

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.

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 pyrox-

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	<i>Frisillo and Barsch</i> [1973]
Olivine	0.0102	<i>Kumazawa and Anderson</i> [1969]
Garnet	0.00784	<i>Soga</i> [1967]

enite 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

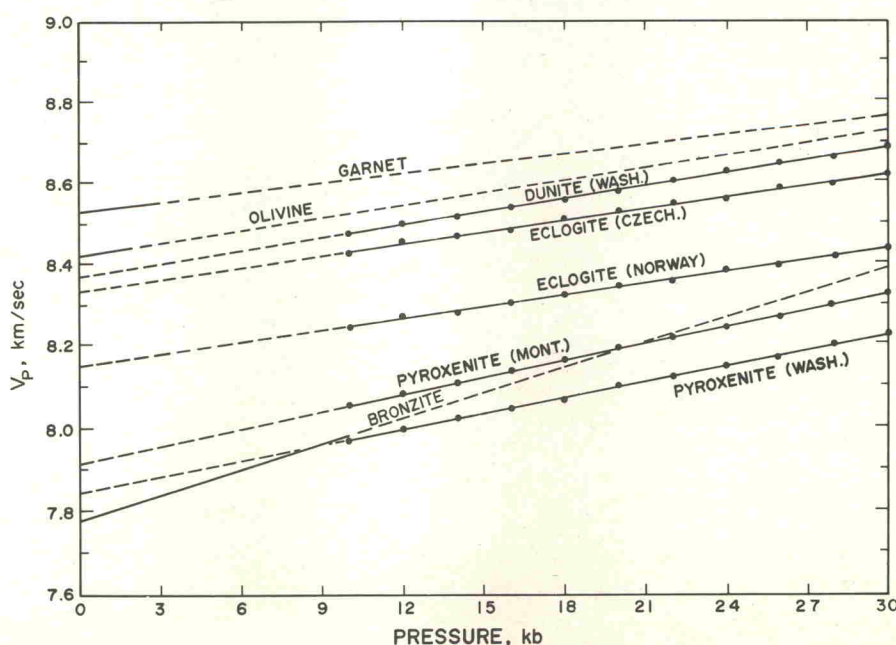


Fig. 3. A comparison of 30-kbar rock velocity data with extrapolated single-crystal data. Extrapolated velocities are shown as dashed lines.

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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REFERENCES

- Anderson, O. L., E. Schreiber, R. L. Liebermann, and N. Soga, Some elastic constant data on minerals relevant to geophysics, *Rev. Geophys. Space Phys.*, **6**, 491-524, 1968.
- Babuška, V., Elasticity and anisotropy of dunite and bronzitite, *J. Geophys. Res.*, **77**, 6955-6965, 1972.
- Birch, F., Interpretation of the seismic structure of the crust in the light of experimental studies of wave velocities in rocks, in *Contributions in Geophysics in Honor of Beno Gutenberg*, edited by H. Benioff, M. Ewing, B. F. Howell, Jr., and F. Press, pp. 158-170, Pergamon, New York, 1958.
- Birch, F., The velocity of compressional waves in rocks to 10 kilobars, 1, *J. Geophys. Res.*, **65**, 1083-1102, 1960.
- Birch, F., The velocity of compressional waves in rocks to 10 kilobars, 2, *J. Geophys. Res.*, **66**, 2199-2224, 1961.
- Birch, F., Density and composition of the upper mantle: First approximation as an olivine layer, in *The Earth's Crust and Upper Mantle*, *Geophys. Monogr. Ser.*, vol. 13, edited by P. J. Hart, pp. 18-36, AGU, Washington, D.C., 1969.
- Birch, F., Numerical experiments on the velocities in aggregates of olivine, *J. Geophys. Res.*, **77**, 6385-6391, 1972.
- Birch, F., E. C. Robertson, and S. P. Clark, Jr., Apparatus for pressures of 27,000 bars and temperatures of 1400°C, *Ind. Eng. Chem.*, **49**, 1965-1969, 1957.
- Bridgman, P. W., The resistance of nineteen metals to 30,000 kg/cm², *Proc. Amer. Acad. Arts Sci.*, **72**, 157-205, 1938.
- Bridgman, P. W., Rough compressions of 177 substances to 40,000 kg/cm², *Proc. Amer. Acad. Arts Sci.*, **76**, 71-87, 1948.
- Bridgman, P. W., Linear compressions to 30,000 kg/cm², including relatively incompressible substances, *Proc. Amer. Acad. Arts Sci.*, **77**, 189-234, 1949.
- Christensen, N. I., Compressional wave velocities in metamorphic rocks at pressures to 10 kilobars, *J. Geophys. Res.*, **70**, 6147-6164, 1965.
- Christensen, N. I., Elasticity of ultrabasic rocks, *J. Geophys. Res.*, **71**, 5921-5931, 1966.
- Christensen, N. I., Composition and evolution of the oceanic crust, *Mar. Geol.*, **8**, 139-154, 1970.
- Christensen, N. I., and R. Ramanantoandro, Elastic moduli and anisotropy of dunite to 10 kilobars, *J. Geophys. Res.*, **76**, 4003-4010, 1971.
- Christensen, N. I., and G. H. Shaw, Elasticity of mafic rocks from the mid-Atlantic ridge, *Geophys. J. Roy. Astron. Soc.*, **20**, 271-284, 1970.
- Chung, D. H., Elasticity and equations of state of olivines in the Mg₂SiO₄-Fe₂SiO₄ system, *Geophys. J. Roy. Astron. Soc.*, **25**, 511-538, 1971.
- Frisillo, A. L., and G. R. Barsch, Measurement of single-crystal elastic constants of bronzite as a function of pressure and temperature, *J. Geophys. Res.*, **77**, 6360-6384, 1972.
- Graham, E. K., and G. R. Barsch, Elastic constants of single-crystal forsterite as a function of temperature and pressure, *J. Geophys. Res.*, **74**, 5949-5960, 1969.
- Kumazawa, M., and O. L. Anderson, The elastic moduli, pressure derivatives, and temperature derivatives of single-crystal olivine and single-crystal forsterite, *J. Geophys. Res.*, **74**, 5961-5972, 1969.
- Manghnani, M. H., Elastic constants of single-crystal rutile under pressures to 7.5 kilobars, *J. Geophys. Res.*, **74**, 4317-4328, 1969.
- Ringwood, A. E., and D. H. Green, Petrological nature of the stable continental crust, in *The Earth beneath the Continents*, *Geophys. Monogr. Ser.*, vol. 10, edited by J. S. Steinhardt and T. J. Smith, pp. 611-619, AGU, Washington, D.C., 1966.
- Schreiber, E., and O. L. Anderson, Pressure derivatives of the sound velocities of polycrystalline forsterite with 6% porosity, *J. Geophys. Res.*, **72**, 762-764, 1967.
- Simmons, G., Velocity of shear waves in rocks to 10 kilobars, 1, *J. Geophys. Res.*, **69**, 1123-1130, 1964.
- Soga, N., Elastic constants of garnet under pressure and temperature, *J. Geophys. Res.*, **72**, 4227-4234, 1967.
- Spetzler, H., E. Schreiber, and R. O'Connell, Effect of stress-induced anisotropy and porosity on elastic properties of polycrystals, *J. Geophys. Res.*, **77**, 4938-4944, 1972.
- Thomsen, L., Elasticity of polycrystals and rocks, *J. Geophys. Res.*, **77**, 315-327, 1972.
- Wang, C., Pressure coefficient of sound velocity for several rocks (abstract), *Eos Trans. AGU*, **54**, 473, 1973.

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