



Fig. 1. Pressure-density relations for material undergoing a shock-induced phase change. Low-pressure regime represents Hugoniot of material with zero-pressure density ρ_0^1 . High-pressure regime represents Hugoniot of material that has been completely converted to high-pressure phase with zero-pressure density ρ_0 . Metastable Hugoniot, adiabat, and isotherm for high-pressure phase are centered at state $P = 0, T = 25^\circ\text{C}$.

perature) equation of state for the high-pressure material. In these forms the reduced shock data can be applied to the study of the earth's interior.

The zero-pressure densities for the high-pressure phases obtained in the reduction can be compared with the densities of high-pressure polymorph or reaction products produced in static high-pressure quenching experiments on the same or analogous compounds and with the densities of possible polymorphs determined from crystal chemical considerations. Such comparisons may be used to infer the crystal structures of the minerals likely to be present at the high shock pressures and to form a basis for discussions of the crystal structures of minerals present in the deep mantle. The equation of state parameters, zero-pressure densities, and probable crystallography of the high-pressure polymorphs and/or reaction products produced in twenty-four rocks and minerals are obtained in the present study.

In the initial analysis of their data *McQueen et al.* [1967b] employed the high-pressure Hugoniot data independently to derive the density of the high-pressure (metastable) phase at standard temperature and pressure. The transformation energies were obtained by assuming that the pressure of the onset of the transition along the Hugoniot represented a state along the phase boundary between the low- and the high-pressure phase, i.e., thermodynamic equilibrium. *Wang* [1967] questioned this assumption and reported an analysis of these data that employed the linear relation between sound speed and density suggested by *Birch* [1961] to constrain the zero-pressure density at the foot of the adiabat of the high-pressure phase (hpp) material. Integration along the Hugoniot as an approximation to the virtual thermodynamic paths through the mixed phase region was used to account for the transformation energy. *Anderson and*

Kanamori [1968] reduced these and other data to a series of metastable Hugoniot curves, the feet of which were constrained to satisfy the seismic equation of state of *Anderson* [1967] and thus to yield the zero-pressure density.

In the present analysis we employ the adiabatic zero-pressure bulk modulus (or seismic parameter) and the mean atomic weight to constrain by means of the seismic equation of state [*Anderson*, 1967], the zero-pressure density of the (metastable) high-pressure phase. Where possible, supplementary thermodynamic data derived from high-pressure quenching experiments are used to calculate appropriate transformation energies.

CALCULATIONAL PROCEDURE

The raw Hugoniot data for minerals, illustrated in Figures 1 and 3-9, may often be represented as lying in one or more of the three regimes designated as the low-pressure phase, mixed-phase, and high-pressure phase regime. For many of the subject materials the low-pressure regime corresponds to stress-volume-energy states in material that has yielded under one-dimensional compression and has thus been shocked into states that are in an effectively hydrostatic state of stress; i.e., the principal stresses are nearly equal. In some cases, however (for example, Al_2O_3 and MgO), significant stress differences appear to be present at Hugoniot states up to substantial stress levels. These instances are discussed below. The mixed-phase region is assumed to represent a mixture of both the high- and the low-pressure phase material, and states in the high-pressure regime are assumed to represent material that has been wholly converted to the high-pressure phase. In the present analysis, we analyze only the shock data in the high-pressure region, although in practice it is often difficult to ascertain the lower pressure limit of this regime. It should be noted that the states lying in the high-pressure regime are achieved by direct shock transition from the low-pressure initial phase which is at standard conditions. No assumption of the equation of state of the low-pressure phase material need be made in the present procedure.

The Hugoniot and other forms of the equation of state are usually formulated in terms of expressions containing one or two adjustable parameters. These equations relate pressure to volume or density along a particular thermodynamic path such as the adiabat or isotherm. The two-parameter equations commonly employed include (A) the equation obtained from the linear shock-particle velocity equation [*Rice et al.*, 1958], (B) the Murnaghan equation, and (C) the Birch-Murnaghan second-order equation.

$$(A) \quad P = C_0^2(V_0 - V)/[V_0 - S(V_0 - V)]^2 \quad (1)$$

where C_0 represents the bulk sound speed at zero pressure, and S is the adjustable parameter in the relation of shock velocity to shock particle velocity ($U_s - U_p$):

$$U_s = C_0 + SU_p$$

Equation 1 is particularly well suited for fitting raw Hugoniot data. However, the thermodynamic restraints imposed by the linear U_s versus U_p relation, which has recently been discussed by *Ruoff* [1967], reduced the usefulness of this rela-