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Elastic Properties of Polycrystalline Magnesium, Iron, and Manganese Carbonates to 10 Kilobars

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Compressional- and shear-wave velocities to 10 kb and the chemistry for naturally occurring polycrystalline aggregates of magnesite $MgCO_3$, siderite $FeCO_3$, and rhodochrosite $MnCO_3$ are reported. Velocity-density relationships for the magnesite-siderite series show a dependence on mean atomic weight similar to that observed for the olivine series. Iron substitution for magnesium in carbonates decreases the shear modulus and increases Poisson's ratio. The bulk modulus, however, changes relatively little with iron substitution. Manganese substitution in carbonates affects the velocities and elastic parameters in much the same way as iron.

An important source of information on the composition of the earth's interior is derived from measurements of elastic-wave velocities in rocks and minerals. Birch [1961a] has shown that, to a first approximation, compressional-wave velocities are related to density and mean atomic weight. This relationship has been used to obtain mantle compositions by estimating velocities in olivine aggregates with varying iron content [e.g., Birch, 1961b, 1969; Christensen, 1968]. Recently, new experimental data on the elastic properties of the olivine series have become available from single-crystal studies [Graham and Barsch, 1969; Kumazawa and Anderson, 1969] and from measurements of hot pressed synthetic aggregates [Chung, 1970; Mizutani *et al.*, 1970] and naturally occurring dunites [Mao *et al.*, 1970; Christensen and Ramanantoandro, 1971]. The results of these studies agree well with compressional-wave-density relationships predicted by Birch [1961a] and show that shear-wave velocities in olivine also decrease with increasing iron content.

Many minerals are undoubtedly present in the upper mantle, and it is important to establish how variations in composition within different mineral groups affect elastic-wave velocities and moduli. Birch [1961a] observed that, in addition to the olivine series, an isostructural line connecting spinel to magnetite on a velocity-density plot was approximately at right angles to lines of constant mean atomic weight. Recently, Liebermann [1970] has shown that the

substitutions of 3d transition elements for magnesium and aluminum in the spinel and corundum lattices have similar effects on velocity-density relationships.

In this paper velocities and elastic moduli are presented for three carbonate end members: magnesite, siderite, and rhodochrosite. The changes in elastic properties with iron-magnesium substitution in carbonates are shown to be remarkably similar to the olivine series. The data for rhodochrosite are used to estimate the effect of manganese substitution on the elastic properties of minerals.

SAMPLES AND DATA

The samples are naturally occurring aggregates. Chemical analyses determined by atomic absorption and expressed in weight per cent are given in Table 1. X-ray diffraction patterns of the siderite and rhodochrosite show no additional minerals present in either sample. Thus the moderate amounts of calcium in the rhodochrosite and the moderate amounts of manganese and magnesium in the siderite are within the crystal lattices in solid solution. A small peak that was observed at a d value of 3.04 Å for the magnesite sample suggests that some of the calcium in the chemical analysis of this specimen is present as calcite.

Velocities to 10 kb were measured for each sample in three mutually perpendicular directions from cores 1.9 cm in diameter and 4 to 5 cm in length by a pulse transmission technique similar to that described by Birch [1960]. These velocities and the bulk densities of each core

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
<i>Magnesite</i>					
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
<i>Siderite</i>					
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
<i>Rhodochrosite</i>					
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 com-

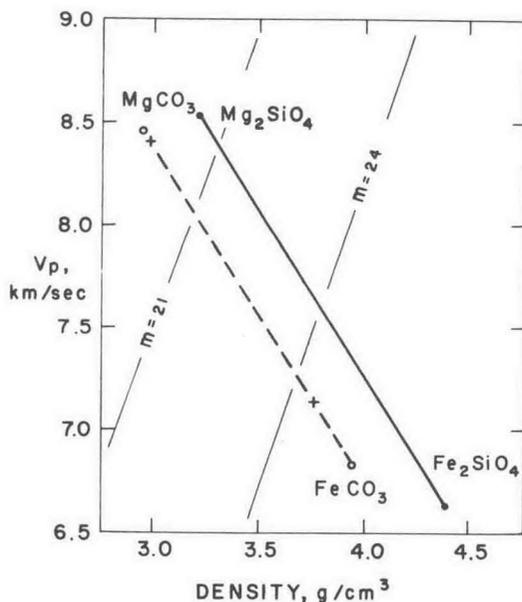


Fig. 1. Compressional-wave velocity-density relations for the olivine series Mg_2SiO_4 - Fe_2SiO_4 [Chung, 1970] and the siderite-magnesite series $FeCO_3$ - $MgCO_3$ (between the plus signs). The extended velocity-density lines to the densities of pure $MgCO_3$ and $FeCO_3$ are also shown.

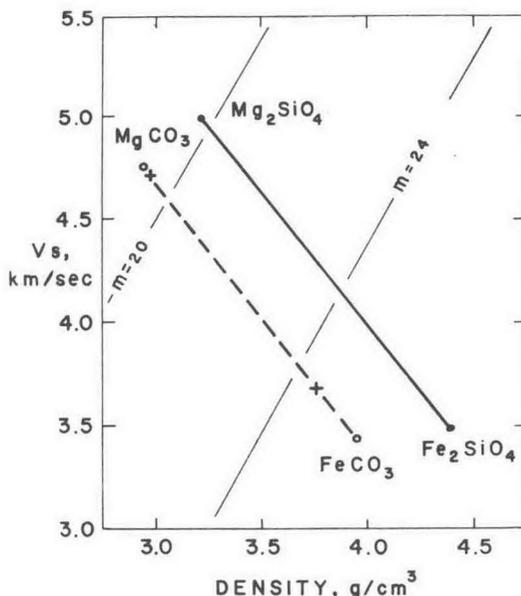


Fig. 2. Shear-wave velocity-density relations for the olivine series Mg_2SiO_4 - Fe_2SiO_4 [Chung, 1970] and the siderite-magnesite series $FeCO_3$ - $MgCO_3$ (between the plus signs). The extended velocity-density lines to the densities of pure $MgCO_3$ and $FeCO_3$ are also shown.

pared 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.

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].