GRAD-DE 75-1154

VOL. 80, NO. 35 JOURNAL OF GEOPHYSICAL RESEARCH DECEMBER 10, 1975

Hugoniot Sound Velocities and Phase Transformations in Two Silicates

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Rarefaction wave velocities have been used to estimate sound velocities on the Hugoniot for a quartz rock and for a perthitic feldspar. The Hugoniot states and rarefaction wave velocities were determined with multiple manganin stress gages placed between successive slabs of the sample material. Hugoniot stress states were produced by impact from explosively driven flyer plates. The sound velocity was determined from the transit time across gage planes of the initial characteristic of the rarefaction wave originating at the flyer plate free surface. Sound velocities (referred to Eulerian coordinates) measured in quartzite were 7.6, 8.1, and 10.5 mm/μs at Hugoniot stresses of 220, 250, and 355 kbar, respectively. Sound velocities measured in feldspar were 7.4, 8.7, and 9.2 mm/μs at Hugoniot stresses of 255, 345, and 460 kbar, respectively. These velocities are close to estimated bulk velocities and imply an almost complete loss of material strength behind the shock front. On the basis of our measured sound velocities and earlier observations by others we suggest that the Hugoniot yielding phenomenon is an adiabatic shear process resulting in partial melting behind the shock front. We further suggest that inhomogeneity in the adiabatic shear process may account for many details of the nonequilibrium mixed phase Hugoniot observed in silicates.

INTRODUCTION

Hughes and McQueen [1958] were among the first to demonstrate that shock wave measurements could be applied to the study of the earth's interior. Since that time, shock wave data have become generally accepted as constraints for models of the earth [*Press*, 1968; *Ahrens et al.*, 1969]. For geophysical purposes, isothermal or adiabatic equations of state are required. The reduction of the Hugoniot states measured in shock wave experiments to isotherms or adiabats requires knowledge of the dependence of the Grüneisen parameter on volume, and, in principle, this behavior can be determined through measurements of Hugoniot sound velocities. Care must be taken in using Hugoniots to generate isotherms for further use in modeling the earth. Although Hugoniot data apply to states achieved in shock compression, they may not apply to states achieved by pressure and temperatures inside the earth. It is important therefore to use all the available evidence to determine whether the Hugoniot states measured in experiments of microsecond duration are thermodynamically equilibrated states.

Wackerle [1962] and *Fowles* [1967] have noted an apparent total loss of strength in the shock compression of quartz above the Hugoniot elastic limit in contrast to the elastic-plastic behavior of most ductile materials. This loss of strength has been reported to occur in other brittle solids [*Graham and Brooks*, 1971] and has not been satisfactorily explained.

Numerous studies on recovered samples of quartz and feldspar after shock loading provide accounts of lamellar features and identification of amorphous and high-density polymorphs of the original sample [*De Carli*, 1968; *Carter*, 1968; *Chao*, 1968; *Bunch*, 1968]. The genesis of these petrographic details is apparently linked to the shock deformation process. The results of these studies have been summarized in an excellent review by *Stöffler* [1972]. The residual features observed in recovered specimens of silicate materials are (1) planar fractures, (2) planar elements (shock lamellae), (3) deformation bands, (4) irregular plastic lattice deformation (mosaicism), (5) high-density phase, and (6) fused glass and diaplectic glass.

In this paper we report measurements of sound velocity on the Hugoniot for a quartz rock (Arkansas novaculite, initial density of 2.63 g/cm^3) and for a perthitic feldspar (75% orthoclase, 25% albite; initial density of 2.58 g/cm^3) over the stress range of 220–460 kbar. The present data also suggest loss of strength on the Hugoniot and further suggest that this loss of strength persists for some duration after shock passage.

These and earlier data suggest to us a physical model for the shock yielding mechanism and the Hugoniot phase transitions in quartz and feldspars. We will describe this model and show that it appears to provide reasonable explanations for the curious Hugoniot and shock wave properties of silicates and certain other brittle materials.

EXPERIMENTAL METHOD

Each experimental assembly was constructed of four parallel plates of the sample material. Manganin foil stress transducers were placed between plates, and the assembly was bonded with epoxy. The four-terminal manganin transducers were supplied by constant current sources, and voltage outputs were observed with high-quality camera oscilloscopes. Hugoniot stress states were achieved by the planar impact of explosively accelerated metal flyer plates. The experimental arrangements and a set of voltage-time records for one experiment are shown in Figure 1.

Because of the constant current, these voltage-time records are equivalent to resistance-time records, which can be transformed to stress-time data by using the dynamic calibration for manganin of *Lyle et al.* [1969]. The reduced multiple stress-time profiles for one experiment are shown in Figure 2 to indicate the propagation characteristics of the stress wave.

These records can be interpreted from inspection of Figure 3, a distance-time plot of the loading and rarefaction waves in the experiment. At impact of the flyer plate with the sample a shock propagates into the sample, and another shock propagates back into the flyer plate. When the shock in the flyer plate reaches the rear surface of the flyer, it reflects as a relief wave that propagates through the flyer and into the sample, eventually overtaking the shock wave in the sample. Since the

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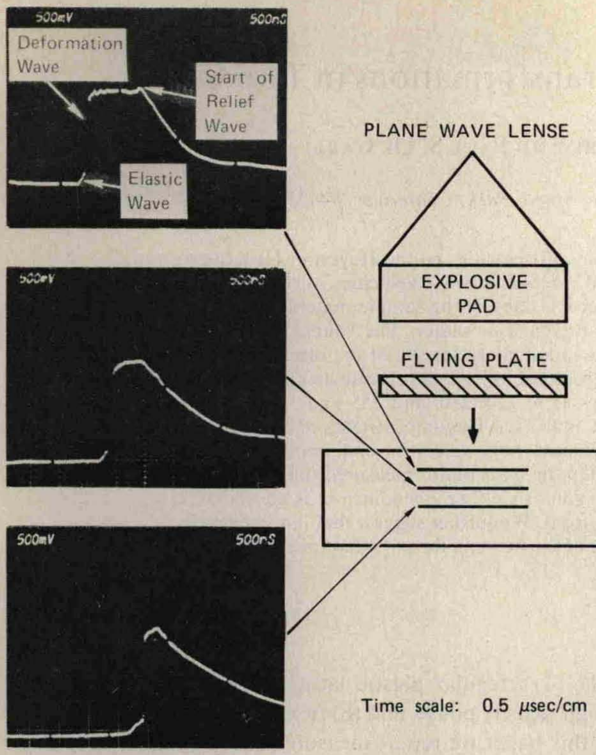

Fig. 1. Experimental stress profiles in feldspar obtained with manganin piezoresistant gage elements. Peak stress is approximately 350 kbar. Stress states are achieved by planar impact of the explosively accelerated metal flyer plate.

distances between transducer planes (usually about 3 mm) have been carefully measured beforehand, the gage records yield shock velocity and stress, which establish the Hugoniot state in each experiment.

The Lagrangian sound velocity on the Hugoniot is estimated by measurement of the transit time of the leading characteristic of the overtaking relief wave across the three transducer planes, as is indicated in Figure 2 and Figure 3. The relationship of the Lagrangian (initial length per unit time) velocity to the Eulerian sound velocity is the ratio of the initial density to Hugoniot density of the sample. The error in determining the Hugoniot density is conservatively estimated to be about 5% and is the major uncertainty in the present work. The finite thickness (about 0.025 mm) of the transducer plane slightly degrades the frequency response of the measurement but does not substantially limit the accuracy of determining the time of arrival of the relief wave. Special care in instrumentation (matched cable lengths, matched oscilloscopes and preamplifiers, a common z axis time mark, and careful calibration of instrumental time delays) was necessary to ensure proper time correlation among the oscilloscopes. The error bars on the data to be presented are believed to be conservative; the larger error bars are for experiments performed before all the time correlation problems were understood.

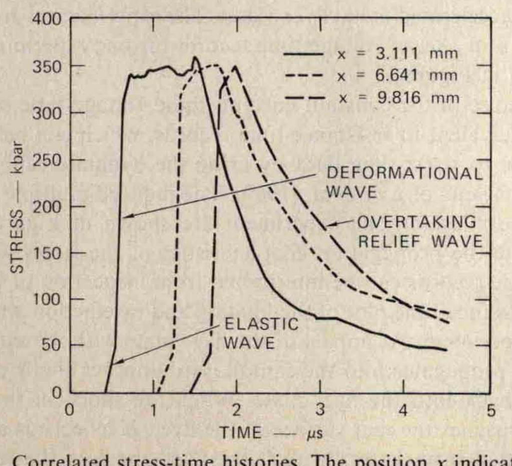

Fig. 2. Correlated stress-time histories. The position x indicates the distance of the gage from the impact interface.

EXPERIMENTAL RESULTS

The experimental data for quartz and feldspar are given in Table 1, and the sound velocities on the Hugoniot are plotted in Figure 4 as a function of the Hugoniot stress. These measurements ranged from 220 to 460 kbar in stress.

To understand the stress dependence of the measured sound velocities, it is instructive to consider two cases. First, if the silicate is assumed to have no mechanical strength and to behave as a fluid, it is possible to calculate the dependence of the bulk sound velocity on stress. A Murnaghan equation was used to estimate the compressibility of the low- and high-density phases and to determine the stress dependence of the bulk sound velocity. The results of this calculation are shown in Figure 4. The dashed lines represent extension into the mixed phase region. In these calculations we have assumed for each silicate that the low-pressure phase persists to 100 kbar, that the mixed phase region ranges from 100 to 400 kbar, and that the high-pressure phase occurs above 400 kbar.

In the second case, material strength is considered. A constant Poisson's ratio of $\gamma = 0.25$ was assumed for both low- and high-pressure phases. Use of Poisson's ratio allows a calculation of the variation of the longitudinal sound speed with stress. The results are curves labeled longitudinal sound speed in Figure 4.

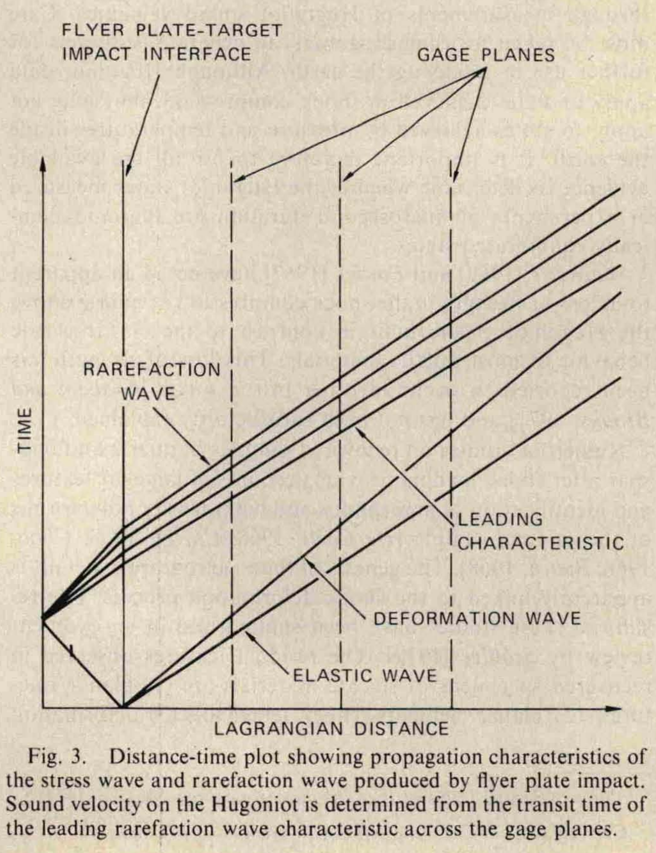

Fig. 3. Distance-time plot showing propagation characteristics of the stress wave and rarefaction wave produced by flyer plate impact. Sound velocity on the Hugoniot is determined from the transit time of the leading rarefaction wave characteristic across the gage planes.