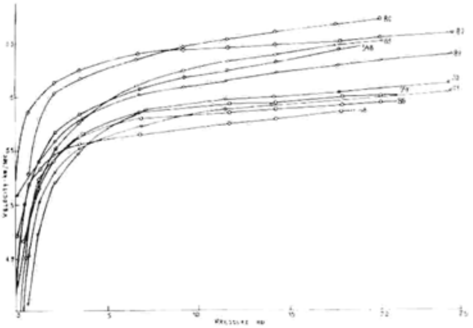

FIG. 1 - Variation diagrams of P-wave velocity with pressure for the effusive rocks of Kamchatka.
Numbers corresponds to sample numbers in Table 1.

The variations of V_P values for the effusive rocks at atmospheric pressure are very large, 2.8 ÷ 5.25 km/sec. This wide range of values may be explained by the great influence of porosity, and especially microjointing, on the elastic wave velocities in roks at the lower pressures. As pressure increases, the effects of microjointing are essentially eliminated, and the area of V_P values is considerably narrowed — $V_P = 5.85\text{-}6.75$ km/sec at pressure of 20 kb (Fgi. 1). At high pressures, the velocity values depend strongly on the mineralogical composition of the individual rock — the more acid and more glassy is the rock the lower is the position of the corresponding curve $V_P = f(p)$ in the diagram of Fig. 1.

The positions and slopes of the curves $V_P = f(p)$ are influenced by the volume and geometry of the pores in the effusive rock (porosity from 1 to 15 %) on the whole interval of pressure adopted in the experiments (WALSH, 1965).

The values of the velocity $V_P = 6.2\text{-}6.5$ km/sec at pressure of 10

TABLE 1 - Description of rock specimens.

Sample No.	*Rock type*	*Locality*	*Specific weight g/cm³*	*Mineral composition vol %*
68	andesite-dacite SiO_2 62 %	Karymsky volcano	2.50	15 pl, 5 px, 50 gl, 30 groundmass (pl+px+mt)
86	andesite-dacite SiO_2 62 %	Karymsky volcano	2.52	20 pl, 10 px, 60 gl, 10 groundmass (pl+px+mt)
70	andesite (SiO_2 57 %)	Koryaksky volcano	2.62	60 pl, 2 px, 28 gl, 10 groundmass (pl+px+mt)
71	andesite (SiO_2 57 %)	Koryaksky volcano	2.50	48 pl, 5 px, 30 gl, 17 groundmass(pl+px+mt)
87	andesite (SiO_2 57 %)	« Camel » extrusion	2.47	10 pl, 2 px, 4 ho, 35 gl, 49 groundmass (pl+px+mt)
79	andesite	Bezymianny volcano, somma	2.54	18 pl, 10 ho, 2 opx, 60 gl. 10 groundmass (pl+mt)
89	andesite-basalt SiO_2 56 %	Avacha volcano, somma, extrusion	2.62	60 pl, 10 opx, 4 cpx, 1 mt, 15 gl, 10 groundmass (pl+px+mt)
85	andesite-basalt SiO_2 56 %	Avacha volcano, somma, extrusion	2.69	40 pl, 3 px, 2 ol, 55 groundmass (pl+px+mt)
548	andesite-basalt SiO_2 55 %	Tao-rysur caldera, Onecotan	2.68	2 pl, 3 px, 25 gl, 70 groundmass
80	basalt SiO_2 55 %	Avacha volcano	2.71	45 pl, 10 px, 5 ol, 25 gl, 15 groundmass
7	intrusive pyroxenite	Karaginsky Is.	3.06	95 cpx, 5 serp
14	intrusive pyroxenite	Kamchatka Middle Ridge	3.19	95 cpx, 3 ca, 1 bi, 1 am
37	intrusive pyroxenite	Kamchatka Middle		

21	intrusive pyroxenite	Kamchatka Middle Ridge	3.09	85 cpx, 10 am, 3 ore mineral, 2 chl
3/1	amphibolite	Kamchatka Middle Ridge	3.20	90 ho, 10 cpx
52	amphibolite	Kamchatka Middle Ridge	3.14	50 ho, 40 cpx, 10 bi
5	amphibolite	Kamchatka Middle Ridge	3.11	86 ho, 5 cp, 7 bi, 2 ca
55	amphibolite	Kamchatka Middle Ridge	3.08	80 ho, 8 hs, 10 pl, 2 mt
39	pyroxenite xenolith	Kirganik pass	3.27	97 cpx, 3 am, mt-traces
10	amphibolized peridotite xenolith	Bezymianny volcano, « Expedition Dome »	3.03	83 am, 10 cpx, 5 ol, 2 opx
1	peridotite xenolith	Avacha volcano, somma	3.17	60 ol, 40 px
2	peridotite xenolith	Avacha volcano, somma	3.19	82 ol, 16 opx, 1 cpx, 1 chr
3	peridotite xenolith	Avacha volcano, somma	3.19	70 ol, 28 opx, 2 chr
1381b	pyroxenite xenolith	Avacha volcano, somma	3.21	95 cpx, 5 ol, cpx, chr-traces
1381c	pyroxenite xenolith	Avacha volcano, somma	3.21	90 cpx, 10 ol, am-traces
1381d	pyroxenite xenolith	Avacha volcano, somma	3.21	85 cpx, 15 ol

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am = amphibole; bi = biotite ca = calcite; chl = chlorite; chr = chromite; cpx = clinopyroxene; gl = glass; ho = hornblende; hs = hastingsite; mt = magnetite; ol = olivine; opx = ortopyroxene; pl = plagioclase; px = pyroxene; serp = serpentine.

kb for the most basic rocks of Kamchatka are in good agreement with the data for the Triassic basalts of North America (CHRISTENSEN, 1968).

At low pressures ($p < 10$ kb) pyroxenites and amphibolites give approximately the same values of P-wave velocities (Figs. 2 and 3).

At higher pressures the values of the curves $V_P = f(p)$ for pyroxenites are a little greater than those for amphibolites. The curves $V_P = f(p)$ for amphibolites, in the pressure range of ca. $10 \div 25$ kb, show a steeper slope than for the corresponding curves for pyroxenites. This fact may be explained by considering the effect of the higher compressibility of amphiboles.

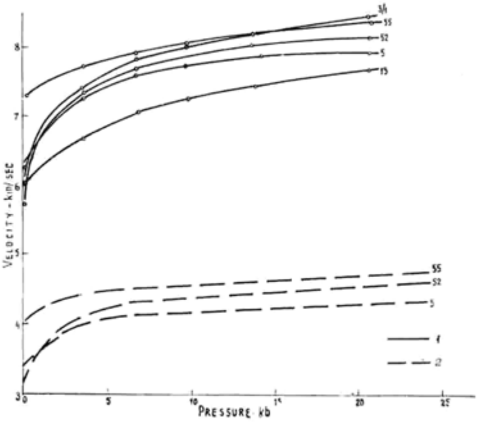

FIG. 2 - Variation diagrams of P- and S-wave velocity with pressure for the Kamchatka amphibolites.
1 = P-wave velocity; 2 = S-wave velocity. The curve No. 13 corresponds to an olivine basalt from the foot of the Piton de la Fournaise volcano, Réunion Island.

The relative positions of the curves $V_S = f(p)$ for the pyroxenites and amphibolites are in general similar to those for the curves $V_P = f(p)$.

As pressure increases, the values of the ratio V_P/V_S, in a pressure range of ca. 7 to 25 kb, decrease slightly from ca. 1.8 to ca. 1.74 for pyroxenites and vary in the range of 1.75 to 1.78 for amphibolites.

The values of P- and S-wave velocities of the Kamchatka amphibolites at a pressure of 10 kb are slightly greater than the values other authors have obtained for amphibolites (BIRCH, 1960; SIMMONS, 1964; CHRISTENSEN, 1965, 1966). This may be due to the presence in their specimens of some amount of low velocity secondary minerals. On the other hand, our specimens contain some amount of high velocity mineral — pyroxene (see Table 1).

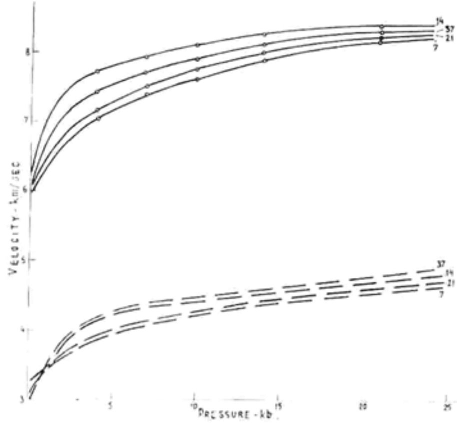

FIG. 3 - Variation diagrams of P- and S-wave velocity with pressure for the Kamchatka pyroxenites.

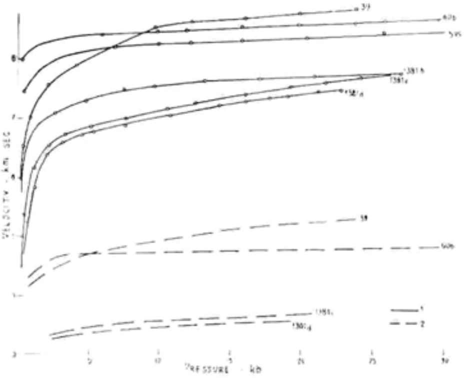

FIG. 4 - Variation diagrams of P- and S-wave velocity with pressure for ultramafic xenoliths (pyroxenites).
1 = P-wave veolocity; 2 = S-wave velocity. The samples Nos. 606 and 599 are from VOLAROVICH and LEVYKIN, 1965.

The P- and S-wave velocities of ultramafic xenoliths are shown in Figs. 4 and 5, in which the curves $V_P = f(p)$ for the peridotites Nos. 587 and 609, and for the pyroxenites Nos. 606 and 599 from the

Baltic shield (¹) are given together with the curves $V_S = f(p)$ for the samples Nos. 587 and 606 obtained by us.

In the whole pressure range considered, ultramafic xenoliths from the Avacha volcano have V_P and V_S values lower than the Baltic shield samples and the pyroxenite xenolith No. 39, which was collected from Late Cretaceous-Paleogene trachybasaltic lava breccia of the Kamchatka Middle Ridge.

The values of the ratio $V_S(606)/V_S(1381c)$, $V_S(587)/V_S(2)$ in the pressure range of 10 to 20 kb are about 1.3, while the values of the ratio $V_P(606)/V_P(1381c)$ is about 1.15-1.20 and $V_P(587)/V_P(2)$ is about 1.05 in the same pressure range. This fact indicates a stronger reduction in V_S than in V_P in the Avacha xenoliths, which are characterized by a value of the ratio V_P/V_S between 1.95 and 2.12 in the pressure range of 5 to 20 kb while the ratio V_P/V_S for the other ultramafic rocks studied is between 1.68 and 1.80.

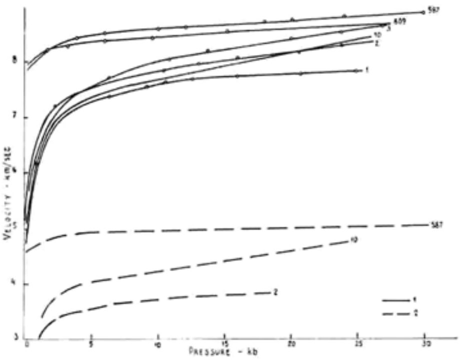

FIG. 5 - Variation diagrams of P- and S-wave velocity with pressure for ultramafic xenoliths (peridotites).
Keys as in Fig. 4. The samples 587 and 609 are from VOLAROVICH and LEVYKIN, 1965.

All the above mentioned differences in the ultramafic rock elasticity can not be explained by the differences in mineral composition of the comparable groups of rocks (see Table 1 and the description of samples in VOLAROVICH and LEVYKIN, 1965). As it was shown recently (LEVYKIN and FARBEROV, 1969) the low elasticity of the Avacha ultramafic xenoliths is due to the microporosity (up to 5 % in volume) of olivine and especially pyroxene grains (MASURENKOV and SELIANGIN,

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(¹) These data are quoted by VOLAROVICH and LEVYKIN, 1965.

1969). The values of the ratio of minor to major axis for these pores range from 0.1 to 1.0. The pressure required to close such pores is 100-1000 kb (WALSH, 1965), a pressure beyond the capability of our apparatus.

The reduction of the ultrabasic xenolith elasticity may be due not only to the effects of some imperfections in the rock structure but also may be produced by a process of rock amphibolization. In such case, however, the S-wave velocity reduction is not greater than the P-wave velocity reduction. This can be seen in Fig. 5 by comparing the corresponding curves for samples Nos. 2 and 10.

Discussion

On the basis of seismological data (FEDOTOV and SLAVINA, 1968) the upper mantle under the Kamchatka peninsula is characterized by a low P-wave velocity, $V_P = 7.2\text{-}7.8$ km/sec. The depths to which such velocities refer are not known exactly and have been estimated by the AA. as 60-160 km.

According to LUBIMOVA (1964), the temperature at a depth of 70 km under the southern Kurile Islands is about 920 C°. Taking this value for the Kamchatka upper mantle and using the appropriate temperature correction factors (BIRCH, 1934, 1958), the longitudinal velocities of the rocks under study were calculated at the above values of depth (2). The results of these calculations are given in Table 2.

The calculated longitudinal velocities in most of the studied rocks (with exception of the effusive rocks) vary in the same range as the V_P data for the upper mantle under Kamchakta given in FEDOTOV and SLAVINA (1968).

The lowest observed value of the P-wave velocity ($V_P = 7.2$ km/sec) may be due to the presence in the mantle of rocks as enriched by the gaseous phase as the Avacha ultramafic xenoliths which are probably the residual products of a volcanic differentiation

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(2) At such depths the temperature estimates are not quite reliable (MAGNITZKY, 1965) and may differ by hundreds of degrees among the various investigators (see, e.g., SMIRNOV, 1968). Therefore the present calculations should be considered as rough estimates of the P-wave velocity because of the temperature data in the upper mantle. Also the correction factors for P- and S-wave velocities should be considered as approximate, this approximation being confirmed experimentally by Soga for forsterite (SOGA *et al.*, 1966).

process. According to MASURENKOV and SELIANGIN (pers. comm., 1968) the depth of origin of the gaseous inclusions in xenoliths is of the order of few ten km. According to an alternative hypothesis (FEDOTOV and SLAVINA, 1968) the residual product is a basaltic material in the upper mantle under Kamchatka. The value of V_P in an olivine basalt (sample No. 13, Fig. 2) from Réunion Island is interesting in this sense, but it must be still confirmed for the analogous Kamchatka rocks.

The pyroxenite xenolith (sample No. 39) from the Middle Ridge of Kamchatka is probably an erratic mass from the upper mantle material (FLEOROV, pers. comm., 1968). This assumption is in agreement with recent P-wave velocity determinations under this region (V_P = 8.0-8.2 km/sec) (SLAVINA and FEDOTOV, 1969).

TABLE 2 - Observed and calculated longitudinal velocities in the studied rocks at 20 kb (depth = ca. 70 km).

Rock type	*Sample No.*	*V_p, km/sec* Observed in the laboratory	*V_p, km/sec* Calculated. Temperature correction factors as in BIRCH, 1943 and 1958
olivine basalt	13	7.62	7.27
pyroxenite xenoliths	1381 b, c, d	7.40-7.60	6.94-7.13
peridotite xenoliths	1, 2, 3	7.80-8.42	6.95-7.50
intrusive pyroxenites	7, 21, 37, 14	8.25-8.50	7.74-7.97
amphibolites	55, 3/1	8.30	7.92
pyroxenite xenolith	39	8.75	8.21

The small differences between V_P values for intrusive pyroxenites and amphibolites (see Table 2) once more indicate to us that it is impossible to determine the mineralogical composition of the upper mantle only on the basis of seismic data. It is not excluded that the velocity anomaly observed under Kamchatka reflects not so much differences in the composition of the mantle under particular structures as differences in the physical conditions.

The observed part of the mantle between the crust and the focal zone is characterized by low seismicity, and is the area of location of magmatic chambers (GORSHKOV, 1967; FEDOTOV and FARBEROV, 1966; GORELCHIK and FARBEROV, 1969). These facts allow one to suppose the existence of high temperatures and tension stresses in this part of the mantle.

The lowest velocities ($V_P = 7.2$ km/sec) are observed for seismic waves passing under the area of the Kliuchevskaya group of volcanoes and, further on the south, under other volcanic zones. Therefore the V_P minimum may correspond to the maximum tension stresses in the upper mantle. This is confirmed from a physical point of view by the experimental data on the decrease of the V_P in granite and marble by ca. 9 % under the influence of tension stresses ranging from 40 to 70 kg/cm^2 (RZEVSKY *et al.*, 1969).

Some decrease in the V_P velocity may be also due to lateral refraction of the seismic waves passing through magmatic chambers located in the upper mantle.

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