Quartz to Stishovite: Wave Propagation in the Mixed Phase Region

D. E. GRADY, W. J. MURRI, AND G. R. FOWLES

Poulter Laboratory, Stanford Research Institute
Menlo Park, California 94025

This work reports on phase transition kinetics and wave propagation in Arkansas novaculite, a fine-grained polycrystalline α quartz rock, when it is subject to high-pressure dynamic loading and relief. The stress region studied is between 150 and 400 kbar, where the polymorphic phase transition from α quartz to stishovite is believed to occur. Particular emphasis was focused on the unloading behavior in the mixed phase region. High-pressure loading is provided by conventional explosive methods. Measurements of the transient flow field are obtained with in-material manganin stress gages or magnetic particle velocity gages. Results showed partial transformation to the high-density phase occurring in the shock front, the degree of transformation depending on peak driving stress. A continuing transformation rate behind the shock front is very small, i.e., at least 3 orders of magnitude slower than the initial transformation rate. Unloading from stress-volume points in the mixed phase region is observed to occur along, or close to, paths of frozen phase concentration down to approximately 80 kbar. Below this stress the data indicate a transition of the high-density phase to a lower-density phase.

The present work reports on an investigation of Arkansas novaculite, a naturally occurring polycrystalline α quartz rock, when it is subject to shock wave loading. The pressure region studied is between 150 and 400 kbar, within which the polymorphic transformation of α quartz to stishovite has been reported to occur. Of primary interest is the unloading behavior of the material.

In earlier work, attention has focused on the shock wave properties of quartz for several reasons. Since it is pure silicon dioxide in a structure of silicon in tetrahedral coordination with oxygen and since this is the fundamental building block of more complex silicate minerals, understanding of the behavior of quartz is prerequisite to that of the more complicated minerals. One line of geophysical interest has stemmed from observation of mineral content in the vicinity of meteorite craters, where several polymorphs of high-density quartz have been uncovered [*Chao et al.*, 1962]. It is believed that they originated as a result of shock metamorphoses during meteorite impact. Further geophysical interest is provided by a quest to understand the mineral composition and polymorphic structure of the earth's mantle [*Wang*, 1968; *Anderson and Kanamori*, 1968; *Ahrens et al.*, 1969]. Pure silicon dioxide exhibits a high-pressure polymorphic phase transition, which is possibly representative of the expected behavior of most of the candidate mantle silicates. Quartz and other silicates and silicate-bearing rock constitute a large portion of the earth's surface, and accurate prediction of energy coupling and dynamic wave propagation in the vicinity of high velocity or explosive impact also requires studies of this kind.

Single-crystal and amorphous quartz were extensively investigated under shock loading by *Wackerle* [1962] to about 700 kbar. He observed an anomalous compression in the region from 150 to 400 kbar. An independent static investigation of quartz identified a high-density polymorph [*Stishov and Popova*, 1961]. *McQueen et al.* [1963] concluded that stishovite was formed under shock compression and formulated a high-pressure equation of state from the shock wave results. Further shock wave studies by *Fowles* [1967] on single-crystal quartz provided more complete data in the region below and slightly above the Hugoniot elastic limit of the material. *Ahrens and Rosenberg* [1968] studied Arkansas novaculite and single-crystal quartz under shock loading in the mixed phase region and estimated the unloading response by observing the shock states transmitted by the quartz into liquid buffers. Recently, *Trunin et al.* [1971] have investigated quartz of varying porosity under shock loading in and above the mixed phase region. Their results for the lowest-density specimens strongly suggest that the extremely high temperatures developed may have induced transformation to the coesite phase. This interpretation has been questioned by *Davies* [1972]. He suggested shock-induced melting as an alternative process.

The experiments performed in the current work focus on the stress region from slightly above the Hugoniot elastic limit to about 400 kbar. The experimental data were obtained from two types of experiments. In the first, aluminum or magnesium flyer plates thrown by explosive systems impacted targets of Arkansas novaculite. Shock loading resulted from impact, and relief occurred by shock reflection from the flyer plate free surface. Manganin stress gages provided records of stress-time histories at increasing distance from the impact surface.

In the second type of experiment, Arkansas novaculite was loaded by in-contact explosive. Material unloading occurred initially by the Taylor relief wave originating behind the explosive detonation front. Subsequent relief to zero stress occurs from the reflection of the shock wave off the novaculite free surface. Initial unloading rates were several orders of magnitude lower than those obtained in the flyer plate experiments. In this type of experiment, magnetic particle velocity gages provided records of particle velocity history at different material points. The experimental objective was to determine whether the α quartz to stishovite transition continued, at some reduced rate, behind the shock front.

The stress-time and particle velocity-time data were analyzed by a method suggested by *Fowles and Williams*