TABLE 1. Hugoniot and Sound Velocity Data in Quartz and Feldspar

Material	Initial Specific Volume, cm³/g	Hugoniot Pressure, kbar	Hugoniot Specific Volume, cm³/g	Lagrangian Sound Velocity, mm/μs	Eulerian Sound Velocity, mm/μs
Feldspar	0.386	258*	0.257	11.1	7.4
Feldspar	0.386	345*	0.237	14.1	8.7
Feldspar	0.386	460	0.234	15.2	9.2
Quartz	0.380	222*	0.273	8.9	6.4
Quartz	0.380	252*	0.263	10.4	7.2
Quartz	0.380	352	0.233	21.0	12.9

* Precursor observed in these tests.

The data used to make the sound velocity estimates were obtained from *Anderson et al.* [1966], *Ahrens et al.* [1969], *Ahrens and Liu* [1973], and *Clark* [1966]. In the mixed phase region we assumed stress and particle velocity equilibrium but not temperature equilibrium. In addition we assumed that the sound velocity propagated as if the medium were one of frozen phase concentration; i.e., the sound velocity is given by the slope of the isentrope. The last assumption is justified by previous experimental work [*Grady et al.,* 1974] on quartz.

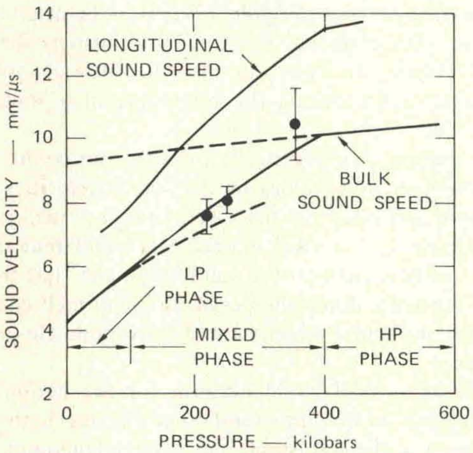
DISCUSSION

We conclude from the above calculations and our experimental data that sound waves on the Hugoniot in the materials studied travel at the bulk sound speed. This conclusion suggests an almost complete loss of shear strength in these materials behind the shock wave. *Graham and Brooks* [1971] observed a similar loss of shear strength in crystalline Al_2O_3 above the Hugoniot elastic limit. *Wackerle*'s [1962] data for *z*-cut quartz and those of *Graham and Ingram* [1969] for *x*-cut quartz also indicate a loss of shear strength above the Hugoniot elastic limit.

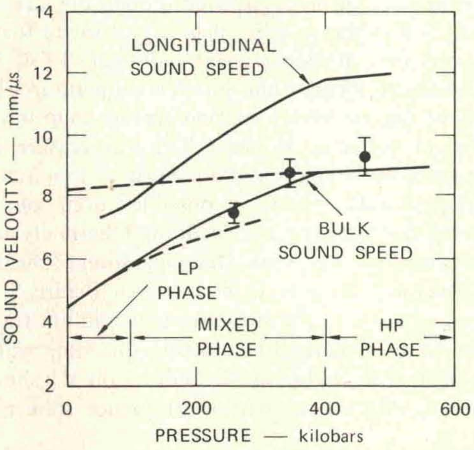
We suggest that the low values of the sound velocity measurements and the apparent loss of strength result from partial melting in the silicate materials behind the shock front. It is also possible that the thermodynamics of the phase change occurring over an extended stress range in the silicates may explain our observed data. However, since several of the data points lie well into the stress region in which a single phase exists, we consider this explanation less likely.

Over the stress range covered in the present experiments the increase in energy produced by shock compression is not sufficient to melt completely the silicate material. Furthermore, observations on samples recovered after shock loading also rule out complete melting in the stress range studied [*De Carli,* 1968; *Chao,* 1968; *Von Engelhardt and Stöffler,* 1968].

We believe that the melting is localized in shear deformation bands that result as the material is shock-loaded above the Hugoniot elastic limit and undergoes heterogeneous yielding. Specimens of silicate recovered after shock loading both in explosive experiments and in the vicinity of meteorite craters exhibit planar features commonly called deformation lamella [*Stöffler,* 1971, 1972]. These planar lamella attest to a nonuniform yield process. Such a heterogeneous yield process where energy transport is not sufficient to disperse the viscous energy generation has been called 'adiabatic' shear [*Zener and Holloman,* 1944]. In these shear bands a large portion of the localized plastic slip energy is converted to heat that causes the local temperature to increase (see also *Gruntfest* [1963] and *Nitsan* [1973]). Such localized melting has been observed in sandstone during frictional sliding in triaxial experiments by *Logan and Rigert* [1973]. *Giardini* [1974] observed rapid shear-strain-induced melting in granodiorite during triaxial compression experiments. Heterogeneous adiabatic shear would provide for a highly nonuniform distribution of thermal energy during yielding within the shock front. Calculations indicate that extreme temperature gradients of hundreds, even thousands, of degrees per micron can persist for several microseconds in the shear bands after shock passage because of the low thermal conductivity of silicate minerals. In these calculations we first estimated the dissipative energy resulting from the shock compression process. At a given Hugoniot stress this



(a) QUARTZ



(b) FELDSPAR

Fig. 4. Hugoniot sound velocities measured in quartz and feldspar. Approximate locations of phase boundaries on the Hugoniot are indicated. Solid lines show the estimated bulk and longitudinal sound velocity in the low-pressure, mixed, and high-pressure phase regions. Dashed lines are metastable extensions of the estimated sound velocity out of the stability field of the low- and high-pressure phases, respectively.

energy is the difference between the Hugoniot energy and the hydrostatic, compressional energy of α quartz, both of which can be determined with reasonable accuracy. The dissipative energy was then partitioned along planar regions in the material, and elementary heat flow solutions were used to estimate thermal evolution after shock-induced yielding. Ambient lattice thermal properties for silicate minerals were used in the analysis. Estimates of the radiative contribution to the heat flow were not significant in the time intervals of interest. The density of planar features can only be estimated roughly from inspection of recovered samples and depends on both shock amplitude and rise time [*Stöffler*, 1972]. This unknown distribution lends a qualitative aspect to the calculations performed; however, the general conclusion of high local temperatures and extreme temperature gradients appears to be correct if the proposed adiabatic shear process occurs during shock compression.

In Figure 5 we indicate the thermal state in the vicinity of a shear plane at some fixed time shortly after passage of the shock front. The ordinate is temperature which can approach several thousands of degrees in the center of the shear zone. The abscissa is distance from the shear zone. The distance between shear zones as suggested from the petrographic details of recovered specimens [*Stöffler*, 1972] is in the neighborhood of 2–10 μm. The extremely low thermal diffusivity for silicate minerals (about 1 $\mu m^2/\mu s$) will allow for little change in the temperature profile during the brief time of a shock wave measurement.

Partial melting is energetically possible and could account for the observed low values of the sound velocities. *Walsh* [1968, 1969] has analyzed the case of random penny-shaped liquid inclusions in a solid matrix. He found that the bulk modulus remains close to the solid value and that the shear modulus is greatly diminished even for small melt concentrations; hence the sound velocity could correspond closely to the bulk value.

The present model could account for the curious phase transition behavior of quartz (and other silicates) in the 'mixed phase' region of the metastable shock wave Hugoniot. Partial transformation, presumably to stishovite, occurs during the rise time of the shock front (less than 10^{-7} s); however, further transformation is not observed even though the stress is sustained well within the stability field of stishovite for several microseconds after shock passage [*Grady et al.*, 1974]. Heterogeneous adiabatic shear would provide temperatures that are thousands of degrees hotter in shear regions than in immediately adjacent material. In these high-temperature regions, transformation to the high-pressure phase or to a liquid form of the high-density phase is possible, even on a submicrosecond time scale, by a conventional thermally activated nucleation and growth process. Our suggestion of the distribution of transformed material is shown in Figure 5. Cooler regions not adjacent to the shear zones would not transform, and owing to slow thermal conduction this state will persist and give the illusion, within the short duration of a shock wave measurement, that an equilibrium Hugoniot state has been attained.

The model outlined above may also account for the proportions of low-density, high-density, and amorphous material identified in recovered specimens subject to shock loading in this pressure range. In Figure 5 we indicate qualitatively the change in material state with increasing distance from the shear zone. Melting will occur in the extreme temperature region of the shear zone. The low-density phase will persist in the region where the temperature is low and the thermal activation barrier prevents transformation within the time scale of the shock wave experiment. Finally, there would exist a small intermediate region where the temperature is sufficient to allow transformation to the high-density solid state within this brief time span. Quenching of the phases during rapid unloading would account for amorphous material and traces of the high-density phases observed [*De Carli and Milton*, 1965].

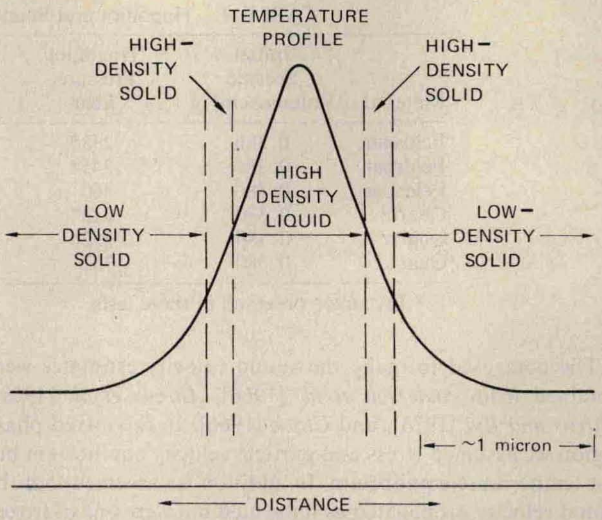


Fig. 5. Schematic temperature-distance profile based on heat flow calculations in the neighborhood of an adiabatic shear zone shortly after passage of the shock front. Indicated are the degree and state of phase transformation determined by the local temperature.

This work suggests that caution should be exercised when shock wave data are used to deduce high-pressure equilibrium thermodynamic properties of rocks and minerals. The apparent problem is thermal nonequilibrium, which is due to low thermal conductivity, and a heterogeneous deposition of thermal energy during the yielding process. A possible solution may be to study samples prepared from a fine powder, which would provide for a more homogeneous generation of thermal energy during the shock process.

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