Elasticity of Ultrabasic Rocks

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Ultrasonic measurements of compressional and shear wave velocities are reported for peridotite, dunite, partially serpentinized dunite and peridotite, and serpentinite at hydrostatic pressures to 10 kb. Compressional wave velocities for monomineralic aggregates of olivine, pyroxene, and serpentine approximate 8.54, 7.93, and 5.10 km/sec, respectively. Shear wave velocities for similar aggregates are 4.78, 4.65, and 2.35 km/sec. The relationships between velocity and mineralogy are reported for rocks containing olivine, pyroxene, and serpentine. Young's modulus, Lamé's constant, the bulk modulus, and the shear modulus of peridotites and dunites decrease rapidly with serpentinization. Poisson's ratio and compressibility increase with serpentinization. The effect of olivine orientation on velocity is discussed and found to account for compressional wave anisotropy. High velocities correspond to propagation parallel to maximum concentrations of olivine *a* axes, and low velocities are characteristic of propagation parallel to *b* axes.

INTRODUCTION

Much information on the structure and composition of the earth's interior has been obtained from the study of earthquake and artificially produced elastic waves. The determination of composition from velocities is a problem that depends for its solution on laboratory measurements of velocities for a variety of rocks. Measurements of the elastic properties of rocks at high pressures have been reported by many investigators (for bibliography, see *Simmons* [1965]). In this paper compressional and shear wave velocities are reported for rocks believed to be important constituents of the earth's upper mantle and oceanic crust. Emphasis is placed on the effects of variations of mineral proportions on velocities and elastic constants. Many samples included in the new measurements were selected so that we could examine the elastic changes which accompany the alteration of peridotite to serpentinite.

The techniques of the measurement of velocities to 10 kb are similar to those used by *Birch* [1960], *Simmons* [1964], and *Christensen* [1965*b*]. Barium titanate transducers were used to generate compressional waves and ac-cut quartz transducers were used for measurement of shear velocities. The transducers had natural resonant frequencies of 1 and 3 Mc/s. The circuit consisted of a DuMont 404B pulse generator, a Tektronix 545 oscilloscope, and Tektronix 1162 preamplifiers. Time measurements were made with a variable mercury delay line. Velocities obtained by this technique are believed to be accurate to about 1%.

NOTATION

V_p, compressional wave velocity, km/sec.
V_s, shear wave velocity, km/sec.
ρ, density, g/cm^3.
β, compressibility, Mb^{-1}.
λ, Lamé's constant, Mb.
μ, shear modulus, Mb.
σ, Poisson's ratio.
ϕ, $(\rho\beta)^{-1}$, (km/sec)^2.
E, Young's modulus, Mb.
K, bulk modulus, Mb.

DESCRIPTION OF SPECIMENS

The serpentinite and partially serpentinized peridotites are part of a rock suite collected from a large ultramafic body in the Santa Lucia Range about 15 km west of Cape San Martin, California. The serpentinite is primarily composed of chrysotile, although subordinate antigorite is also present. Textural contrasts between bastite pseudomorphs of completely altered enstatite and mesh-textured serpentine after olivine indicate that the original peridotite contained approximately 25% pyroxene.

Unaltered minerals in the partially serpentinized peridotites indicate that the original rocks were diopsidic harzburgites. Thin, closely spaced exsolution lamellas of diopside are common in the enstatite crystals. Serpentine of the less altered peridotites occurs in veinlets which form an evenly spaced mesh structure. In the more highly serpentinized peridotites many of the pyroxene grains have been completely serpentinized to a bastite structure. Brucite was not observed in thin section but was detected by X rays in all the altered peridotites.

The peridotite samples were taken from xenolithic nodules in the 1800–1801 Kaupulehu flow of the Hualalai volcano on the Island of Hawaii. Olivine and clinopyroxene (probably a diopsidic augite) occur as equidimensional grains with sharp extinction. Small interstitial grains of a light green chromium diopside are also present. No alteration was observed in either specimen.

Both peridotites have loose granular textures which produce relatively low velocities over the first few kilobars. This is illustrated in Figure 1, where the variations of velocity with pressure are plotted for samples of peridotite 2 and partially serpentinized peridotite 3. The initial rapid increases of velocity are due to closure of pore space, and the slower increases above a few kilobars result from intrinsic effects of pressure on the mineral components

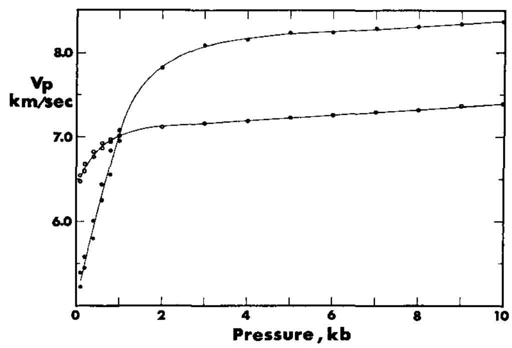

Fig. 1. Compressional wave velocities for specimens of peridotite 2 (dots) and partially serpentinized peridotite 3 (circles).

[*Birch,* 1961]. The curve for the altered peridotite is relatively normal for ultrabasic rocks, whereas the peridotite shows an extremely rapid increase in velocity over the first few kilobars.

The Twin Sisters dunite is similar to the specimens studied by *Birch* [1960] and *Simmons* [1964]. The rock consists of large olivine grains with undulatory extinction in a fine equigranular mosaic of unstrained olivine. Large crystals of enstatite with the typical exsolution lamellas are present in minor amounts along with chromite.

TABLE 1. Modal Analyses
Percentages by volume.

Rock	Olivine	Orthopyroxene	Clinopyroxene	Serpentine	Chromite + Magnetite	Spinel
Serpentinite				95.2	4.8	
Partially serpentinized peridotite 1	34.0 fo_{94}	4.2 en_{93}		60.8	1.0	0.1
Partially serpentinized peridotite 2	37.2 fo_{94}	9.1 en_{92}		52.7	0.6	0.4
Partially serpentinized peridotite 3	57.2 fo_{94}	12.9 en_{92}		28.9	0.2	0.8
Partially serpentinized peridotite 4	57.3 fo_{92}	12.4 en_{90}		29.4	0.1	0.8
Partially serpentinized peridotite 5	63.4 fo_{93}	13.5 en_{92}		22.4	0.1	0.6
Partially serpentinized peridotite 6	62.1 fo_{93}	14.8 en_{92}		22.4	0.1	0.7
Peridotite 1	58.3 fo_{82}		39.5		2.2	
Peridotite 2	70.0 fo_{85}		27.2		2.8	
Dunite	94.1 fo_{91}	4.9 en_{90}			1.0	
Partially serpentinized dunite	82.7 fo_{90}			16.3	1.0	

The Addie, N. C., dunite contains a mosaic of uniform-size olivine grains. Serpentinization occurs along grain boundaries and in fractures through the olivine crystals.

Modal analyses are given in Table 1. More than 5000 points were counted from each specimen. Universal stage measurements of optical angle were used to obtain the olivine and enstatite compositions in Table 1.

Data

Compressional and shear wave velocities and densities are given in Table 2. The densities were calculated from the weight and dimensions of the rock cylinders used for the velocity measurements. Velocities were recorded for both increasing and decreasing pressure. Below about 1 kb hysteresis is usually significant; it is primarily related to the adjustment of pore spaces to the change in pressure.

Corrections for the change in length of the specimens under pressure have not been applied to the velocities. The tabulated values for the dunites and peridotites at 10 kb are higher by about 2 units in the last figure [*Birch*, 1960]. For most rocks this correction is less than the accuracy of the measurements and has meaning only for the calculation of pressure derivatives and elastic constants.

From the formulas for isotropic elasticity [*Birch*, 1961, p. 2206] the elastic constants of the rocks can be calculated from V_p, V_s, and ρ. *Simmons and Brace* [1965] have recently shown that elastic constants calculated from velocities are in good agreement with static values. Values of the elastic constants are given in Table 3. The velocities and densities used in the calculations have been corrected for length changes due to compressibility. The equations used in calculating the elastic constants are

$$2\sigma = [(V_p/V_s)^2 - 2]/[(V_p/V_s)^2 - 1]$$

$$\phi = V_p^2 - 4V_s^{2/3}$$

$$K = \rho\phi$$

$$\beta = (\rho\phi)^{-1}$$

$$\mu = \rho V_s^2$$

$$E = 2\mu(1 + \sigma)$$

$$\lambda = \rho(V_p^2 - 2V_s^2)$$

If we assume an accuracy of $\pm 1\%$ for V_p and V_s, an estimate of the accuracy of the data in Table 3 can be made as follows. If V_p and V_s are 8.00 and 4.50 km/sec, respectively, and the two velocities are in error in opposite directions, we obtain $\pm 5\%$ for σ and ϕ, $\pm 4\%$ for β and K, $\pm 7\%$ for E, and ± 9 for λ.

Discussion

The velocities in Table 2 agree, in general, with those reported by previous investigators. *Birch* [1960] found 8.42 km/sec for V_p of the Twin Sisters dunite at 10 kb; this is slightly lower than the mean velocity of 8.66 km/sec of the present specimen. The difference appears to be due to the extreme anisotropy of the dunites. *Simmons* [1964] reported a mean of 4.83 km/sec at 10 kb for the Twin Sisters dunite, which is close to the 4.74 km/sec in Table 2. Previously reported compressional wave velocities for peridotites at 10 kb are slightly lower than the 8.21- and 8.36-km/sec velocities of the Hawaiian peridotites. *Birch* [1960] found a mean velocity of 7.95 km/sec for harzburgite, and *Kanamori and Mizutani* [1965] reported velocities of 7.59 and 8.02 km/sec for peridotites 0029 and 0035. The lower velocities can be explained by the reported partial alteration of the peridotites to serpentine. Peridotite shear velocities at 10 kb measured by Kanamori and Mizutani are also lower than the shear velocities of the Hawaiian peridotites.

Anisotropy of the elastic properties of rocks is generally attributed to preferred mineral orientation. *Brace* [1965] correlated the variation with direction of linear compressibility with preferred orientation of mica, quartz, and calcite. *Christensen* [1965*a*, *b*, 1966] found that the degree of preferred orientation and abundance of mica and hornblende account for compressional and shear wave velocity anisotropy in metamorphic rocks. *Birch* [1961] found a variation of velocity with direction for a variety of metamorphic rocks and dunite. The anisotropy of dunite was successfully correlated with the orientation of olivine and the anisotropy of the olivine crystal.

Petrofabrics have been analyzed for the two dunites with the objective of correlating the olivine orientation patterns with compressional wave velocity anisotropy. The angular relation-

TABLE 2. Velocities (km/sec) in Ultrabasic Rocks

Rock	Density, g/cm³	Propagation Direction	Pressure, kb 0.1 V_s	0.1 V_p	0.5 V_s	0.5 V_p	1.0 V_s	1.0 V_p	2.0 V_s	2.0 V_p	4.0 V_s	4.0 V_p	6.0 V_s	6.0 V_p	8.0 V_s	8.0 V_p	10.0 V_s	10.0 V_p
Serpentinite	2.51	A	2.1	4.2	2.19	4.38	2.20	4.46	2.21	4.56	2.23	4.72	2.27	4.83	2.30	4.96	2.33	5.06
Burro Mtn., Calif.	2.53	B	2.2	4.2	2.27	4.47	2.28	4.54	2.30	4.67	2.32	4.84	2.35	4.95	2.38	5.05	2.40	5.14
	2.53	C	2.1	4.5	2.28	4.77	2.32	4.91	2.35	5.03	2.40	5.18	2.44	5.28	2.47	5.40	2.50	5.49
mean	2.52		2.1	4.3	2.25	4.54	2.27	4.64	2.29	4.75	2.32	4.91	2.35	5.02	2.38	5.14	2.41	5.23
Partially serpentinized	2.75	A	2.9	5.7	2.98	5.82	3.03	5.86	3.04	5.92	3.07	6.00	3.10	6.11	3.11	6.19	3.12	6.28
peridotite 1	2.76	B	2.9	6.0	2.97	6.14	3.00	6.17	3.02	6.24	3.03	6.32	3.06	6.39	3.09	6.48	3.11	6.55
Burro Mtn., Calif.	2.75	C	2.7	5.5	2.80	5.65	2.85	5.70	2.86	5.77	2.89	5.82	2.91	5.93	2.93	5.99	2.95	6.08
mean	2.75		2.8	5.7	2.92	5.87	2.96	5.91	2.97	5.98	3.00	6.05	3.02	6.14	3.04	6.22	3.06	6.30
Partially serpentinized	2.82	A	3.0	5.8	3.05	5.96	3.07	6.01	3.09	6.11	3.11	6.17	3.13	6.27	3.15	6.32	3.16	6.37
peridotite 2	2.85	B	3.0	6.1	3.03	6.18	3.08	6.23	3.10	6.28	3.12	6.36	3.13	6.44	3.16	6.52	3.18	6.59
Burro Mtn., Calif.	2.85	C	2.9	6.0	3.03	6.13	3.08	6.18	3.09	6.22	3.11	6.30	3.12	6.39	3.14	6.45	3.16	6.53
mean	2.84		3.0	6.0	3.04	6.09	3.08	6.14	3.09	6.20	3.11	6.28	3.13	6.37	3.15	6.43	3.17	6.50
Partially serpentinized	3.03	A	3.6	6.1	3.68	6.38	3.71	6.53	3.74	6.67	3.82	6.75	3.87	6.86	3.89	6.96	3.92	7.05
peridotite 3	3.05	B	3.5	6.6	3.58	7.07	3.61	7.18	3.65	7.27	3.69	7.40	3.72	7.46	3.73	7.52	3.75	7.59
Burro Mtn., Calif.	3.06	C	3.6	6.5	3.66	6.84	3.70	7.00	3.76	7.12	3.82	7.20	3.84	7.27	3.86	7.32	3.88	7.40
mean	3.05		3.6	6.4	3.64	6.76	3.67	6.90	3.72	7.02	3.78	7.12	3.81	7.20	3.83	7.27	3.85	7.35
Partially serpentinized	3.07	A	3.5	6.5	3.64	6.76	3.70	6.82	3.74	6.90	3.76	7.04	3.79	7.11	3.81	7.18	3.83	7.23
peridotite 4	3.07	B	3.7	6.5	3.78	6.74	3.82	6.83	3.87	6.95	3.91	7.04	3.93	7.08	3.95	7.12	3.97	7.17
Burro Mtn., Calif.	3.08	C	3.5	6.1	3.58	6.58	3.62	6.69	3.65	6.76	3.69	6.87	3.72	6.96	3.74	7.04	3.97	7.12
mean	3.07		3.6	6.4	3.67	6.69	3.71	6.78	3.75	6.87	3.79	6.98	3.81	7.05	3.83	7.11	3.86	7.17

Partially serpentinized	3.11	A	3.4	6.6	3.52	6.91	3.58	7.01	3.64	7.12	3.68	7.23	3.70	7.32	3.73	7.42	3.76	7.51
peridotite 5	3.11	B	3.3	6.7	3.50	6.94	3.62	7.01	3.66	7.10	3.72	7.23	3.74	7.32	3.76	7.39	3.78	7.47
Burro Mtn., Calif.	3.16	C	3.4	7.2	3.61	7.35	3.69	7.44	3.76	7.53	3.81	7.64	3.84	7.74	3.87	7.80	3.91	7.87
mean	3.13		3.4	6.8	3.54	7.07	3.63	7.15	3.69	7.25	3.74	7.37	3.76	7.46	3.79	7.54	3.82	7.62
Partially serpentinized	3.14	A	3.8	6.7	3.95	6.95	4.01	7.03	4.04	7.12	4.09	7.18	4.12	7.25	4.14	7.31	4.16	7.37
peridotite 6	3.13	B	3.7	6.6	3.87	6.94	3.93	7.05	3.95	7.12	3.95	7.19	3.96	7.26	3.97	7.33	3.98	7.40
Burro Mtn., Calif.	3.15	C	3.7	6.9	3.83	7.10	3.89	7.20	3.92	7.25	3.94	7.33	3.95	7.38	3.96	7.45	3.98	7.50
mean	3.14		3.7	6.7	3.88	7.00	3.94	7.09	3.97	7.16	3.99	7.23	4.01	7.30	4.02	7.36	4.04	7.42
Peridotite 1	3.29	A	3.1	5.3	3.45	6.44	3.82	7.04	3.91	7.45	4.09	7.84	4.22	7.94	4.25	7.98	4.29	8.04
Kailua, Hawaii	3.30	B	3.3	5.3	3.71	6.67	4.01	7.39	4.31	7.85	4.51	8.17	4.57	8.21	4.59	8.26	4.62	8.31
	3.29	C	3.2	5.5	3.58	6.69	3.93	7.21	4.26	7.60	4.44	7.98	4.50	8.13	4.54	8.20	4.57	8.28
mean	3.29		3.2	5.4	3.58	6.60	3.92	7.21	4.16	7.63	4.35	8.00	4.43	8.09	4.46	8.15	4.49	8.21
Peridotite 2	3.29	A	3.8	5.3	4.06	6.12	4.32	7.05	4.51	7.82	4.61	8.15	4.65	8.24	4.70	8.30	4.75	8.34
Kailua, Hawaii	3.29	B	3.2	5.2	3.59	6.35	3.90	7.18	4.19	7.88	4.46	8.25	4.55	8.36	4.59	8.44	4.62	8.53
	3.28	C	3.2	5.6	3.62	6.84	4.01	7.30	4.33	7.69	4.50	8.00	4.57	8.06	4.62	8.14	4.66	8.20
mean	3.29		3.4	5.4	3.76	6.44	4.08	7.18	4.34	7.80	4.52	8.13	4.59	8.22	4.64	8.29	4.68	8.36
Dunite	3.33	A	4.5	8.8	4.75	8.82	4.83	8.93	4.83	8.96	4.84	8.98	4.86	9.02	4.87	9.06	4.89	9.09
Twin Sisters	3.32	B	4.1	8.1	4.30	8.17	4.35	8.19	4.38	8.22	4.41	8.27	4.45	8.30	4.48	8.32	4.51	8.35
Peaks, Wash.	3.33	C	4.4	8.2	4.59	8.31	4.70	8.35	4.72	8.37	4.74	8.41	4.77	8.46	4.80	8.52	4.83	8.55
mean	3.33		4.3	8.4	4.55	8.43	4.63	8.49	4.64	8.52	4.66	8.55	4.69	8.59	4.72	8.63	4.74	8.66
Partially serpentinized	3.20	A		6.9		6.86		6.90		7.12		7.23		7.34		7.41		7.49
dunite	3.19	B		6.9		7.08		7.20		7.33		7.51		7.55		7.60		7.66
Addie, N. C.	3.20	C		6.9		7.11		7.28		7.38		7.50		7.59		7.65		7.70
	3.20	D		7.0		7.33		7.43		7.50		7.62		7.71		7.80		7.88
	3.18	E		7.1		7.35		7.43		7.53		7.63		7.74		7.81		7.88
	3.18	F		7.1		7.36		7.42		7.56		7.75		7.81		7.87		7.93
	3.18	G		7.1		7.44		7.54		7.65		7.77		7.81		7.87		7.93
mean	3.19			7.0		7.22		7.32		7.44		7.57		7.65		7.72		7.78

TABLE 3. Elastic Constants Calculated from V_p, V_s, and σ

Pressure, kb	V_p/V_s	σ	ϕ, (km/sec)^2	K, Mb	β, Mb^{-1}	μ, Mb	E, Mb	λ, Mb
Serpentinite								
0.5	2.02	0.34	13.86	0.35	2.86	0.13	0.35	0.26
2.0	2.29	0.38	15.54	0.39	2.55	0.13	0.36	0.30
6.0	2.14	0.36	17.73	0.45	2.22	0.14	0.38	0.36
10.0	2.17	0.37	19.42	0.50	2.02	0.15	0.41	0.40
Partially Serpentinized Peridotite 1								
0.5	2.01	0.34	23.09	0.63	1.58	0.23	0.62	0.48
2.0	2.01	0.34	23.95	0.66	1.52	0.24	0.64	0.50
6.0	2.03	0.34	25.39	0.70	1.42	0.25	0.67	0.54
10.0	2.06	0.35	26.99	0.75	1.33	0.26	0.70	0.58
Partially Serpentinized Peridotite 2								
0.5	2.00	0.33	24.77	0.70	1.42	0.26	0.69	0.53
2.0	2.01	0.34	25.66	0.73	1.37	0.27	0.72	0.55
6.0	2.03	0.34	27.35	0.78	1.28	0.28	0.75	0.60
10.0	2.05	0.34	28.62	0.82	1.22	0.29	0.78	0.63
Partially Serpentinized Peridotite 3								
0.5	1.86	0.30	28.03	0.85	1.17	0.40	1.04	0.59
2.0	1.89	0.31	30.79	0.94	1.06	0.42	1.07	0.66
6.0	1.89	0.31	32.36	0.99	1.01	0.44	1.15	0.70
10.0	1.91	0.31	33.99	1.05	0.96	0.45	1.18	0.75
Partially Serpentinized Peridotite 4								
0.5	1.82	0.28	26.80	0.82	1.22	0.41	1.05	0.55
2.0	1.83	0.29	28.43	0.87	1.15	0.43	1.11	0.59
6.0	1.85	0.29	30.23	0.93	1.07	0.45	1.16	0.64
10.0	1.86	0.30	31.28	0.97	1.03	0.46	1.20	0.66
Partially Serpentinized Peridotite 5								
0.5	2.00	0.33	33.28	1.04	0.96	0.39	1.04	0.78
2.0	1.97	0.33	34.37	1.08	0.93	0.43	1.15	0.79
6.0	1.98	0.33	36.66	1.15	0.87	0.44	1.17	0.86
10.0	1.99	0.33	38.37	1.21	0.83	0.46	1.22	0.91
Partially Serpentinized Peridotite 6								
0.5	1.80	0.28	28.93	0.91	1.10	0.47	1.20	0.59
2.0	1.80	0.28	30.22	0.95	1.05	0.49	1.25	0.62
6.0	1.82	0.28	31.72	1.00	1.00	0.51	1.31	0.66
10.0	1.84	0.29	33.10	1.05	0.95	0.52	1.34	0.70
Peridotite 1								
0.5	1.84	0.29	26.47	0.87	1.15	0.42	1.08	0.59
2.0	1.83	0.29	35.14	1.16	0.87	0.57	1.47	0.78
6.0	1.83	0.29	39.17	1.29	0.77	0.65	1.68	0.86
10.0	1.83	0.29	40.27	1.34	0.75	0.66	1.70	0.89
Peridotite 2								
0.5	1.71	0.24	22.62	0.74	1.34	0.47	1.17	0.43
2.0	1.80	0.28	35.73	1.18	0.85	0.62	1.59	0.76
6.0	1.79	0.27	39.37	1.30	0.77	0.69	1.75	0.84
10.0	1.79	0.27	40.44	1.34	0.75	0.72	1.83	0.86
Dunite								
0.5	1.85	0.29	43.46	1.45	0.69	0.69	1.78	0.99
2.0	1.84	0.29	43.88	1.46	0.68	0.72	1.86	0.98
6.0	1.83	0.29	44.32	1.48	0.68	0.73	1.88	0.99
10.0	1.83	0.29	44.77	1.50	0.67	0.75	1.94	1.00

ships between the directions of measured velocity in Table 2 and the orientation of the olivine crystallographic axes are given in Figure 2. Propagation directions A, B, and C in the Twin Sisters dunite are nearly parallel to the maximum concentrations of *a*, *b*, and *c* crystallographic axes of olivine, respectively. Velocities recorded for these directions (Table 2) are consistent with single-crystal forsterite velocities of 9.87, 7.73, and 8.65 km/sec in the *a*, *b*, and *c* crystallographic directions reported by *Verma* [1960]. Compressional wave velocities in the A and B directions are lower and higher, respectively, than the single-crystal velocities. This is to be expected because the crystallographic axes deviate considerably from perfect orientation. The velocity recorded in the C direction is slightly lower than that reported by Verma for the *c* direction in olivine. Since some olivine *a* axes are also oriented parallel to propagation direction C, one would expect a slightly higher velocity for this direction. The discrepancy may be due to slight variations in composition of the three cores selected for the measurements and variation of fabric along the core axes.

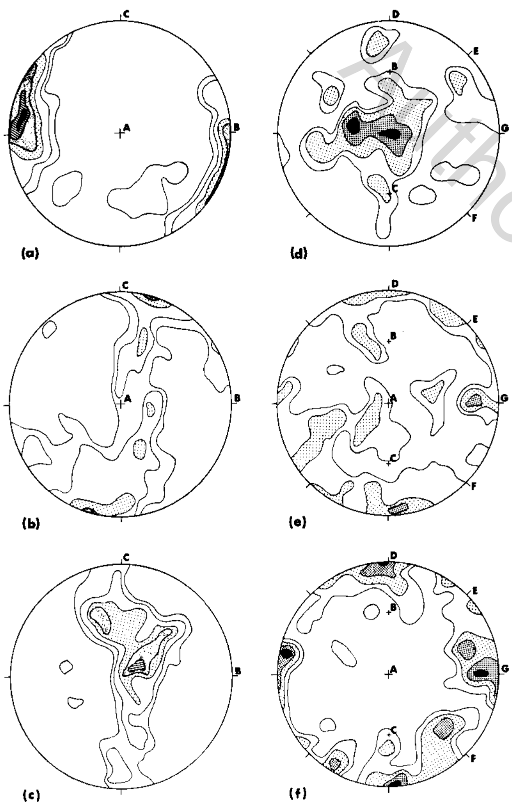

Fig. 2. Orientation diagrams for 120 grains of olivine in Twin Sisters dunite (*a–c*) and Addie dunite (*d–f*). (*a*) *b* axes, contours at 10%, 8%, 6%, 4%, 2%, and 1% per 1% area. (*b*) *c* axes, contours at 6%, 4%, 2%, and 1% per 1% area. (*c*) *a* axes, contours at 8%, 6%, 4%, 2%, and 1% per 1% area. (*d*) *b* axes, contours at 6%, 4%, 2%, and 1% per 1% area. (*e*) *c* axes, contours at 4%, 2%, and 1% per 1% area. (*f*) *a* axes, contours at 6%, 4%, 2%, and 1% per 1% area.

Compressional wave velocities were measured for seven directions in the Addie dunite (Table 2). Propagation direction A, which coincides with the maximum concentration of olivine *b* axes, is normal to a weak banding in the specimen. As expected, this direction corresponds to the lowest velocity. The olivine *a* and *c* axes have a nearly random distribution in the plane of the banding. Thus the velocities recorded for propagation directions D, E, F, and G were approximately the same at pressures above a few kilobars. The velocities at 45° to the banding are intermediate to those measured in the plane of the banding and normal to the banding.

The variation of V_p accompanying serpentinization of dunite has recently received much attention. *Hess* [1959] and *Birch* [1961] have plotted velocity-density curves for ideal serpentine-olivine aggregates. *Birch's* [1961] velocity-density relationship at 10 kb gives velocities of 6.00 and 8.50 km/sec for densities of 2.60 and 3.32, respectively. The solution at 10 kb in Table 4 gives slightly lower velocities because of the presence of pyroxene in the specimens. A similar study by *Kanamori and Mizutani* [1965] for serpentine-olivine aggregates gave slightly lower velocities than the values obtained by Birch. It was postulated that the differences were due to the effects of accessory minerals.

The method of least squares has been used to obtain straight lines of the form $V = m\rho + b$ for the peridotites, partially serpentinized peridotites, and serpentinite (Table 4). The velocity data for the peridotites at 2 kb were corrected for porosity by extending the linear parts of the velocity-pressure curves down to 2 kb. The relations at 10 kb between V_p, V_s, and ρ for serpentinization of peridotite are

TABLE 4. Least-Squares Parameters of the Form $V = m\rho + b$ for the Peridotites, Partially Serpentinized Peridotites, and Serpentinite

Velocity	Pressure, kb	m	b	Correlation Coefficient
V_p	2	4.05	−5.31	0.996
V_s	2	2.72	−4.61	0.998
V_p	6	3.96	−4.93	0.998
V_s	6	2.81	−4.80	0.993
V_p	10	2.83	−4.39	0.993
V_s	10	2.79	−4.67	0.994

illustrated in Figure 3. The dashed curve of Poisson's ratio has been calculated from the two least-squares lines of Figure 3.

The relationship between mineral composition and velocity in the ultrabasic rocks can be expressed by triangular composition diagrams in which the apexes are olivine, pyroxene, and serpentine (Figures 4 and 5). In such diagrams the accessory minerals, chromite and magnetite, and variations in chemical composition of the end members are neglected. Velocities reported for reasonably pure monomineralic aggregates have been selected for the three end members in Figures 4 and 5. Olivine and pyroxene aggregate velocities are fairly consistent, whereas serpentinites show a wide range of velocities (Figure 6). This variability is probably the result of many factors, the most important being sorption of water, differing proportions of the various varieties of serpentine, and the presence of other minerals. The high densities of many of the specimens in Figure 6 suggest that they contain appreciable amounts of olivine, pyroxene, magnetite, or chromite. Calculations by *Huggins and Shell* [1965] gave densities of 2.19 to 2.27 g/cm³ for pure chrysotile. Measured densities ranged from 2.2 to 2.4 g/cm³. *Deer et al.* [1962] reported densities of 2.55 and 2.6 g/cm³ for lizardite and antigorite. Thus the lower densities and corresponding lower velocities in Figure 6 appear more reasonable for pure serpentine aggregates.

References used for determining the aggregate velocities at 10 kb in Figures 4 and 5 are summarized in Table 5. The velocities have been corrected both for changes in length resulting from compression and for reported accessory minerals. The contours of equal velocity in Figures 4 and 5 were constructed from the mean of the Voigt and Reuss averages [*Brace,* 1965, p. 394] for different proportions of olivine, pyroxene, and serpentine. Mean

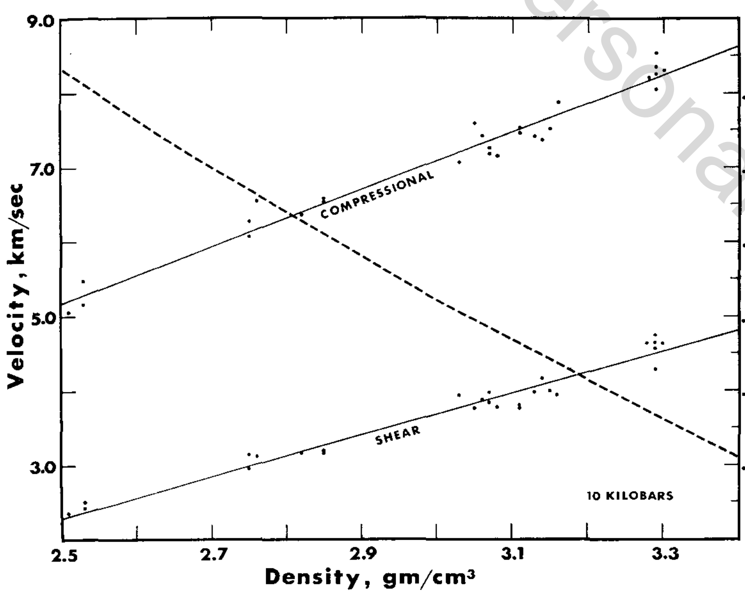

Fig. 3. Velocity at 10 kb versus density for peridotites and serpentinized peridotites. The dashed line is Poisson's ratio calculated from the velocity curves.

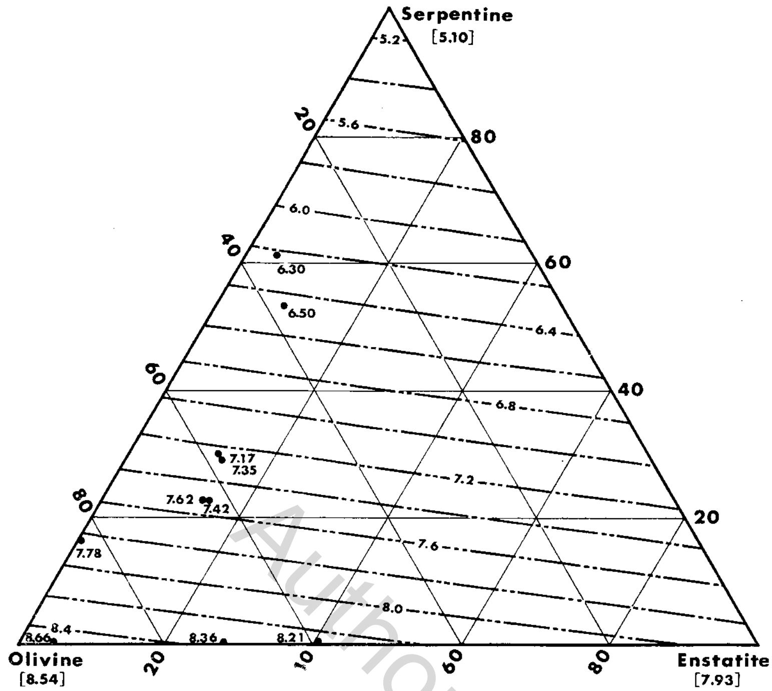

Fig. 4. Compressional wave velocities at 10 kb for different proportions of olivine, enstatite, and serpentine.

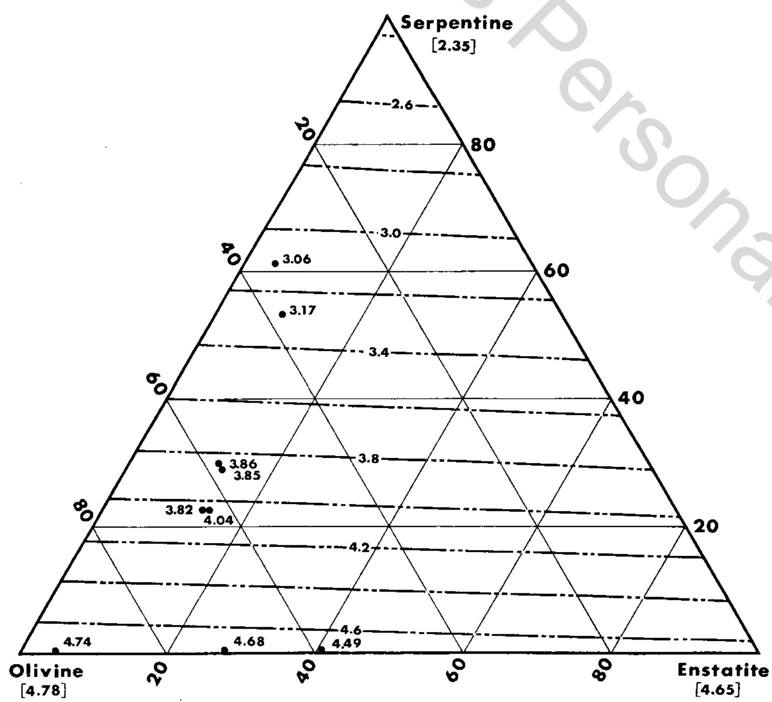

Fig. 5. Shear wave velocities at 10 kb for different proportions of olivine, enstatite, and serpentine.

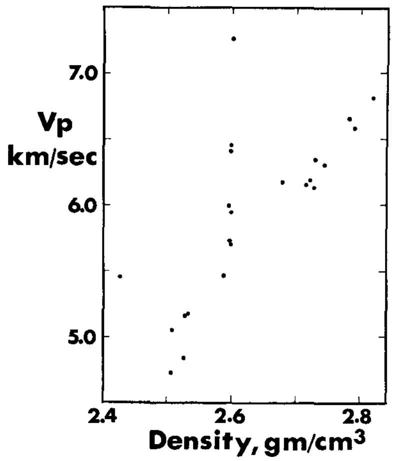

Fig. 6. Compressional wave velocity at 4 kb versus density for serpentinites reported by *Birch* [1960, 1964] and this paper.

velocities at 10 kb for the specimens in Table 2 are also plotted in the diagrams. The velocities calculated from the aggregate velocities generally agree with the measured velocities to within 0.1 km/sec. The mean shear velocities for peridotite 1 and partially serpentinized peridotite 5 are about 0.2 km/sec lower than the predicted velocities in Figure 5. Both specimens have relatively high shear anisotropy which may explain some of the differences.

Serpentinization of peridotite also produces a systematic change in the elastic constants.

TABLE 5. Mean Velocities at 10 Kilobars for Aggregates of Olivine, Pyroxene, and Serpentine

Mineral	Velocity, km/sec	Reference
Olivine	V_p = 8.54	Mean velocities for Twin Sisters dunite reported by *Birch* [1960] and Table 2
Pyroxene	V_p = 7.93	Mean velocities given for 3 pyroxenites by *Birch* [1960]
Serpentine	V_p = 5.10	Serpentinite, Table 2
Olivine	V_s = 4.78	Mean velocities for Twin Sisters dunite reported by *Simmons* [1964] and Table 2
Pyroxene	V_s = 4.65	Stillwater bronzitite, *Simmons* [1964]
Serpentine	V_s = 2.35	Serpentinite, Table 2

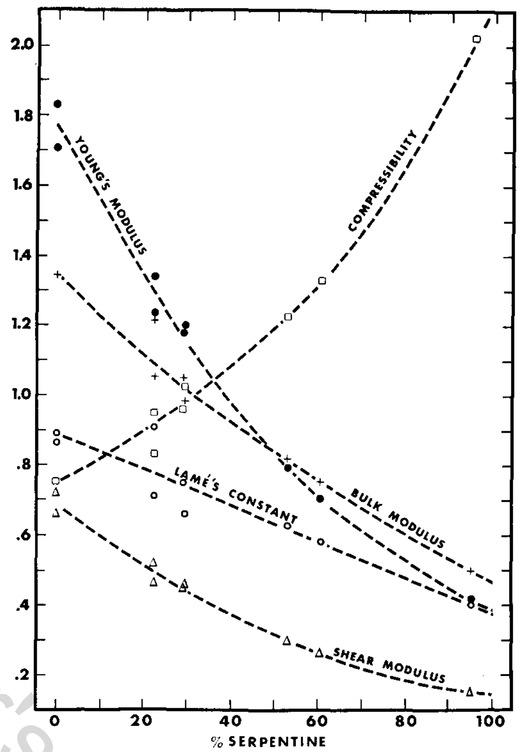

Fig. 7. Variations of the elastic constants at 10 kb with serpentinization of peridotite. Units are Mb^{-1} for β and Mb for λ, μ, E, and K.

This is illustrated in Figure 7, where the elastic constants at 10 kb (Table 3) are plotted versus percentage of serpentine for the serpentinite, partially serpentinized peridotites, and peridotites.

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