A Shock-Induced Phase Change in Orthoclase

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New shock compression data to 340 kb for single-crystal orthoclase (along 001) demonstrate the onset of a shock-induced phase change at ~135 kb. Along the Brezina's monoclase phase region extends to ~300 kb, above which data are believed to correspond to the properties of a high-pressure phase having the hollandite structure (zero pressure density of 3.84 g/cm³) reported by Ringwood et al. If the hollandite value for the zero pressure density is used, the zero pressure bulk modulus of this phase is approximately 2.8 ± 0.2 Mb.

The very high pressure equation of state of orthoclase is of importance both in describing the effects of intense shock waves on potash feldspar-bearing rocks on the earth and the moon (Hubbard et al., 1971; Drake et al., 1974; Chao, 1974; Kleeman, 1971; von Engelhardt and Stoffler, 1968) and in studying the earth's mantle. The latter is important because the orthoclase structure provides a model of the response of feldspar-bearing rocks to the high pressures of the earth's interior. Previously reported Hugoniots for muscovite (Ahrens et al., 1968) demonstrated that this mineral, like quartzite (McQueen et al., 1967), begins to transform to a new phase or phases at about 120 kb (along the Hugoniot). This phase change appears to go to completion for shock states above ~300 kb. Above this level the limited Hugoniots for muscovite suggested that the properties of a denser high-pressure phase were being sampled. The zero pressure density for the high-pressure phase inferred by Ahrens et al. (1968) and Davies and Anderson (1971) of ~3.5 g/cm³ compares unfavorably and incompletely with densities of 3.2 and 3.84 g/cm³ expected for the possible high-pressure phases in the 3 cristobalite jadeite endmember and hollandite. Because previous static high-pressure quenching experiments on both albite and germanium (analogue) potassium feldspars yielded only the hollandite-structured phase (Ringwood et al., 1967a, b; Kume et al., 1965) and because the inferred high-pressure phase assemblage density for garnet (Ahrens et al., 1969b; Davies and Anderson, 1971) is consistent with the formation of the hollandite phase (in KASLO), we assume that this phase is produced in our experiments.

To further study the equation of state of potassium feldspar, a series of Hugoniot experiments were carried out on a suite of single crystals of orthoclase from Madagascar (Table 1). These single crystals possess perfect cleavage along (001) and distinct cleavage along (010) (Winchell and Winchell, 1951). The samples were prepared by mounting and polishing the crystals in a parallel lapping jig on the 001 cleavage planes. Thin sections of the same orientation were also prepared for microprobe observation. Under conoscopic observation all thin sections showed slightly off-centered optical normal figures, which confirm that the sample axes are parallel to the 001 cleavage (Deer et al., 1965). The experimental procedures used in importing these samples is described by Ahrens et al. (1971) and Ahrens and Gaffney (1971).

In most of the experiments at least two shock arrivals were recorded at the specimen face surface when shock waves were driven into the sample assemblies. For final shock states below about 200 kb these initial shock arrivals, which we believe represent finite-amplitude elastic shocks, have an average velocity of 7.39 ± 0.06 km/sec (weighted mean and standard deviation). To substantiate this value, compressional

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TABLE 1. Orthoclase Formula Proportions

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<tr>
<td>Mg</td>
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<tr>
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Microwave analysis by A. Chodra (California Institute of Technology). Orthoclase samples from Strongay, Wajagwar. * Based on eight oxygen atoms.

The elastic velocity along the (001) direction was measured by ultrasonic interferometry [Spetzler, 1970] to be 7.55 ± 0.02 km/sec. Hugoniots and Almgren, 1965 measured the elastic velocities of a series of potassium-muscovite micas. Their reported value of compressional velocity along the (001) direction of a flake plane containing 78.2% orthoclase is 7.01 km/sec. Because the other components of the flake plane, anorthite and albite, have lower velocities than orthoclase, this value agrees in trend with our measurement. The free-surface velocities resulting from the free-surface reflection of this elastic shock were used to determine the amplitude (Hugoniot elastic limit, HEL) of this wave (via the free-surface approximation [Wakelam and Christlieb, 1953]). Observed values lie between 41 and 91 kbar (Table 2). The data (with the exception of shots 170 and 164) suggest that the HEL value is related to the final shock pressure, not unlike the situation in single-crystal and polycrystalline quartz [Wakelam, 1962; Akolas and Parrott, 1965]. For three shots with final shock pressures below 200 kbar the average HEL value is 43.3 ± 1.0 kbar. For shots with final pressures above this level a similar average yields 72.3 ± 7.7 kbar (weighted mean and standard deviation). The present HEL values bracket the earlier data for microcline.

Above the HEL the Hugoniot states (Table 2 and Figure 1), representing final shock states, were calculated by the impedance match method [Rice et al., 1936]. An intermediate 66.6-6.8 km/sec velocity wave was observed for shots with final states above 300 kbar. We infer that this shock front was due to the phase transition, corresponding to a shock state of ~100 kbar, and a density of ~4.0 g/cm³. The interaction of the elastic shock reflected at the free surface with the following second phase shock was neglected. Figure 1 demonstrates that above ~115 kbar the Hugoniot states achieved an asymptote at a greater density than the Hugoniot state inferred from the extrapolation of Brugnagn’s (1945) isotherm to 39 kbar for orthoclase. These isothermal data were fit to a Birch-Murnaghan equation and yielded the zero pressure isothermal bulk modulus Kᵢ = 229.5 kbar and (dKᵢ/dP)₀ = 4.4. Similarly, the Voigt-Reuss-Hill average of elastic constants for a series of potassium-rich feldspars reported by Alexandrov and Rakhman [1982], Rakhman [1984], and Rakhman and Alexandrov [1986] gives a similar value for the (isentropic) bulk modulus Kᵢ, which varies from 472 to 574 kbar. Isobars based on the extreme values of the ultrasonic data are also shown in Figure 1. On the basis

Fig. 1. Hugoniot data for single-crystal orthoclase. Shock states for microcline and the orthoclase-isothermal compression state of Brugnagn’s (1945) are also shown. Dashed curve above and below Brugnagn’s data represent the trend in bulk moduli observed ultrasonically for orthoclase-rich micas by Alexandrov and Rakhman (1982), Rakhman (1984), and Rakhman and Alexandrov (1986).
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**Table 1:** Initial data for single crystal observations made along (001)
TABLE 3. Calculated Shock Temperatures in High-Pressure Regime

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<th>Density, g/cm³</th>
<th>Hugoniot Pressure, P</th>
<th>Isentropic Pressure, P</th>
<th>Hugoniot Temperature, T</th>
<th>Isentropic Temperature, T</th>
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<td>310</td>
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<td>472</td>
<td>401</td>
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<td>552</td>
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*Obtained at zero pressure and 298 K.

of the intersection of the present orthorhombic Hugoniot and the isentrope data at 115 ± 10 kbar we infer that this pressure represents a minimum value for the onset for shock-induced phase change in orthorhombic to the hollandite structure. This conclusion is based on the observation that the inferred pressure value for the transition agrees closely with the 120 kbar value (at 900°C) obtained by Ringwood et al. [1977a, b] for the formation of the hollandite-structured phase from sanidine and that the present Hugoniot data, when they are taken with the earlier microphone results, imply a marked increase in the bulk modulus along the Hugoniot at densities greater than 1.4 g/cm³ (~200 kbar). The steep Hugoniot above 200 kbar would presumably correspond to the properties of the hollandite structure. A minimum transition energy of 1.5 × 10⁶ erg/cm³ for K₂Si₂O₇ (orthorhombic) → K₂Si₄O₁₀ (hollandite) (1)

is implied by the observed transition pressure. In analogy to the case of shock compression of quartz and fused quartz [Wardlaw, 1962; McQueen et al., 1963] we infer that the Hugoniot between 115 and 200 kbar represents a mixed-phase regime. Whether some phase other than the hollandite structure forms in this interval is uncertain, however, no other intermediate high-pressure phase or phase assemblage is currently known.

When the data of Akers et al. [1986a] are also used, a Birch-Murnaghan equation curve was fit through the eight raw Hugoniot data points, corresponding to the presumed high-pressure phase, by using a zero pressure density of 3.84 g/cm³ [Ringwood et al., 1977a, b]. This procedure gives the parameters K₀ = 2890 kbar and K₀'' = 6.8. Excluding the lowest pressure, more uncertain datum at 290 kbar, yields K₀ = 2807 kbar and K₀'' = 5.1, which are our preferred values. Excluding the two highest pressure points from the fitting procedure yields K₀ = 2859 kbar and K₀'' = 6.0. The sensitivity of these parameters to change in the data indicates an uncertainty in the high modulus of the high-pressure phase of ±2% and of some 15% in the value of K₀''. As a result both of using the new data and of making the outright assumption that the high-pressure phase has the hollandite structure, the bulk modulus obtained in this study is greater than that given by Akers et al. [1986b] by nearly a factor of 2.

For application to the study of naturally shocked potassium feldspar in rocks subjected to hypervelocity input, it is useful to calculate a series of shock temperatures (Table 3). These are calculated by the method of Akers et al. [1986b]. A constant value of the product of the Gruneisen parameter and a density of 3.84 and a transition energy of 1.5 × 10⁶ erg/cm³ was assumed. Although the equations of state of parameters of the high-pressure phase obtained in the present work are very different from those given by Akers et al. [1986a], the calculated shock temperatures, which depend entirely on the absolute increase in density upon compression, are rather similar to the earlier results.

Acknowledgments. We are grateful for the help of B. E. Gibbons, P. Riesz, and A. Chodos in obtaining and characterizing our samples and
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