TABLE 3. Elastic Properties of Magnesite, Siderite, and Rhodochrosite

Pressure, kb	K_s, mb	μ, mb	V_p/V_s	σ_s	ϕ, (km/sec)^2
Magnesite					
2.0	1.12	0.62	1.77	0.27	37.8
6.0	1.19	0.65	1.78	0.27	39.8
10.0	1.22	0.66	1.79	0.27	40.9
Siderite					
2.0	1.16	0.48	1.94	0.32	31.0
6.0	1.22	0.50	1.94	0.32	32.2
10.0	1.24	0.51	1.94	0.32	32.8
Rhodochrosite					
2.0	1.20	0.41	2.05	0.34	33.6
6.0	1.24	0.44	2.04	0.34	34.5
10.0	1.25	0.45	2.02	0.34	34.8

Because of their relative purity, carbonates offer an excellent opportunity to examine the effect of iron, magnesium, and manganese substitution on the elastic moduli and wave velocities in minerals. In Figures 1 and 2 the data of *Chung* [1970] for the olivine series are compared with velocities of magnesite and siderite at 10 kb. Velocity-density relations for the magnesite-siderite series appear to be remarkably similar to those for the olivine series. The agreement between the two series suggests that velocity measurements for additional carbonates may provide important information about the relationships between various cation substitutions and elastic properties, which can be applied to silicates.

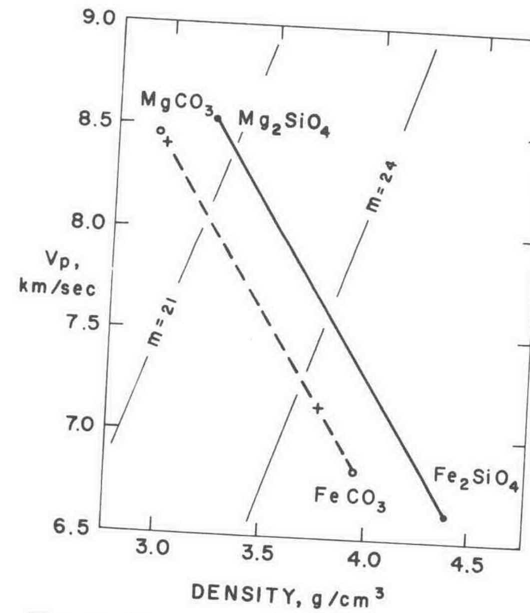

Fig. 1. Compressional-wave velocity-density relations for the olivine series Mg_2SiO_4-Fe_2SiO_4 [*Chung*, 1970] and the siderite-magnesite series $FeCO_3$-$MgCO_3$ (between the plus signs). The extended velocity-density lines to the densities of pure $MgCO_3$ and $FeCO_3$ are also shown.

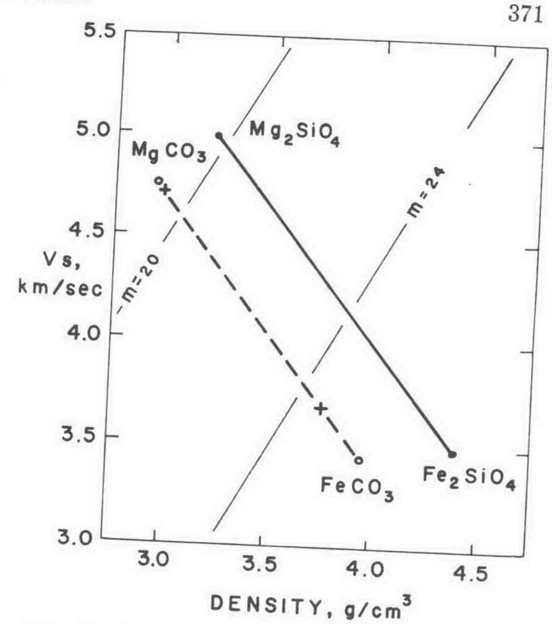

Fig. 2. Shear-wave velocity-density relations for the olivine series Mg_2SiO_4-Fe_2SiO_4 [*Chung*, 1970] and the siderite-magnesite series $FeCO_3$-$MgCO_3$ (between the plus signs). The extended velocity-density lines to the densities of pure $MgCO_3$ and $FeCO_3$ are also shown.

The bulk moduli K_s and shear moduli μ for the pure end members $MgCO_3$ and $FeCO_3$, estimated by extending the velocity-density lines of Figures 1 and 2 to the densities of pure $MgCO_3$ and $FeCO_3$, show changes with iron substitution of -0.02% and -29.9%, respectively. A similar relation between K_s and iron substitution in the olivine lattice has been noted by *Mao et al.* [1970] and *Chung* [1970]. The small decreases in K_s for both magnesite-siderite and olivine are presumably related to the similar unit cell volumes for the end member of each series. For corundum Al_2O_3 to hematite Fe_2O_3, however $\Delta K_s = -20\%$, which is comparable to the volume increase of 23% [*Liebermann*, 1970].

The behavior of μ with iron substitution in the magnesite-siderite and olivine series does not show so simple a relationship with cell volume as K_s.

The data for rhodochrosite in Table 2 indicate that the effect of manganese substitution in carbonates on elastic properties is quite similar to that of iron. A similar conclusion was noted by *Liebermann* [1970] for the spinel and corundum lattices, in which substitution of any 3*d* transition element appeared to have about the same effect on velocities and elastic moduli. Because of the relatively high anisotropy of the rhodochrosite specimen (Table 2) and the significant amounts of calcium in the rhodochrosite analysis (Table 1), the similarities in the elastic properties of $MnCO_3$ and $FeCO_3$ may be even greater than is indicated in Table 3.

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REFERENCES

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*a*.

Birch, F., Composition of the earth's mantle, *Geophys. J. Roy. Astron. Soc., 4,* 295–311, 1961*b*.

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.

Christensen, N. I., Chemical changes associated with upper mantle structure, *Tectonophysics, 6,* 331–342, 1968.

Christensen, N. I., and R. Ramananantoandro, The elastic moduli and anistropy of dunite to 10 kilobars, *J. Geophys. Res., 76,* 4003–4010, 1971.

Chung, D. H., Effects of iron/magnesium ratio on *P* and *S* wave velocities in olivine, *J. Geophys. Res., 75,* 7353–7361, 1970.

Deer, W. A., R. A. Howie, and J. Zussman, *Rock Forming Minerals,* Vol. 5, *Non-Silicates,* pp. 256–262, John Wiley, New York, 1962.

Graham, E. K., Jr., 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, J., and O. L. Anderson, Elastic moduli pressure derivatives, and temperature derivatives of single-crystal olivine and single-crystal forsterite, *J. Geophys. Res., 74,* 5961–5973, 1969.

Liebermann, R. C., Velocity-density systematics for the olivine and spinel phases of Mg_2SiO_4-Fe_2SiO_4, *J. Geophys. Res., 75,* 4029–4034, 1970.

Mao, N., J. Ito, J. F. Hays, J. Drake, and F. Birch, Composition and elastic constants of hortonolite dunite, *J. Geophys. Res., 75,* 4071–4076, 1970.

Mizutani, H., Y. Hamano, Y. Ida, and S. Akimoto, Compressional-wave velocities in fayalite, Fe_2SiO_4 spinel, and coesite, *J. Geophys. Res., 75,* 2741–2747, 1970.

Simmons, G., Velocity of compressional waves in various minerals at pressures up to 10 kilobars, *J. Geophys. Res., 69,* 1117–1121, 1964*a*.

Simmons, G., Velocity of shear waves in rocks to 10 kilobars, *J. Geophys. Res., 69,* 1123–1130, 1964*b*.

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