JOURNAL OF GEOPHYSICAL RESEARCH VOL. 75, NO. 35, DECEMBER 10, 1970

Effects of Iron/Magnesium Ratio on *P*- and *S*-Wave Velocities in Olivine

D. H. CHUNG

Department of Earth and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Velocities of both the compressional and the shear waves measured on seven synthetic olivines with different Fe/Mg ratios are reported. The olivine compositions studied were 100% Fo, 95% Fo, 90% Fo, 85% Fo, 80% Fo, 50% Fo (where Fo stands for forsterite), and 100% fayalite. Effects of the Fe/Mg ratio on the compressional, shear, and bulk velocities, the bulk modulus, and the seismic parameter are examined for olivine at ambient conditions. An iron substitution in the olivine lattice results in a systematic decrease in these velocities, the seismic parameter, and the bulk modulus such that, for fayalite as compared with forsterite, there is a 22% decrease in V_p, a 30% decrease in V_s, a 16% decrease in V_Φ, a 30% decrease in seismic Φ, and only about a 4.7% decrease in K_s. The iron substitution increased Poisson's ratio of olivine by 19% for fayalite relative to forsterite. It was also found that the bulk modulus of olivine decreases almost linearly with increases in the iron content in the olivine lattice.

Experimental information on the elastic-wave velocities in olivines of the forsterite-fayalite series is essential to a better understanding of the physics and chemistry of the upper mantle. Literature dealing with elastic properties of olivine is abundant. *Adams* [1931] studied effects of iron content on compressibility of olivine. *Verma* [1960] reported the complete set of single-crystalline elastic constants determined on gem-quality periodot crystals. *Birch* [1960, 1961*a*], *Simmons* [1964], *Kanamori and Mizutani* [1965], and *Christensen* [1966] measured velocities in various dunites under pressures up to 10 kb. *Birch* [1962] reported *S* velocity in dunite as a function of temperature to about 800°K at 9 kb. *Schreiber and O. L. Anderson* [1967] studied the behavior of *P* and *S* velocities to about 2 kb on a synthetic forsterite sample with 6% porosity; on a similar specimen, *Soga and O. L. Anderson* [1967] reported velocities as a function of temperature to about 1000°K. *Trunin et al.* [1965] and *McQueen et al.* [1967] published shock-compression data on various dunites. More recently, *Graham and Barsch* [1969] and *Kumazawa and O. L. Anderson* [1969] reported both pressure and temperature derivatives at room temperature of the elastic constants for single-crystal forsterite. While the present work was in progress, data on the compressional velocity in fayalite have been reported by *Mizutani et al.* [1970]. *Fujisawa* [1970] also reported both the compressional- and the shear-velocities measured in a polycrystalline fayalite sample with 2.5% porosity. However, except for the work of *Adams* [1931], none of these investigators studied effects of Fe/Mg ratio on the elastic properties of olivine. In the literature, many authors (see, for example, *Birch* [1961*a*, *b*], *McQueen et al.* [1964], *Press* [1968*b*], and *Christensen* [1968]) called attention to the need of a study for effects of iron on the elasticity of olivine.

In his measurements on the effect of pressure on the volume of 'pure fayalite,' Adams found 1.04 as the bulk modulus of fayalite having a density of 4.068 gm/cm³. On the assumption that Poisson's ratio is 0.27, Adams then found 6.6 km/sec as the velocity of *P* waves for fayalite at ambient conditions. The crystal density of fayalite is 4.393 g/cm³ [*Yoder and Sahama*, 1957; *Robie et al.*, 1966] and suggests Adams's fayalite sample may not have been a representative sample of fayalite. The fayalite sample used by Adams was recently discussed by *Birch* [1969, p. 33]; Birch suggested a redetermination of elastic properties on a fayalite sample with the correct density.

In this paper, we report new data on the compressional (*P*) and shear (*S*) wave velocities

determined on artificially produced olivines with widely varying Fe/Mg ratio. Effects of the Fe/Mg ratio on velocities, bulk modulus, and seismic parameter are studied for these olivines at ambient conditions. The results reported here should be of interest to the scientific community concerned with the physical state and chemical composition of the earth's upper mantle, since they represent the only such systematic data existing for the forsterite-fayalite series. Sample preparation and experimental procedures are described in section 1. In section 2, experimental data are presented for 7 olivines with different Fe/Mg ratios. Although our velocity data reported here are at ambient conditions only, their relative variations in velocities as the Fe/Mg ratio changes may be useful in correlating to the first order with the velocities of elastic waves within the earth's mantle, determined from seismological data. On this basis, a brief discussion related to the earth is made in section 3.

1. Samples and Experimental Procedure

1.1 Preparation and Characterization of Specimens

Forsterite. Starting with stoichiometric amounts of MgO and SiO_2 powders, forsterite was prepared by solid state reaction at 1350°C for 120 hours. The starting powders were obtained as follows: SiO_2 (cristobalite) was prepared from reagent grade silicic acid (Baker Chemical Company) by heating for 12 hours at 1300°C. Microscopic examinations revealed that over 80% of the particles had mean diameter of about 5–15 μ, about 10% of the particles were less than 5 μ, and about 10% were greater than 15 μ size. A similar fraction of MgO was obtained by milling AR-grade periclase powders (Mallinckrodt Chemical Works). The stoichiometric amounts of these powders were hand mixed in acetone, and the process was continued as the acetone evaporated. The powders were then dried and heated in a temperature-controlled, platinum-wound furnace for periods up to 120 hours at 1350°C. The extent of solid-state reaction was determined by use of x-ray diffraction and microscopic observations. The forsterite powders thus prepared were then crushed and milled to about 1–10 μ in particle size; they were then hot-pressed into a dense-formed disk with a procedure described earlier [see *Crandall et al.*, 1961].

Fayalite. Starting with stoichiometric amounts of SiO_2 and iron oxalate, fayalite was prepared by solid-state reaction under a controlled atmosphere. The reaction temperature was 1200°C for 72 hours. SiO_2 (cristobalite) as a starting material was prepared as above (see 'Forsterite') from reagent grade silicic acid by heating. The ion oxalate (Amend Drug and Chemical Company, Inc.) was used as the source of 'FeO' because iron in iron oxalate is in the ferrous state. In addition, under solid-state reaction with silica, the iron oxalate generates a slightly reducing atmosphere, e.g.,

$$SiO_2 + 2FeC_2O_4 \cdot 2H_2O + O_2 \rightarrow Fe_2SiO_4 + 4CO_2 + 4H_2O$$

This reducing condition is essential in the formation of fayalite. X-ray diffraction and microscopic examination were used as before to characterize the formed fayalite. The fayalite powders thus prepared were then crushed and milled down to about 1–10 μ in particle size; they were hot-pressed into a dense-formed disk.

Forsterite-fayalite solid solutions. Our synthesis of the olivine solid solutions followed a procedure used by *Yoder and Sahama* [1957] and also by *Akimoto and Fujisawa* [1968]. In brief, starting with ready-made powders of forsterite and fayalite crystallites, the desired proportions of the two end-member olivines were made to react at 1200°C under a controlled atmosphere for 12 hours. Five solid-solution olivines thus prepared are 95% Fo, 90% Fo, 85% Fo, 80% Fo, and 50% Fo where '% Fo' designates a mole per cent forsterite. X-ray diffraction and microscopic examinations were used throughout to characterize each reaction product. All the reaction products used in the present work were found to be mostly (better than 95% by volume) a single-phase olivine of the specified composition. The resistant hot-pressing method was used for making dense-formed disks of these olivine specimens.

The hot-pressed disks were then appropriately cut,[1] ground, and polished to give rectangular

[1] Most hot-pressed samples show apparent anisotropies in their elastic properties, an effect often due to a preferred orientation of mineral grains and to the orientation of pores (including