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AUTHOR(S) J. N. Fritz and J. McQueen

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REFLECTED SHOCKS IN SiO_2*

J. N. Fritz and R. G. McQueen

Los Alamos National Laboratory
Los Alamos, NM 87545

Pavlovskii et al.[1], by compression by a magnetic field, find a transition on the quartz isentrope at 125 GPa. The transition, having a 2-fold increase in density over and above the density increase from quartz to stishovite, is ascribed to the metalization of quartz. The geophysical implications of such a transition would be profound. One would not see such a transition in singly-shocked quartz because all the shock energy would be increasing the thermal energy. Accordingly, we have performed second-shock experiments on a fine-grained quartz. These data will be presented. No evidence for a catastrophic volume collapse was found for second shocks up to 145 GPa.

INTRODUCTION

A two-fold increase in density in SiO_2 at 125 GPa over and above the increase in density from quartz to stishovite would have enormous geophysical consequences. Much of the conjecture about the composition of the lower mantle depends on the relative incompressibility of stishovite and other oxide phases which are assumed to behave in a similar manner. Indeed, such a tremendous density change makes SiO_2 a viable candidate for a core constituent. It would even be a conductive constituent if the transition producing such a large density change was to a metallic phase of SiO_2.

The absence of such a transition in single-shock data starting from a material with quartz-like density is not an argument against the existence of such a transition. In the exact expression for the slope of the Hugoniot curve, the factor $1 - \gamma(P,V)(V_0-V)/2V$ occurs in the denominator. Although the factor does not vanish until a density of 13 g/cm^3 is attained (for the assumption of γ constant and a γ_0 = 1.52 at stishovite density) it is already amplifying the locally-high isentropic slope by a factor of three by the time the density (5.7 g/cm^3) at which Pavlovskii et al.[1] see the transition is attained on the single-shock Hugoniot. This is another way of saying all the extra energy one puts into a single shock goes into thermal energy and doesn't increase the density. Multiple shocks provide a way of getting to the higher densities with an isentropic compression being the limiting case of multiple shocking. If stishovite were available as a starting material one could observe the transition in single-shock data (the V_0 in the factor is much reduced). For now we present two reflected shock curves, centered at two different pressures on the novaculite Hugoniot.

Experimental

Two thin slabs of Arkansas novaculite, a fine-grained quartz aggregate with a density of 2.64 g/cm^3 and an impurity content of less than 1%, were used as base plates in one of our standard configurations for measuring shock velocities. Explosive systems drove metal plates (2024 Al for the lower pressure shot and 347 stainless steel for the higher) through a 25 mm He-gas-filled free run to impact on the novaculite base plates (5 and 4 mm thick for the lower and higher pressure experiments). Twenty-six samples were mounted in an assembly that held them to the other side of the novaculite. Light from flash gaps on the base plate and sample surfaces was recorded by a streak camera and served to measure the shock velocities in the samples. Shock velocities in novaculite samples gave the base-plate state (our initial state for the subsequent reflected shock) and four other materials of higher impedence reflected shocks at various strengths into the base plate.

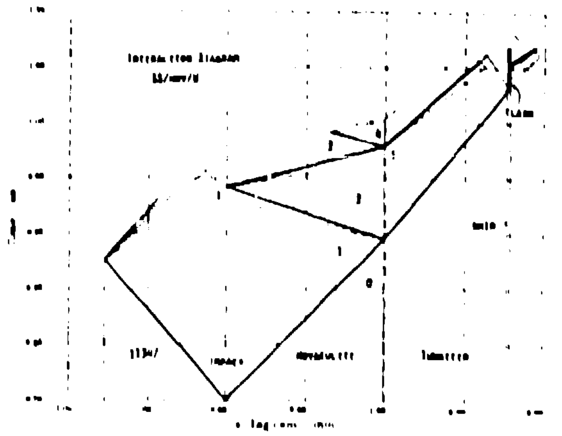

Fig. 1. Lagrangian coordinate vs time interaction diagram.

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The single-shock equation of state of these materials then permits us to obtain the P-u_p points of the reflected shock in the base plate, centered on the initial shock state measured by the novaculite sample.

Because of the high wave velocities in compressed SiO_2, one needs to take special care that the u_s measured in a sample is uncontaminated by multiple wave interactions from the rear. Figure 1 shows the wave interactions appropriate to the W sample for the highest pressure shot. The SS347 driver must be thick enough so that the release wave from its back surface does not interfere, and the W u_s sample must be thin enough so that the next shock from the novaculite will not catch up and give a spuriously high shock velocity. The bulk calculations (solid lines) indicate safety. Possible elastic precursors (dashed lines) cut into this margin. If we add up the time increments indicated by the added parenthesis and subtract this time from the extrapolated second shock in W we still have a safety margin of 0.07 μs after the first shock in the W slams into the aluminum shim and flashes the gap. The precursor before the shock converting the singly-shocked novaculite (1; a 55 GPa state) to the doubly-shocked novaculite (2, 150 GPa) is unlikely. The state 2 is our chief concern. If the transition were present the wave converting 1 to 2 would be approximately as shown, but would only convert the novaculite to 125 GPa. A second shock emanating from the novaculite-W interaction traveling at a very slow velocity would accomplish the actual phase transition. The P-u_p states corresponding to the polygonal areas in the y-t interaction diagram are shown in Fig. 2. State 1 is the singly-shocked novaculite and it bounces up between the W and SS347 Hugoniots. Straight solid lines are chords connecting the interaction states. The dotted line from 1 up is the calculated version of the reflected shock curve we wish to measure. Shock-velocity measurements of various materials on the base plate put experimental points on this plane. If a 2-wave structure goes back into the base plate above 125 GPa the dotted wave with the 2′ on it will result. Unlike forward shocks in samples, a sample sitting on the base plate measures the state behind the second shock. This second shock (third shock actually) was computed by centering it on the break-over point on the doubly-shocked curve and assuming a vertical P,V curve as the endpoint at a density of 10 g/cm^3. Clearly the form of this alternate section of the reflected-shock curve depends on form of the transition in the P-V plane.

For the calculations in this section and the rest of this note the EOS for novaculite we have used is a Hugoniot curve for stishovite: ρ_0 = 4.287 g/cm^3, $_0$ = 7.626 km/s, s = 1.5; and the off-Hugoniot specification of energy: ργ const. with γ_0 (stishovite) = 1.52, and E_0(stishovite) - E_0(quartz) = 0.80 J/mg.

Results

Figure 3 shows the u_s measurements. For each material they come in two groups, one for the lower-pressure shot and one for the higher. The spread in velocities is an indication of the precision and is also a consequence (possibly) of variation in base-plate pressure in the lateral dimension. In either case, averages are appropriate. The EOS's of the various materials permit us to plot these points in the u_s-u_p plane and in Fig. 4, in the P-u_p plane, where the measured reflected-shock curves are now obvious. Figure 5 shows the calculated reflected shocks from the measured points on the single-shock Hugoniot and Figure 6 shows these curves and

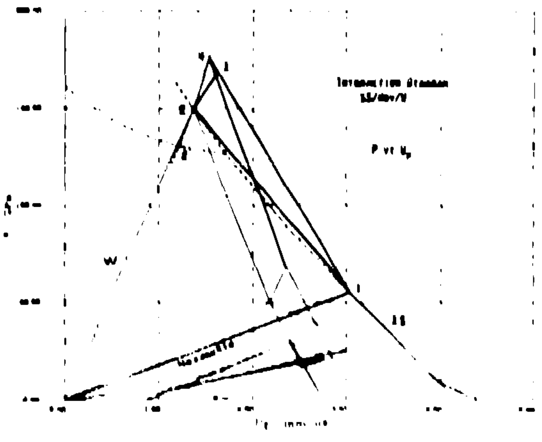

Fig. 2. P-u_p interaction diagram.

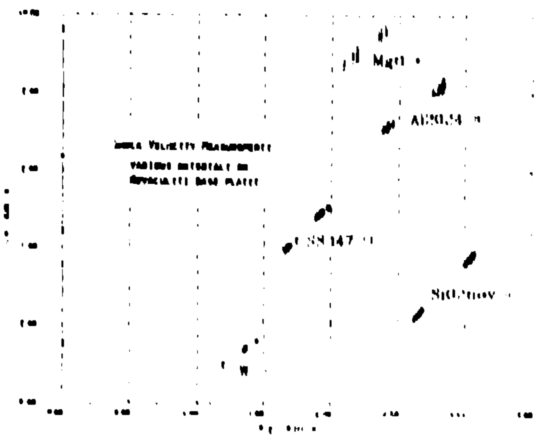

Fig. 3. Shock-velocity measurements, u_s-u_p plane.

compares them with the averaged experimental points. If the transition were to have occurred the upper W point would have fallen on the lower one, but it is on the continuation of the doubly-shocked curve.

These results are sensitive to the closure time of the flash gaps on the base plate. If, upon releasing to a low pressure at a free surface the stishovite does not reconvert to quartz, the time required to close the gap is appreciably longer. This has the effect of lowering the measured shock velocity in the higher impedance samples (the effect is symmetric on the novaculite samples and introduces no error). If it reconverts, then $u_{fs} = 2u_p$ (or a little greater). Some experiments were done to investigate this point and indicate the latter is correct. Thus, the open symbols are preferred and the closed symbols are shown to illustrate the magnitude of this effect.

Discussion

The W result at 150 GPa contradicts the existence of a transition at 125 GPa. If there is an incubation time associated with this transition, our experiment is ill-suited to detect it. The shock velocity set up in the tungsten initially is the instantaneous response of the novaculite. If it caves in later, then this information must travel to the advancing shock front in tungsten and slow it down. Our break-over point, if we had detected it, would have been considerably hotter than the one observed by Pavlovskii et. al. on the isentrope (this is very close to an stishovite Hugoniot). A positive dP/dT for the transition would require us to look higher in pressure. It is difficult to get a higher impedance material to probe higher along these particular reflected shocks. However, it is quite feasible to go to a higher initial state and get to substantially higher reflected pressures. Some experiments along these lines should be done. Good, large slabs of novaculite, for us for the moment unfortunately, had become scarce.

Two other arguments, pro and con, can be given. Rutile, in the rutile structure is known to have a large volume collapse. This high-pressure phase could be a candidate for the high-density SiO_2 phase. On the other hand, it is difficult to understand why there isn't a huge discontinuity in density in the mantle at 125 GPa.

The structure in the lower part of our reflected-shock curves could be interpreted in terms of the phase changes found by Lyzenga et al.(2) and ourselves. The brevity of this note and length of our uncertainties preclude making too much of this.

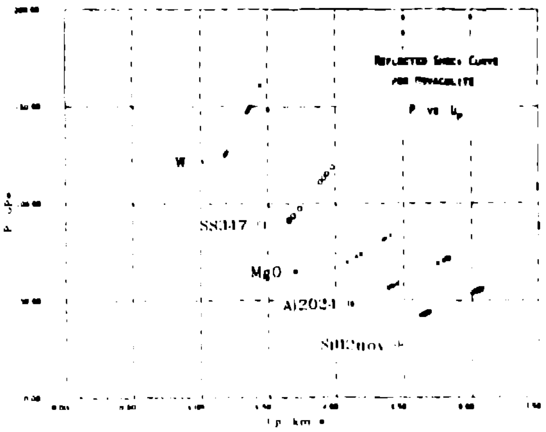

Fig. 4. Individual P-u_p points on the SiO_2 reflected shocks.

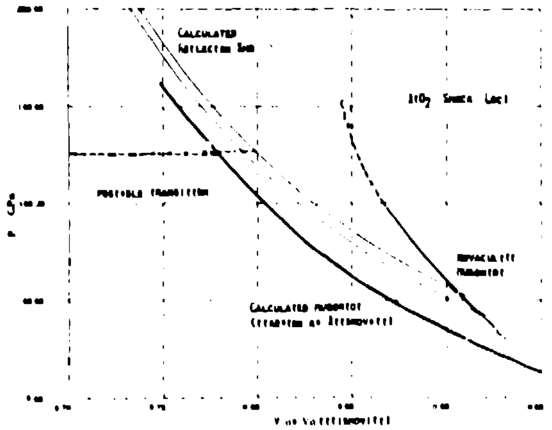

Fig. 5. SiO_2 single-shock loci, SiO_2 initial states for our reflected shock, and calculated double shocks.

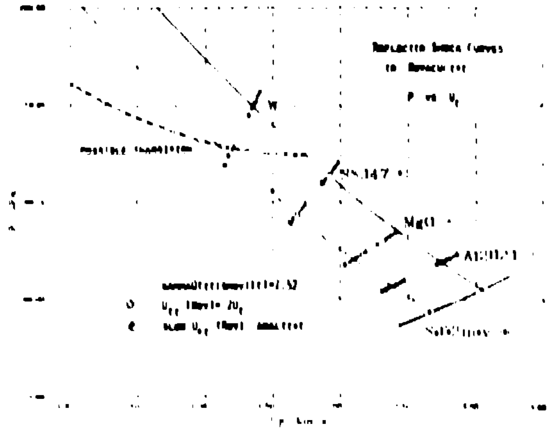

Fig. 6. Calculated double shock and experiments for two initial SiO_2 states.

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1. A. I. Pavlovskii, N. P. Kolokol'chikov, M. I. Dolotenko and A. I. Bykov, JETP Lett. 27, 264 (1978).

2. G. A. Lyzenga, T. J. Ahrens, and A. C. Mitchell, J. Geophys. Res. 88, 2431 (1983).