

stishovite) which has a mean density at zero pressure $\bar{\rho}_0$ of 4.08 g/cm³. This value of $\bar{\rho}_0$ compares very well with 4.10 (± 0.05) g/cm³, the density value obtained by extrapolation of trajectory (4) to the zero-pressure point by the use of the Birch equation of state. Thus, the usefulness of the proposed scheme for identification of phases and their densities at high pressures is readily observed.

In summary, then, the author concludes the following: a) the analytical scheme proposed in this paper involving eqs. (3) and (5) is useful for constructing equations of state of solid phases that cannot be determined experimentally given the present state of technology, and b) one now should be able to model in the laboratory the elasticity and constitution of the earth's interior by incorporating the information on experimental petrology, high-pressure compression data and geophysical field observations in this approximation scheme. In a subsequent series of communications, the results of such an attempt shall be reported.

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* The Hugoniot curve is found from the pressure-volume-energy (PVE) surface specified by the input through the constraint equation

$$E_2 - E_1 = \frac{1}{2} (p_1 + p_2) (V_1 - V_2)$$

which is the energy-jump condition for a shock transition from State 1 to State 2. In the case of a phase transition, the Gibbs free energy is found by integrating the equation of state of each phase and the additional constraint that "the Gibbs free energy must be equal" is imposed in the mixed-phase region. The slope of the equilibrium Hugoniot curve in the mixed-phase region depends on the entropy difference and volume difference between phases. For any reasonable value of these parameters, the slope of the equilibrium Hugoniot curve in the mixed-phase region is much smaller than the slope of the actual shock-wave data points. Therefore, the transition does not go to completion in the shock experiments and in this intermediate region consisting of mixed phases no conclusion on density of the high-pressure phase can be drawn.

References

- [1] F. Birch, Elasticity and constitution of the earth's interior, *J. Geophys. Res.* 57 (1952) 227.
- [2] F. Birch, Composition of the earth's mantle, *Geophys. J. Roy. Astron. Soc.* 4 (1961) 295;
D.H. Chung, Birch's law: Why is it so good? *Science* 177 (1972) 261.
- [3] D.H. Chung, Elasticity and equations of state of olivines in the Mg₂SiO₄-Fe₂SiO₄ system, *Geophys. J. Roy. Astron. Soc.* 25 (1971) 511;
Effects of iron/magnesium ratio on P- and S-wave velocities in olivine, *J. Geophys. Res.* 75 (1970) 7353.
- [4] C.Y. Wang, Equation of state of periclase and some of its geophysical implications, *J. Geophys. Res.* 74 (1969) 1451;
R.G. McQueen, S.P. Marsh and J.N. Fritz, On the composition of the earth's interior, *J. Geophys. Res.* 69 (1964) 2947.
- [5] O.L. Anderson, E. Schreiber, R.C. Liebermann and N. Soga, Some elastic constant data on minerals relevant to geophysics, *Rev. Geophys.* 6 (1968) 491; for discussion, see ref. [6].
- [6] D.H. Chung, Pressure coefficients of elastic constants for porous materials: Correction for porosity and discussion on literature data, *Earth Planet. Sci. Letters* 10 (1971) 316. In table 4 on page 322 and in the text, the porosity-corrected hematite data should have been ($d\mu^0/dp$) = 0.73 and (dK_s^0/dp) = 4.57, not 0.89 and 4.91.
- [7] D.H. Chung, First pressure derivatives of polycrystalline elastic moduli: Their relation to single-crystal acoustic data and thermodynamic relations, *J. Appl. Phys.* 38 (1967) 5104.
- [8] H. Mao, T. Takahashi, W.A. Bassett, J.S. Weaver and S. Akimoto, Effect of pressure and temperature on the molar volumes of wüstite and of three (Fe, Mg)₂SiO₄-spinel solid solutions, *J. Geophys. Res.* 74 (1969) 1061.
- [9] P.W. Bridgman, The compression of 39 substances to 100,000 kg/cm², *Proc. Am. Acad. Arts & Sci.* 76 (1948) 55.
- [10] D.B. McWhan, Linear compression of α -quartz to 150 kbar, *J. Appl. Phys.* 38 (1967) 347.
- [11] W.A. Bassett and J.D. Barnett, Isothermal compression of stishovite and coesite to 85 kbars at room temperature by X-ray diffraction, *Phys. Earth Planet. Interiors* 3 (1970) 54.
- [12] J. Wackerle, Shock-wave compression of quartz, *J. Appl. Phys.* 33 (1962) 822.
- [13] L. V. Al'tshuler, R.F. Truinin and G.V. Simakov, Shock-wave compression of periclase and quartz and compression of the earth's lower mantle, *Phys. Solid Earth* 10 (1965) 657.
- [14] R.G. McQueen, Shock-wave data and equations of state, in *Seismic Coupling*, ed. G. Simmons (Univ. Michigan Geophys. Lab. Publ., Ann Arbor 1968).

- [15] R.G. McQueen, S.P. Marsh and J.N. Fritz, Hugoniot equation of state of 12 rocks, *J. Geophys. Res.* 72 (1967) 4999.
- [16] D.H. Chung, Equations of state of pyroxenes in the $\text{MgSiO}_3\text{-FeSiO}_3$ system, *Trans. Am. Geophys. Union* 52 (1971) 919.
- [17] A.E. Ringwood, Phase transformation in the mantle, *Earth Planet. Sci. Letters* 5 (1969) 401.

References to table 1:

- [18] F. Birch, The velocity of compressional waves in rocks to 10 kilobars, Part 1, *J. Geophys. Res.* 65 (1960) 1083; Part 2, *J. Geophys. Res.* 66 (1961) 2199.
- [19] G. Simmons, The velocity of shear waves in rocks to 10 kilobars, *J. Geophys. Res.* 69 (1964) 1123.
- [20] G. Simmons and A.W. England, Universal equations of state for oxides and silicates, *Phys. Earth Planet. Interiors*, 3 (1969) 69.
- [21] M. Kumazawa, The elastic constants of single-crystal orthopyroxene, *J. Geophys. Res.* 74 (1969) 5973.
- [22] T.V. Ryzhova, K.S. Alexandrov and V.M. Korobkova, The elastic properties of rock-forming minerals; 5. Additional data on silicates, *Izv. Acad. Sci. USSR, Phys. Solid Earth* 2 (1966) 111.
- [23] M. Kumazawa and O.L. Anderson, Elastic moduli, pressure derivatives, and temperature derivatives of single-crystal olivine and single-crystal forsterite, *J. Geophys. Res.* 74 (1969) 5961. The inversion procedure described in this paper, on page 5968 and thereafter, is incorrect. The equation, for example, given by these authors on mid-page 5968 is

$$\frac{dS_{ij}}{dX} = \frac{1}{\Delta_0} [A_{ij} - S_{ij0}\Delta]$$
 and this equation is dimensionally inconsistent. The correct equation should have been

$$\frac{d\hat{S}}{dX} = -\hat{S} \frac{dC}{dX} \hat{S}.$$
- [24] H. Mizutani, Y. Hamano, Y. Ida and S. Akimoto, Compressional wave velocities in fayalite, Fe_2SiO_4 -spinel, and coesite, *J. Geophys. Res.* 75 (1970) 2741.
- [25] R.K. Verma, Elasticity of some high density crystals, *J. Geophys. Res.* 65 (1960) 757.
- [26] M.F. Lewis, Elastic constants of magnesium aluminate spinel, *J. Acoust. Soc. Am.* 40 (1966) 729.
- [27] D.H. Chung, Equations of state of olivine-transformed spinel, *Earth Planet. Sci. Letters* 14 (1972) 348.
- [28] E. Schreiber, Elastic moduli of single-crystal spinel at 25°C and to 2 kbar, *J. Appl. Phys.* 38 (1967) 2508.
- [29] E.H. Bogardus, Third-order elastic constants of Ge, MgO , and fused SiO_2 , *J. Appl. Phys.* 36 (1965) 2504.
- [30] D.H. Chung and W.R. Buessem, The Voigt-Reuss-Hill (VRH) approximation and the elastic moduli of polycrystalline MgO , CaF_2 , $\beta\text{-ZnS}$, ZnSe , and CdTe , *J. Appl. Phys.* 38 (1967) 2535.
- [31] D.H. Chung and G. Simmons, Elastic properties of polycrystalline periclase, *J. Geophys. Res.* 74 (1969) 2133.
- [32] H. Spetzler, Equation of state of polycrystalline and single-crystal MgO to 8 kbar and 800°K, *J. Geophys. Res.* 75 (1970) 2073.
- [33] J.B. Wachtman, Jr., W.E. Tefft, D.G. Lam Jr. and R.P. Stinchfield, Elastic constants of synthetic single-crystal corundum at room temperature, *J. Res. NBS (U.S.A.)* 64A (1960) 213.
- [34] J.H. Gieske and G.R. Barsch, Pressure dependence of the elastic constants of single-crystal aluminum oxide, *Phys. Status Solidi* 29 (1968) 121.
- [35] D.H. Chung and W.R. Buessem, The VRH approximation and the elastic moduli of polycrystalline ZnO , TiO_2 and $\alpha\text{-Al}_2\text{O}_3$, *J. Appl. Phys.* 39 (1968) 2777.
- [36] D.H. Chung and G. Simmons, Pressure and temperature dependences of the isotropic elastic moduli of polycrystalline alumina, *J. Appl. Phys.* 39 (1968) 5316.
- [37] H.J. McSkimin, P. Andreatch and R.W. Thurston, Elastic moduli of quartz versus hydrostatic pressure at 25°C and -195.8°C, *J. Appl. Phys.* 36 (1965) 1624.
- [38] D.H. Chung and G. Simmons, Pressure derivatives of the elastic properties of polycrystalline quartz and rutile, *Earth Planet. Sci. Letters* 6 (1969) 134.