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NIKOLAS I. CHRISTENSEN

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NIKOLAS I. CHRISTENSEN

Department of Geological Sciences and Geophysics Program
University of Washington, Seattle, Washington 98195

The velocities of compressional waves are reported to hydrostatic pressures of 30 kbar for pyroxenites, eclogites, and a dunite. The data above 10 kbar, when corrected for length changes, permit the determination of pressure coefficients of compressional wave velocities, which range from 0.010 km s^{-1} $kbar^{-1}$ in eclogite to 0.014 km s^{-1} $kbar^{-1}$ in pyroxenite. It is shown that pressure coefficients of velocity for rocks determined below 10 kbar are generally unreliable due to the influence of porosity. The pressure coefficient of velocity measured for the dunite agrees well with similar data from single-crystal olivine; however, pressure coefficients of velocity for the pyroxenites are significantly lower than measurements for single-crystal bronzite.

In recent years considerable effort has gone into laboratory investigations of wave velocities and the related elastic properties of rocks and rock-forming minerals. Velocities for a large variety of rocks have been reported to pressures of 10 kbar [e.g., *Birch,* 1960; *Simmons,* 1964; *Christensen,* 1965]. Similarly, velocities in many single crystals and hot-pressed aggregates of geophysical importance have been studied to pressures of a few kilobars [e.g., *Anderson et al.,* 1968; *Manghnani,* 1969; *Chung,* 1971; *Kumazawa and Anderson,* 1969; *Graham and Barsch,* 1969]. The results of these studies are important to geophysics in that they provide data for the interpretation of seismic velocities within the earth in terms of chemical composition and crystal structure.

Wave velocity data for rocks to 10 kbar have been particularly useful in the interpretation of oceanic and continental crustal composition [e.g., *Birch,* 1958; *Ringwood and Green,* 1966; *Christensen,* 1970] and have provided the important relationship between density, velocity, and mean atomic weight [*Birch,* 1961], which has been used extensively in estimating mantle composition. However, the interpretation of rock velocities is complicated due to complex mineralogy, chemistry, porosity, and preferred mineral orientation common to most rocks. For example, the effect of porosity has been shown by *Birch* [1960, 1961] to produce a significant lowering of velocities at pressures below approximately 2 kbar for many rocks. At pressures usually between 2 and 10 kbar, rock velocities appear to be primarily related to the elastic properties of their mineral components; however, it is not clear what influence porosity has on velocity in this pressure range [*Birch,* 1969], and because of this it is tenuous to extrapolate rock velocity data much beyond 10 kbar.

To overcome some of the problems inherent in direct studies of rock elasticity, many investigations have concentrated on measurements of the elastic properties of single crystals and hot-pressed polycrystalline aggregates. These studies offer certain advantages in that the measurements are for a single-crystal structure rather than a composite of crystal structures typical of most rocks, and it is usually possible to use techniques that provide higher degrees of accuracy and precision of the data. However, the elastic properties of hot-pressed polycrystalline aggregates are also significantly influenced by anisotropy, porosity, and residual strain arising from their fabrication process [*Spetzler et al.,* 1972]. Extrapolation of single-crystal data to high pressure is also subject to uncertainty because of theoretical problems in averaging directional elastic properties in anisotropic media [*Thomsen,* 1972; *Birch,* 1972].

Clearly, it is desirable to obtain elastic wave data on naturally occurring mineral aggregates at hydrostatic pressures above 10 kbar. In this study, compressional wave velocities and their pressure derivatives are reported to 30 kbar for five rocks of probable mantle composition. Compressional wave velocities for these rocks are compared with extrapolated velocities of single crystals and similar rocks that have been studied at lower pressures.

EXPERIMENTAL DETAILS

A modified Bridgman-Birch 30-kbar pressure system was used to generate the hydrostatic pressures. Details of similar systems have been described by *Bridgman* [1938] and *Birch et al.* [1957]. A simplified diagram illustrating the operation and construction of the pressure-generating unit is shown in Figure 1. The high-pressure cylinder is slightly conical on its external surface and is driven into a massive support cylinder having a matching conical inner surface by the lower 500-ton press. This produces external pressure on the high-pressure cylinder. The upper 125-ton press drives a packed piston down into the pressure vessel, thereby producing the desired pressure within the cylinder. The upper and lower jacks are operated simultaneously by two 20,000-psi air pumps connected to a single oil reservoir. The press frame, consisting of three plates and six connecting tie rods, serves to contain the thrusts of the upper and lower jacks and locate the assembly.

The tapered pressure vessel is approximately 30 cm long and has a 1.9-cm bore. The electrical leads, which pass through a closure at the lower end of the vessel, are required for measuring the pressure and travel times of the compressional waves. The pressure was measured by observing the change in electrical resistance of a coil of manganin wire located within the pressure chamber. The coil was initially calibrated by Harwood Engineering Company of Walpole, Massachusetts, and calibrations were made independently in our laboratory by observing the change in electrical resistance at the freezing pressure of mercury and the lowest solid-solid transition of bismuth. The pressures reported in this paper are estimated to be accurate to 1%.

The pulse transmission method described in detail by *Birch* [1960] was used to obtain the velocities. Barium titanate transducers of 2-MHz frequencies generated and received the compressional waves. The samples were cylindrical, 1.27 cm in diameter and 3 cm in length, and were jacketed with Cu foil to exclude the pentane and 2-methylbutane pressure medium. The first arrivals received from the samples were matched with similarly shaped first arrivals obtained from a calibrated variable-length mercury delay line.

In velocity measurements to 10 kbar the break of the initial rise from the sample, and thus the ease of matching the delay line signal with the signal from the sample, becomes better defined with increasing pressure. This is probably due to many factors, including closure of pore space in the sample and improved bonding at high pressure between the transducers and the sample. In the runs to 30 kbar the quality of the signal continued to improve beyond 10 kbar to approximately 18 kbar, where a slight decrease in amplitude of the initial rise accompanied increasing pressure. However, even at 30 kbar the initial onset of the first motion was found to be superior to signals commonly observed in rocks at pressures below 2 kbar. The accuracy of the measurements above 2 kbar is estimated to be 0.5%. The precision, which is important in obtaining the pressure derivatives of the velocities, is better than 0.1%.

DESCRIPTION OF SAMPLES

Large blocks of pyroxenite, dunite, and eclogite visibly free of fractures were selected for the study. Particular attention was given in obtaining samples that were as free of secondary alteration as possible. Rocks with abundant pyroxene and olivine commonly possess strong preferred orientation, which often results in significant anisotropy [*Birch,* 1960; *Christensen,* 1966; *Christensen and Ramananantoandro,* 1971; *Babuška,* 1972]. Preliminary petrofabric analyses of the samples showed only weak pyroxene and olivine orientation. To establish the maximum anisotropy, three cores 2.54 cm in diameter and 7–8 cm in length were cut from each sample. Two directions from each sample were selected with the aid of the fabric diagrams to give maximum anisotropy, and velocities were measured to 10 kbar in the three cores from each rock. The results of the measurements at 10 kbar are summarized in Table 1. Separate cores were obtained for the 30-kbar measurements, the axes of which paralleled the cores that gave intermediate 10-kbar compressional wave velocities.

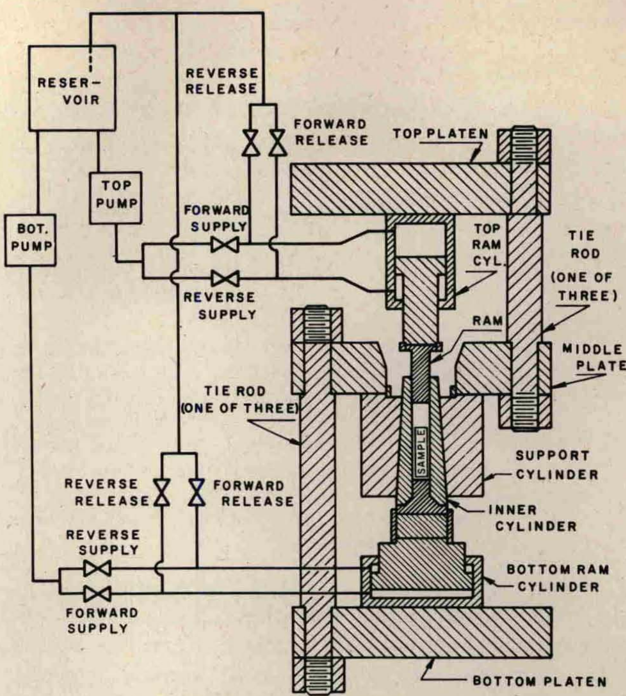

Fig. 1. Bridgman-Birch 30-kbar apparatus.

The pyroxenites differ somewhat in composition. Modal analysis of the Stillwater pyroxenite gives 97% bronzite, 1% olivine, 1% opaque, and less than 1% plagioclase and mica. The Twin Sisters pyroxenite contains approximately 82% enstatite, 18% olivine, and less than 1% opaque and serpentine. The anisotropy observed in the Twin Sisters

TABLE 1. Mean Velocities, Mean Densities, Calculated Elastic Constants, and Anisotropies at 10 kbar

Parameter	Pyroxenite, Stillwater, Montana	Pyroxenite, Twin Sisters, Washington	Dunite, Twin Sisters, Washington	Eclogite, Sunnmöre, Norway	Eclogite, Nové Dvory, Czechoslovakia
Compressional wave velocity, km/s	8.056	7.937	8.496	8.268	8.424
Shear wave velocity, km/s	4.622	4.453	4.834	4.617	4.639
Bulk density, g/cm^3	3.332	3.309	3.329	3.546	3.581
Compressibility, Mbar^{-1}	0.82	0.83	0.73	0.71	0.66
Lamé's constant, Mbar	0.74	0.77	0.85	0.91	1.00
Shear modulus, Mbar	0.71	0.66	0.78	0.76	0.77
Poisson's ratio	0.25	0.27	0.26	0.27	0.28
Seismic parameter, (km/s)^2	36.4	36.5	41.0	39.9	42.3
Young's modulus, Mbar	1.79	1.67	1.96	1.93	1.98
Bulk modulus, Mbar	1.21	1.21	1.37	1.42	1.51
Compressional wave anisotropy	0.7%	3.8%	0.3%	2.4%	0.8%
Shear wave anisotropy	0.5%	3.1%	1.5%	1.4%	1.9%

pyroxenite (Table 1) is a consequence of weak preferred orientation of enstatite and olivine. Both pyroxenites have average grain size less than 0.8 mm.

The Czechoslovakian eclogite is an extremely massive, fresh rock with an average grain size of 0.5 mm. The rock contains approximately 53% garnet, 44% omphacite, 1% opaque, and 2% plagioclase-diopside symplectite. The Norwegian eclogite is slightly altered and somewhat coarser, with an average grain size of 0.8 mm. Modal analysis is 48% garnet, 46% omphacite, 3% hornblende, 2% phlogopite, and 1% opaque.

The Twin Sisters dunite sample is exceptional in that it is fine grained (average grain size 1.0 mm) and has a nearly random mineral orientation. The dunite contains 98% olivine, 1% serpentine, and less than 1% enstatite and opaque. Composition of the olivine is approximately Fo_{90}.

Data

Velocities were recorded at 2-kbar intervals for both increasing and decreasing pressure. To assure that the samples had reached temperature equilibrium, time intervals between successive readings varied from 15 to 30 min. The velocities uncorrected for length changes due to compression are given in Table 2. Above 10 kbar, no apparent hysteresis was observed, whereas below approximately 10 kbar, velocities recorded during decreasing pressure were slightly higher than velocities obtained with increasing pressure. This is illustrated in Figure 2 for the Twin Sisters dunite. The hysteresis is similar to that discussed in detail by *Birch* [1960] and is primarily related to the adjustment of grain boundary porosity to changes in pressure. Velocities below 10 kbar in Table 2 are averages obtained during increasing and decreasing pressure.

The rock densities in Table 2 are bulk densities at atmospheric pressure, calculated from the weights and dimensions of the cores used for the 30-kbar runs. These compare favorably with the mean bulk densities from the larger cores calculated at 10 kbar (Table 1) and illustrate the homogeneity of the specimens.

Pressure Derivatives of Compressional Wave Velocities

To obtain accurate data on the changes of velocities with pressure, corrections have to be made to the data of Table 2 for shortening of the samples under compression. A common procedure, previously useful for rocks in which both compressional and shear velocities are determined, is to calculate adiabatic rock compressibilities and correct for change in length due to compression by using an iterative routine and the dynamically determined compressibilities [*Christensen and Shaw*, 1970; *Christensen and Ramanantoandro*, 1971]. For the rocks included in this study, length corrections at 10 kbar using this technique lower compressional wave velocities by approximately 0.02 km/s.

Volume compressions ($\Delta V/V_0$) of several minerals present in pyroxenites, dunites, and eclogites have been determined by *Bridgman* [1948, 1949] to pressures of approximately 30 and 40 kbar. Bridgman's data for several minerals pertinent to this study are given in Table 3. The olivine is described by Bridgman as peridote and probably is of composition similar to that of the Twin Sisters dunite. The North Carolina garnet is reported as almandite, whereas the British Columbia garnet is grossularite. Although the data are rather limited, there appear to be only minor changes in volume compressibility with composition for the garnets and pyroxenes.

The velocity data have been corrected for length changes at pressures between 10 and 30 kbar by using the volume compressions in Table 3 and the rock modal analyses. Linear compressions were assumed to equal one-third of the volume compressions. The corrected velocities above 10 kbar have been fitted to straight line solutions by the method of least squares, and the results are given in Table 4. Correlation coefficients of the linear least squares fits were better than 0.99 for all the rocks. The slopes of the solutions of Table 4 are estimated to be accurate to 10%.

Discussion

The pressure coefficients of compressional wave velocities determined for rocks at pressures below 10 kbar have been discussed in several papers. *Birch* [1969] summarized much

TABLE 2. Compressional Wave Velocities as a Function of Pressure Uncorrected for Length Changes

Pressure, bars	Velocity, km/s				
	Pyroxenite, Stillwater, Montana $\rho = 3.311$ g/cm^3	Pyroxenite, Twin Sisters, Washington $\rho = 3.286$ g/cm^3	Dunite, Twin Sisters, Washington $\rho = 3.309$ g/cm^3	Eclogite, Sunnmöre, Norway $\rho = 3.504$ g/cm^3	Eclogite, Nové Dvory, Czechoslovakia $\rho = 3.559$ g/cm^3
10	7.651	7.623	7.842	7.501	8.248
2,000	7.895	7.816	8.275	7.972	8.324
4,000	7.967	7.894	8.372	8.112	8.375
6,000	8.010	7.930	8.434	8.173	8.402
8,000	8.052	7.962	8.470	8.225	8.430
10,000	8.081	8.000	8.498	8.270	8.453
12,000	8.117	8.029	8.527	8.292	8.475
14,000	8.151	8.061	8.548	8.320	8.502
16,000	8.180	8.090	8.576	8.342	8.525
18,000	8.212	8.118	8.605	8.365	8.545
20,000	8.248	8.150	8.632	8.390	8.572
22,000	8.280	8.181	8.655	8.418	8.591
24,000	8.311	8.209	8.684	8.435	8.617
26,000	8.341	8.239	8.708	8.462	8.642
28,000	8.376	8.272	8.732	8.485	8.663
30,000	8.408	8.301	8.761	8.508	8.690

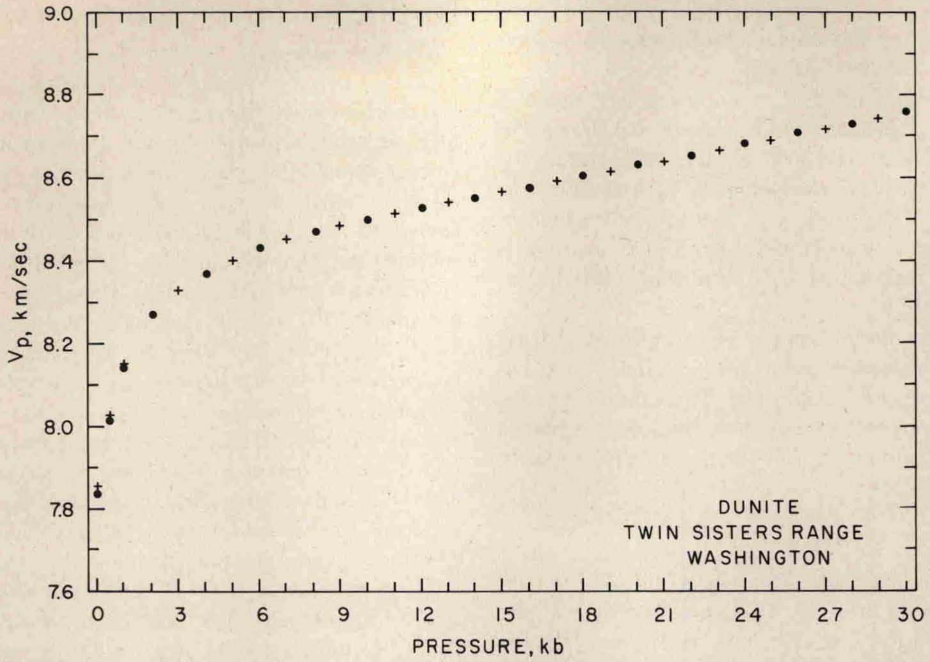

Fig. 2. Experimental points for the Twin Sisters dunite. Dots indicate measurements with increasing pressure; crosses indicate measurements with decreasing pressure.

of the data for dunites available prior to 1968 and compared the data with single-crystal measurements, porous forsterite velocities reported by *Schreiber and Anderson* [1967], and pressure coefficients calculated from the relationships

$$\frac{1}{V_p}\frac{dV_p}{dP} \approx \frac{3}{2K_s} - 1.04\frac{d\sigma}{dP}$$

and

$$\frac{1}{V_p}\frac{dV_p}{dP} = \frac{1}{6K}\frac{13\lambda + 14\mu}{\lambda + 2\mu}$$

where K is the bulk modulus, σ is Poisson's ratio, and λ and μ are Lamé's constants. Birch concluded that the pressure coefficients of velocity measured for dunite to 10 kbar are probably too high because of residual porosity, and with the available data, estimates of the pressure coefficient of velocity at 100 kbar are uncertain by approximately 50%. *Christensen and Ramananantoandro* [1971] also found that the pressure coefficients of velocities in dunites determined to 10 kbar were influenced significantly by porosity. It was shown that between 2 and 10 kbar, pressure derivatives of velocity for unaltered dunites are relatively high, whereas dunites with serpentinization along grain boundaries have significantly lower pressure derivatives of velocity, which are in better agreement with single-crystal measurements.

The compressional wave velocity data to 30 kbar (Table 2) show that pressures higher than 10 kbar are necessary to obtain significant pressure coefficients of velocities in rocks. This is illustrated in Figure 2 for the Twin Sisters dunite. The initial rapid increase of velocity with increasing pressure to approximately 2 kbar has been interpreted in many studies as a result of closure of grain boundary cracks. Between approximately 2 and 10 kbar the effect of porosity on velocities is much less than that observed at lower pressures, but it nevertheless is significant in determining pressure coefficients of velocities. Above approximately 10 kbar there appears to be little deviation from a linear relation between velocity and pressure. This suggests that the effects of grain boundary porosity on rock velocities are not eliminated until pressures of approximately 10 kbar are reached. Thus because of porosity, compressional wave velocity data for rocks determined at pressures below 10 kbar are unreliable for extrapolation to higher pressures.

Wang [1973] has recently reported 0.013 km s^{-1} $kbar^{-1}$ as the pressure coefficient of compressional wave velocity for a bronzitite from the Stillwater complex based on measurements to 25 kbar. This value is in good agreement with the velocity data determined to 30 kbar for the pyroxenites included in the present study (Table 4). Wang noted that

TABLE 3. Volume Compression of Olivine, Garnet, and Pyroxene

Pressure, kg/cm^2	Olivine, Egypt	Garnet, North Carolina	Garnet, British Columbia	Hypersthene, Labrador	Diopside, New York
0	0.0000	0.0000	0.0000	0.0000	0.0000
10,000	0.0079	0.0054	0.0064	0.0101	0.0088
20,000	0.0156	0.0107	0.0125	0.0191	0.0169
30,000	0.0231	0.0159	0.0185	0.0272	0.0245
40,000	0.0304	...	...	0.0347	0.0318

Data from *Bridgman* [1948, 1949].

TABLE 4. Parameters of Least Squares Solutions of the Form $V_p = a + bP$ Corrected for Length Changes

Rock	a, km s^{-1}	b, km s^{-1} kbar^{-1}
Pyroxenite, Montana	7.918	0.0137
Pyroxenite, Washington	7.846	0.0126
Dunite, Washington	8.369	0.0108
Eclogite, Norway	8.149	0.0097
Eclogite, Czechoslovakia	8.333	0.0096

V_p is given in km s^{-1}; P is given in kbar.

TABLE 5. Pressure Coefficients of Velocity from Single-Crystal Data

Mineral	$\partial V_p/\partial P$, km s^{-1} kbar^{-1}	Reference
Bronzite	0.02057	*Frisillo and Barsch* [1973]
Olivine	0.0102	*Kumazawa and Anderson* [1969]
Garnet	0.00784	*Soga* [1967]

the pressure coefficient of velocity for his bronzite differed significantly from that calculated from single-crystal data of bronzite reported by *Frisillo and Barsch* [1972], and because of this, he questioned the use of single-crystal data to predict rock properties.

Measurements of elastic constants, related pressure derivatives, and calculated Voigt-Reuss-Hill aggregate velocities and their pressure derivatives have been reported over limited pressure ranges for garnet, olivine, and pyroxene. The pressure derivatives of velocity for these minerals are given in Table 5 and are shown in Figure 3, where the aggregate velocities are extrapolated as dashed lines to 30 kbar. Rock velocities determined between 10 and 30 kbar from the solutions of Table 4 are shown as solid lines in Figure 3, and extrapolated 'zero porosity' velocities are dashed between 0 and 10 kbar.

Comparisons of the single-crystal and rock data in Figure 3 illustrate, as noted by *Wang* [1973], that pyroxenites have significantly lower pressure coefficients of compressional wave velocity than the Voigt-Reuss-Hill average calculated from single-crystal data of bronzite. The reasons for this discrepancy are at present unknown and must await additional velocity measurements in rock-forming minerals and rocks at pressures above 10 kbar. The Stillwater pyroxenite has a nearly random fabric, and thus preferred mineral orientation does not significantly influence its pressure coefficient of velocity. The lower pressure coefficient of velocity for the Twin Sisters pyroxenite compared with that of the Stillwater pyroxenite is interpreted as being due to the significant olivine content of the Twin Sisters pyroxenite, although it is possible that composition and anisotropy due to preferred mineral orientation in the Twin Sisters pyroxenite may be partially responsible for the differences in the two pyroxenites.

The pressure coefficient of compressional wave velocity calculated for single-crystal olivine is in excellent agreement with that measured for the Twin Sisters dunite. Velocities extrapolated between 2 and 30 kbar closely parallel the observed dunite velocities (Figure 3). The slightly lower velocities of the dunite are expected because of the accessory minerals present in the rock.

Velocities in the two eclogites fall between those of single-crystal garnet and the pyroxenites. The pressure coefficients of velocities of the eclogites are intermediate between those of garnet and the pyroxenites, thus suggesting that the elastic properties of omphacite do not differ significantly from those of enstatite and bronzite. The Czechoslovakian eclogite contains more garnet and less alteration products and therefore has higher velocities than the Norwegian eclogite.

It is concluded that extrapolation to high pressure of

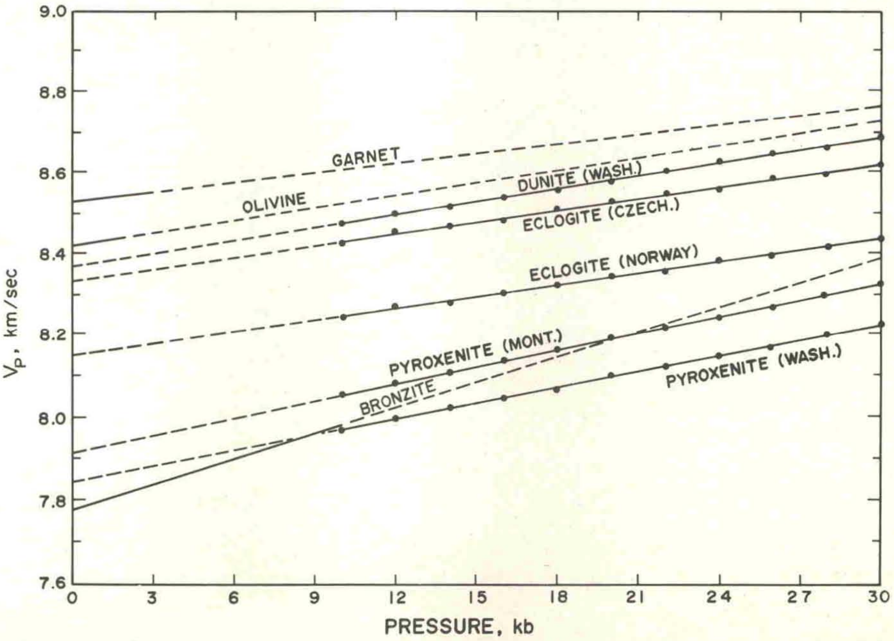

Fig. 3. A comparison of 30-kbar rock velocity data with extrapolated single-crystal data. Extrapolated velocities are shown as dashed lines.

velocity averages from single-crystal data may lead to a valid prediction of rock velocities, as has been illustrated for the Twin Sisters dunite and single-crystal olivine. For pyroxenites, however, extrapolated velocities determined from single-crystal data are not in agreement with rock measurements. Thus the extrapolation of laboratory measurements determined below 10 kbar from both rocks and single crystals to elevated pressures must be viewed with caution.

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