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Pressure Dependence of Elastic Wave Characteristics of Ultramafic Rocks of India *

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Abstract. Some precambrian ultramafic rocks from peninsular India (pyroxenites, dunites, peridotites, eclogites and serpentinites) are studied using an indigenously developed pressure apparatus. Measurements of velocity and absorption of ultrasonic compressional waves employing a double transducer pulse method up to a hydrostatic pressure of 5.12 kilobars are reported. The changes in velocity due to pressure are concordant to the changes in attenuation decrements in the majority of the rock samples. In general, both velocity and absorption changes are large and tend to be rapid up to a pressure of 1.5 to 2.0 kilobars and are followed by lower gradients up to the peak pressure. Velocity scatter in olivine and pyroxene rich rocks is found to be reduced with increase in stress. Elastic hysteresis loop area is found to bear a nearly linear relationship with the percentage rise in velocity. The chemical and mineralogical studies on these rocks viewed as against the physico-elastic characteristics reveal that the eclogites are formed at intermediate pressures, while dunites are subjected to deutric alteration at shallow depths, presenting a picture of incomplete differentiation of the mantle magma.

Key words: Pressure dependence – Physico-elastic characteristics – Ultrasound velocity – Ultrasound absorption – Ultramafics of India.

1. Introduction

The study of ultramafic rocks in general and olivine rich rocks such as dunites and peridotites in particular, under different conditions of pressure are important, since olivine is a major constituent of the possible mantle rocks. Laboratory experiments on the elastic properties with emphasis on olivine rich rocks are reported by Birch (1960, 1961), Christensen (1966, 1968, 1971, 1974), Christensen and Ramananantoandro (1971), Afanasyev *et al.* (1965), Bajuk *et al.* (1967), Kanamori and Mizutani (1965), Kumazawa *et al.* (1971), Babuska (1972) and others. These laboratory experiments on rocks under different confining pressures also assume importance in view of the recent seismological evidences (Hess, 1964; Keen and Tramontini, 1970). Some results in brief, on the ultramafic

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rocks from the Indian sub-continent are reported by Ramana and Rao (1974) on the compressional velocities at pressures up to five kilobars but in the present study a fuller analysis of the measurements is made to explain the nature of the variation in physical properties noticed in them.

2. Experimental

The experimental arrangement is due to Ramana (1970) and some particulars of the technique are already reported by Ramana and Rao (1973, 1974). Rock samples of 2.54 cm dia. and 4 to 6.5 cm long are specially prepared to have lapped plane parallel faces. Lead zirconium titanate (PZT) ceramic circular discs of 10 mm dia. and 1 MHz natural frequency vibrating in the compressional mode housed in transducer holders of 2.54 cm dia. and about the same length are attached to either end of each rock sample allowing direct contact between the piezo-material and the test sample. The sample together with the PZT housings are enclosed in a heat shrunkable thin transparent tube and sealed at both ends taking care to let out the required electrical leads. The transit time in the sample is measured to the nearest 0.01 micro second (with a HP Pulse Generator on the driving side and a Tektronix preamplifier and fast writing oscilloscope with delay time movable marker facility on the receiving side) while it is subjected to different confining pressures. The velocity measurements are accurate to $\pm 1\%$. The high pressure apparatus is of the piston-cylinder type for the application of all sided fluid pressure with a sealed bottom encasing the shielded electrical leads. Pressure is produced under a hydraulic ram at 27° C and can be read to ± 30 bars.

3. Results and Discussion

3.1. Chemical Data

Partial chemical analyses of the samples are carried out by standard wet and dry chemical methods (Shapiro and Braunock, 1962) and the results are shown in Table 1. The computed values of mean atomic weight (m) vary between 18.76 (serpentinite) and 22.18 (eclogite) and the present results are in agreement with the results reported by Birch (1961). The average value of m for the samples studied is found to be 21.10 and this is close to the average value of 21.00 for ultrabasic nodules in basalts and kimberlite diatremes (Christensen, 1968) whose composition is similar to the uppermost portion of the earth's mantle.

Some details of the petrography and mineral chemistry, in particular, of Sittampundi eclogites are reported by Rao *et al.* (1974), where the dependence of compressional wave velocity on the mineral chemistry of eclogites is discussed presenting the view that the Sittampundi eclogites crystallized in their intermediate pressure granulite facies. Eclogites are found to be showing a lower Mg/Fe ratio (average 1.36) in comparison to the other ultramafic rocks (average 4.41). The mineralogical and chemical characteristics of the present rocks together with

Table 1. Partial chemical analysis of the rock samples

Wt%	Dunite		Pyroxenite		Picrite	Eclogite		Serpentinite
	N-26	34	CH-4	SR-7	541	SC-99	SC-58	BT-13
SiO_2	42.32	39.17	54.17	52.87	40.67	43.16	40.50	40.67
TiO_2	Tr	Tr	2.40	3.20	0.33	Tr	Tr	Tr
Al_2O_3	2.64	1.57	2.57	3.35	10.01	16.30	20.03	2.52
Fe_2O_3	1.69	2.26	1.06	2.49	0.76	3.76	2.20	3.37
FeO	7.80	7.32	5.56	4.40	9.32	6.08	9.52	3.04
CaO	0.67	1.34	2.35	3.14	5.38	14.35	10.99	1.46
MgO	39.57	44.59	30.37	28.56	31.72	13.54	15.44	36.94
K_2O	0.13	0.11	0.29	0.36	0.26	0.11	0.12	0.26
Na_2O	0.95	0.80	0.95	1.05	1.75	2.00	0.62	0.55
Total	95.77	97.16	99.72	99.42	100.20	99.30	99.42	88.81
'm'	20.37	20.83	21.06	21.53	21.95	22.18	22.14	18.76

the existing information on Indian ultramafics (Diwakar Rao *et al.*, 1975) indicate that the original magma was heterogeneous and not completely differentiated and they resemble the peridotite komatiite of South Africa containing high Ca, low Al, with forsterite type of olivine.

3.2. Velocity and Amplitude

The results of compressional velocity measured at intervals of 1 kb are presented in Table 2 for the different samples together with their density and porosity values. Using these results, the extrapolated velocity values at 10 kb are evaluated from the linear relationships between log (dv/dp) and log (p). This has enabled

Table 2. Compressional wave velocities (m/sec) in ultramafic rocks at different pressure

Sample No.	Rock Type	Density gm/cc	Porosity %	Pressure in kilobars						
				0.001	1	2	3	4	5	(10)
CH-4	Pyroxenite	3.279	0.24	7545	7725	7793	7825	7850	7850	(7885)
SR-7	Pyroxenite	3.250	0.71	7227	7500	7576	7606	7626	7645	(7712)
B-9	Pyroxenite	3.251	4.01	6332	7500	7635	7708	7812	7824	(7996)
N-26	Dunite	3.130	0.99	6537	6840	6988	7062	7110	7125	(7209)
34	Dunite	2.750	0.40	6547	6656	6725	6780	6818	6825	(7033)
CH-23	Peridotite	3.168	0.32	6619	6810	6936	7020	7055	7088	(7164)
541	Picrite	3.041	0.28	6664	6820	6885	6930	6953	6962	(7130)
BT-13	Serpentinite	2.746	0.58	5585	5700	5810	5883	5930	5980	(6099)
FS-3	Serpentinite	2.269	6.57	3859	4925	5130	5220	5300	5337	(5454)
SC-99	Eclogite	3.147	0.67	6964	7320	7415	7458	7477	7500	(7604)
SC-58	Eclogite	3.583	1.28	6697	7072	7210	7353	7425	7502	(7819)

Table 3. Comparison of the velocity data (km/sec) at 4 and 10 kb of ultamafic rocks

Rock Type	USA			USSR			Japan			Czechoslovakia			India	
	4	10	Ref.	4	10	Ref.	4	10	Ref.	4	10	Ref.	4	10
Pyroxenite	7.88	8.01	1	7.40– 8.00	–	2	–	–		7.40– 7.80	–	5	7.63– 7.85	(7.71– 8.00)
	7.89– 7.97	8.00– 8.08	9	7.50	–	6	–	–						
Dunite (Partially serpentinized)	6.55 7.41	6.79 7.62	1 4	7.70	7.88	6	7.46	7.65	3	7.34	–	5	6.82– 7.12	(7.03– 7.21)
Peridotite (Partially serpentinized)	6.05– 7.37	6.30– 7.62	4	7.70 7.40	– –	2 6	5.90– 7.03	6.33– 7.16	3	5.83– 6.63	–	5	6.95– 7.06	(7.13– 7.16)
Eclogite	7.57– 7.89	7.71– 8.01	1	8.04	8.20	6	8.20– 8.44	8.48– 8.50	3	8.37– 8.40	(8.41– 8.61)	5	7.44– 7.48	(7.60– 7.82)
	7.88– 8.37	(8.01– 8.47)	7				7.98– 8.16	(8.10– 8.27)	7	8.38	8.45	9		
	8.11– 8.38	8.27– 8.45	9											
Serpentinite	5.80– 6.67	6.00– 6.84	1											
	4.91	5.23	4	–	–	–	–	–	–	6.37	–	5	5.30– 5.93	(5.45– 6.10)
	5.09– 5.32	5.45– 5.57	8											

Ref.: 1) Birch (1960). 2) Afanasyev' *et al.* (1965). 3) Kanamori & Mizutani (1965). 4) Christensen (1966). 5) Bajuk *et al.* (1967). 6) Volarovich *et al.* (1967). 7) Kumazawa *et al.* (1971). 8) Christensen (1972). 9) Christensen (1974).

comparison of the present results with those of others (see Table 3). In all the samples studied, as expected, the velocity increased and the absorption decreased with increasing pressure, tending to present saturation values at about 1.5 kb. This initial rise in velocity and increase in normalised pulse amplitude which is a measure of the decrease in absorption due to the application of confining pressure is found to depend largely upon the porosity of the specimens and this is well refelcted by the results of Fig. 1. Assuming that the effect of porosity becomes reduced to an appreciable degree at pressures of the order of 1.5 to 2.0 kb, the changes in elastic wave propagation characteristics above 1.5 kb reveal to a large extent the intrinsic properties of the medium. On this basis, the increase in velocity at different pressures (1.5 to 5.0 kb) with respect to that at 1.5 kb is examined and the results are shown in Fig. 2.

The changes in the amplitude of the first received pulse measured as a function of the applied pressure enabled the computation of attenuation decrement of ultrasonic compressional energy at different pressures. This is done on the basis of the relation

$$\Delta\alpha = \alpha_0 - \alpha_S = \frac{20 \log (A_S/A_0)}{L} \text{ dB/cm}$$

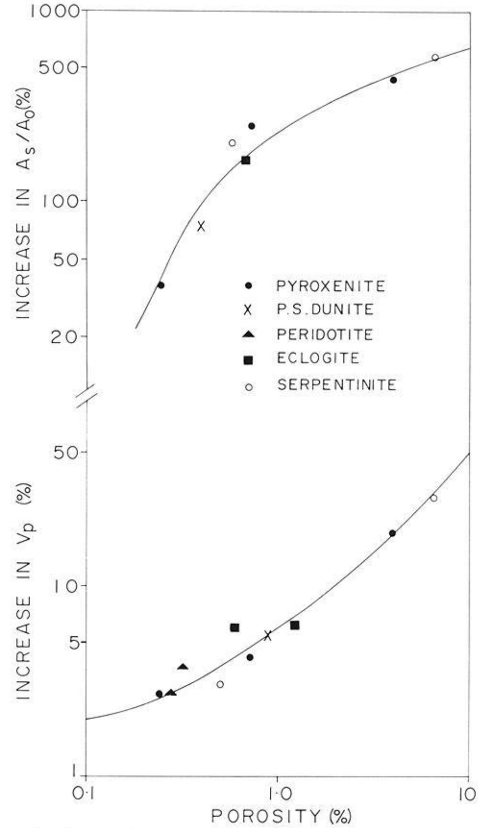

Fig. 1. Effect of porosity on compressional wave velocity and attenuation with pressure between 1 bar and 1.5 kb

where α_0 is the attenuation value at atmospheric pressure, α_S is the attenuation value at the desired pressure, A_S/A_0 is the normalised amplitude of the pulse at the desired pressure, L is the length of the specimen in cm. The amplitude changes are measured in seven specimens and the attenuation decrements computed and plotted against pressure (Fig. 3).

Based on the information available from petrography and chemistry of the rocks studied, variations in the elastic and inelastic properties of individual samples are explained below. Details of textural features and mineral composition of these rocks are reported by Ramana and Rao (1974).

3.3. Pyroxenites

Sample No. B−9 shows, among all samples, the strongest increase in velocity between 1 bar and 1.5 kb and the trend in maintained also up to 5 kb. This is to a certain degree due to its porous nature (porosity 4%). The high porosity of the sample may be explained to be a result of the high degree of uralitization observed in the specimen, especially at the marginal boundaries of the coarse

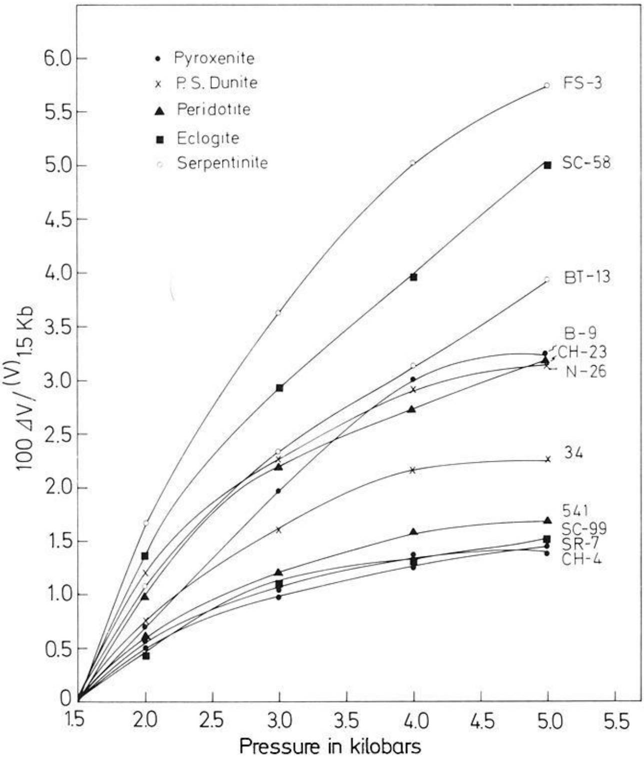

Fig. 2. Change in compressional velocity with pressure normalized to 1.5 kbar

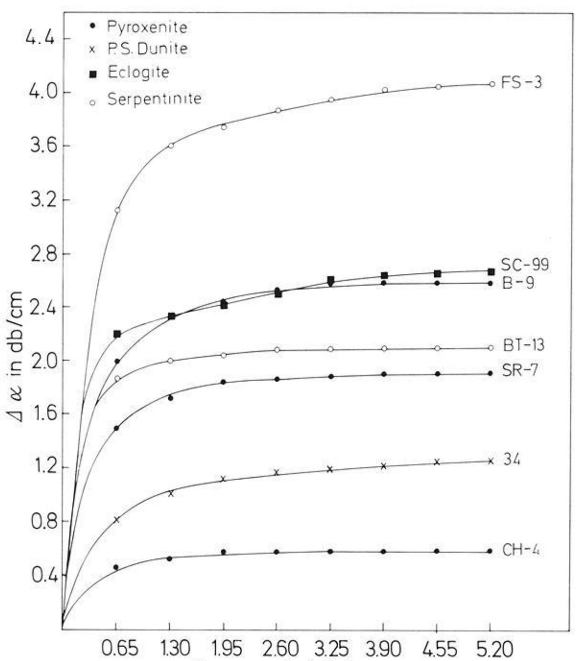

Fig. 3. Change in attenuation decrement with pressure

pyroxene in the groundmass which also contributes to give rise to reduced cohesion between the grains. Pyroxenite from Sukrangi (SR-7) is fairly compact though it has undergone some alteration (serpentine 10%) and does not exhibit a steep rise in velocity in the initial stages. Pyroxenite from Chalk Hills (CH-4) is free from alteration, presenting a strong cohesion in between the grains, and shows small changes in velocity with pressure like the Sukrangi pyroxenite. It is interesting to note that measurements made before and after the pressure tests showed no appreciable change in density and porosity of samples CH-4 and SR-7 while Sample B-9 showed an increase in density by about 2% accounting for a reduction in porosity and these observations are in consonance with the behaviour of the velocity. Also, as seen in Fig. 3, the changes in $\Delta\alpha$ in all the three pyroxenites are truly in accordance with the trend of velocity changes. Since the alteration of pyroxene is not significant, the results obtained are quite comparable to those reported by earlier workers that are presented in Table 3.

3.4. Dunites

The dunite samples collected are from different chromite mines and found to be serpentinized to varying degrees. This explains their low densities and velocities in comparison to the high values of others shown in Table 3. Sample No. 34 is found to be compact and of low porosity (0.4%). This accounts for the small increase in velocity (1.9%) that is observed when the sample is exposed to a pressure of 1.5 kb. The second sample (N-26) presents a large initial increase in velocity (5.7%) which is in accordance with its higher porosity (1%). Appreciable differences in the velocity characteristics are observed in the pressure range 1.5 to 5 kb and 1.5 to 10 kb respectively as seen in Fig. 2 and Table 2. For sample (34) (see Fig. 3), the $\Delta\alpha - P$ gradient is positive beyond 1.5 kb and it is similar to the trend shown by the serpentinite sample (BT-13) and this may be due to its large serpentine content (34%). This improvement in the elastic wave propagation beyond 1.5 kb can be due to the finite compression of the serpentine minerals.

3.5. Peridotite and Picrite

The velocity values at 5 kb (see Table 2) in sample No. N-26 (partially serpentinized dunite) and CH-23 (partially serpentinized peridotite) are comparable and are uniformly higher than the values in sample No. 34 (partially serpentinized dunite) and 541 (picrite) which may be attributed to the higher olivine content of the first two specimens. The velocity values in the Indian peridotitic rocks are comparable with those from other countries at 4 kb.

Changes in velocity characteristics with pressure are found to be nearly identical in both peridotite and picrite despite the presence of plagioclase (19%) and the occurrence of magnetite in negligible quantities in the latter. Initial rise in velocity is in accordance with the porosity value of the peridotite as can be noticed in Fig. 1. Fig. 2 shows that the application of pressure beyond 1.5 kb yielded a comparatively greater rise in velocity in the peridotitic rock (CH-23) than in the picrite (541) which could be due to the difference in their textural features and the distribution of serpentine in the rock.

3.6. Eclogites

Both eclogite samples are from Sittampundi layered complex containing different amounts of garnet, but having similar textural features. Though the porosity values are slightly different, the change in velocity at 1.5 kb is the same (6%) in both samples and this is in general greater than the percentage rise in velocity values shown by all the other rock types, whose porosity values are comparable to the Sittampundi eclogites. Although the porosity is low (1%), the quality of acoustic transmission is poor at room conditions and it improved only after the application of certain pressure. Fig. 2 shows that the velocity gradient in the case of sample No. SC-58 is higher than that of sample No. SC-99 which could be due to the differences in porosity, greater rim alteration noticed in sample No. SC-58, and due to the differences in the mineral chemistry of the two samples. This has been dealt with in detail recently by Rao *et al.* (1974), while examining the possible causes for lower velocity values of Indian eclogites (Table 3) in comparison to those from Japan and Czechoslovakia.

3.7. Serpentinites

The serpentinite samples studied are collected from the same region where chromite is being mined, but differences are noticed in their composition and physical properties. Chrysotile rich rock (FS-3) is characterized by a lower density, higher porosity and hence a larger and more rapid increase (30.8%) in velocity at 1.5 kb than the antigorite rich rock (BT-13), which showed a rise of 3.0%. Also, the percentage rise in velocity at 5 kb in the chrysotile rich rock is greater than in the antigorite rich rock as illustrated in Fig. 2, with the corresponding differences becoming apparent in the attenuation decrements as well, which may be seen in Fig. 3. Of all the samples studied, FS-3 is found to be the most porous rock and also it exhibits the largest increase in velocity and amplitude due to the application of pressure. Differences in the velocity values at 5 kb in the two serpentinites studied are in accordance with the velocity data in serpentine minerals associated with them. The results on the two serpentinite samples studied are comparable with those reported by earlier workers (Table 3).

3.8. Elastic Hysteresis

Wave velocity is measured with increase in pressure from 1 bar to 5 kb as well as with decrease in pressure from 5 kb to 1 bar for some samples and the results are given in Fig. 4. Velocities obtained with increasing pressure are slightly lower than those found with decreasing pressure which is indicative of the elastic hystere-

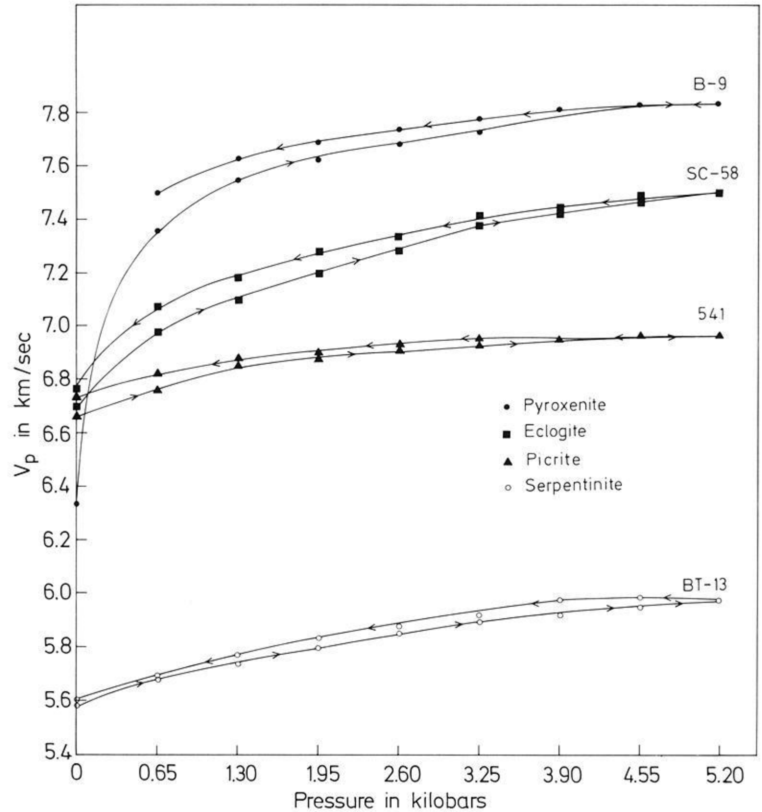

Fig. 4. Pressure hysteresis of compressional wave velocity

sis. Sample Nos. B-9 (Pyroxenite) and SC-58 (Eclogite) are found to exhibit significant hysteresis at pressures below 2 kb, whereas in the fine grained serpentinite (BT-13) and compact picrite (541), departures from the mean curve are low. Fig. 4 enabled the evaluation of individual loop areas (covered between the limits 1 bar and 5 kb) that are a result of the effect of hysteresis in the respective samples. Using these, an interesting relation between the percentage increase in compressional velocity and loop area of the different rock types is drawn in Fig. 5 which assumes a nearly linear relationship. Although hysteresis is attributed primarily to the adjustment of the rock porosity to changes in pressure, it can also indicate to a certain extent the energy dissipated in the sample during a stress cycle.

4. Conclusions

It is clear that the rocks studied are essentially upper mantle rocks having undergone deutric alteration to varying degrees which is reflected by their elastic behaviour under pressure. In general for all the samples, the effect of porosity is

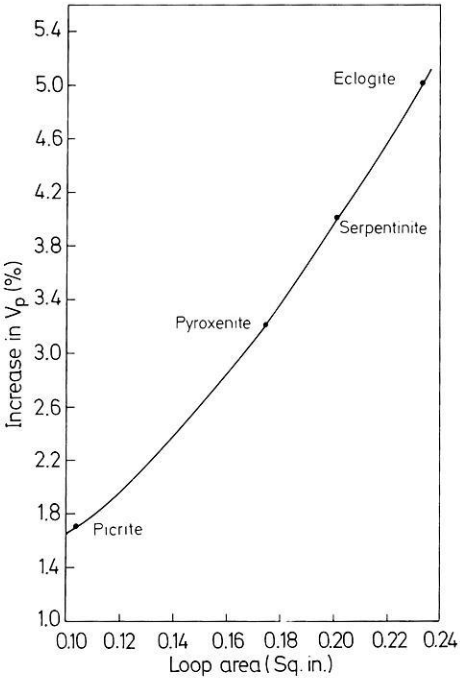

Fig. 5. Dependence of loop area on percentage rise in velocity

prominent up to about 1.5 to 2.0 kb. Variations in elastic wave characteristics beyond 1.5 kb are found to be controlled by the mineralogical composition and texture of rocks. Scatter in velocity values for the group of dunites, pyroxenites, picrite and peridotite is found to be reduced from 8.8% (NTP) to 6.8% (5 kb). The percentage rise in velocity due to the increase of pressure from 1.5 to 5.0 kb is found to bear a linear relation to the loop area of the hysteresis envelope of individual samples.

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