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PARTICLE VELOCITY EXPERIMENTS IN ANORTHOSITE AND GABBRO

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Shock wave experiments have been conducted in San Gabriel anorthosite and San Marcos gabbro to 11 GPa using a 40 mm-bore propellant gun. Particle velocities were measured directly at several points in each target by means of electromagnetic gauges. Hugoniot states were calculated by determining shock-transit times from the gauge records. Sound speeds indicate a loss of shear strength upon shock compression for both rocks, with the strength loss persisting upon release to zero stress in the anorthosite. Stress-density release paths in the anorthosite indicate possible transformation of albite to jadeite + (quartz or coesite), with the amount of material transformed increasing as a function of shock stress. Electrical interference effects in the gabbro precluded the determination of accurate release paths for that rock.

1. INTRODUCTION

In most shock-wave experimental work, only one state--the Hugoniot state--is determined per experiment. By employing particle-velocity gauges, a complete stress-strain history subsequent to shock compression can be determined, along with sound velocity information. Particle velocity experiments provide more information about rheology, mechanical properties, and polymorphism than is available with Hugoniot experiments alone.

Anorthosite and gabbro are two rocks present in the terrestrial and lunar crusts, and effects of impacts into them are controlled by their behavior under shock and rarefaction. The purpose of the present study is to characterize this behavior.

2. EXPERIMENTAL METHODS

Rock samples were shock-loaded by impact of flat-faced polycarbonate (Lexan) projectiles fired from a 40 mm-bore propellant gun at velocities from 1.4 to 2.4 km/sec. Three U-shaped copper gauges were sandwiched between four 1.5 mm-thick slabs of rock with one gauge on the free surface. A uniform magnetic field of 1.8 kG--at right angles to each 1 cm-long gauge and to its direction of motion--was supplied by Helmholtz coils. The voltage across each gauge element is directly proportional to the velocity of the gauge (the particle velocity of the surrounding medium), and was recorded by an array of oscilloscopes. The experiment is shown schematically in Fig. 1.

The geometry and time history of a typical experiment is illustrated by means of an x-t diagram in Fig. 2. Each gauge is stationary until overtaken by the shock wave, at which time it begins moving at the particle velocity associated with the Hugoniot state. After reflection of the shock wave from the free surface, each gauge again accelerates as the resulting rarefaction wave propagates back through the sample.

3. RESULTS AND CONCLUSIONS

Digitized experimental data for anorthosite shocked to 10 GPa are shown in Fig. 3. Hugoniot states were determined by an impedance-match solution[1], where the shock velocity is determined from the shock-transit times taken from the particle velocity records, and the known polycarbonate Hugoniot[2] and projectile velocity are used. Eulerian sound speeds were determined from the transit time of the free-surface rarefaction front, and the Hugoniot density. Hugoniot states and sound speeds for both rocks are given in Tables 1 and 2.

The observed release waves are nonsteady simple waves, and can be inverted to yield the stress-density release paths by numerically integrating the equations for conservation of mass and linear momentum[3]

$$\left(\frac{\partial\rho}{\partial u_p}\right)_h = \frac{\rho^2}{\rho_0 C(u_p)}$$

$$\left(\frac{\partial\sigma}{\partial u_p}\right)_h = \rho_0 C(u_p)$$

where ρ is the density, ρ_0 is the initial density, σ is the stress, u_p is the particle velocity, and h is the Lagrangian space coordinate. $C(u_p)$ is the Lagrangian sound speed, approximated by

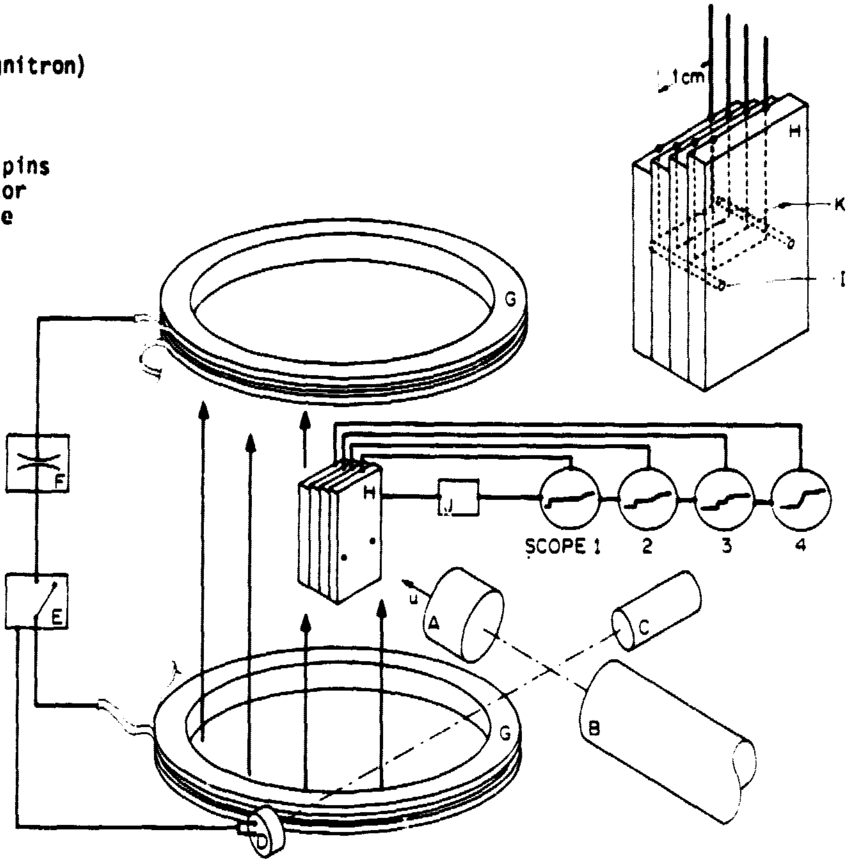

Figure 1:
Particle velocity experiment
A. Polycarbonate projectile
B. 40 mm gun barrel
C. Timing laser
D. Photodetector
E. High-power switch (ignitron)
F. Capacitor bank
G. Helmholtz coils
H. Rock target
I. Self-shorting trigger pins
J. Fiducial pulse generator
K. Particle velocity gauge elements

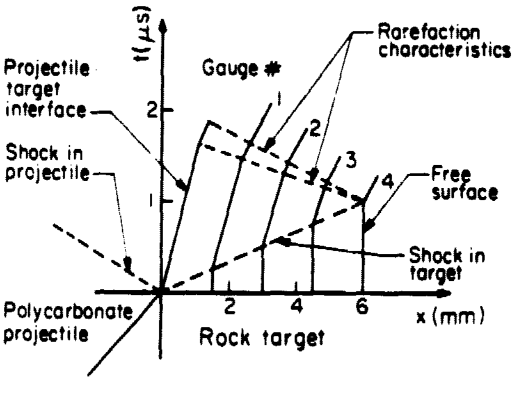

Figure 2: x-t diagram representing experimental event. Projectile approaches stationary target from left and impacts at t=0.

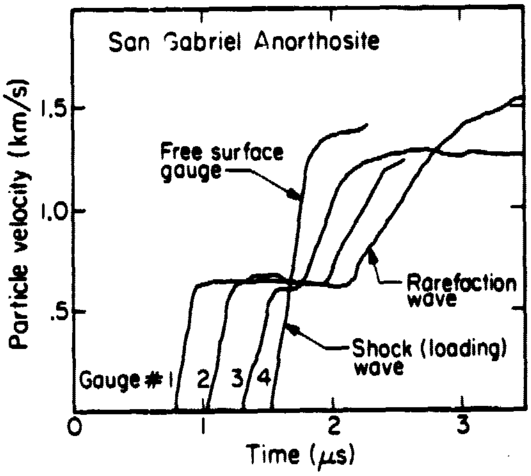

Figure 3: Gauge records for experiment 40-571: anorthosite shocked to 10 GPa.

Table 1
San Gabriel Anorthosite Hugoniot Data

Shot number	Pressure (GPa)	Density (Mg/m^3)	Eulerian Sound speed (km/s)
40-572	5.9	2.86	6.9
40-570	7.5	2.90	7.6
40-571	10.2	2.97	8.4

Table 2
San Marcos Gabbro Hugoniot Data

Shot number	Pressure (GPa)	Density (Mg/m^3)	Eulerian Sound speed (km/s)
40-569	5.4	3.04	6.5
40-573	8.4	3.13	8.5
40-555	9.9	3.14	---
40-556	10.4	3.17	7.0
40-574	11.2	3.18	6.7

$$C(u_p) \approx \frac{\Delta h}{\Delta t}$$

where Δh is the initial distance between gauges, and Δt is the transit time for a disturbance with particle velocity u_p. Eulerian sound speeds, equal to $(\rho_0/\rho)\ C(u_p)$, were calculated for the release paths. Results of these calculations for the two rocks are plotted in Figs. 4-6. The anorthosite data are significantly better than those for gabbro because of the relative noisiness of the gabbro particle velocity records, presumably due to piezoelectric interference from quartz grains in the gabbro. The gabbro contained ~1.4% quartz by volume, whereas only trace quantities were found in the anorthosite.

Measured longitudinal velocities[4,5] in anorthosites of similar composition (An_{40}) are in the range 6.91 to 7.47 km/sec, and shear velocities are 3.87 to 4.09 km/sec. Calculated bulk sound speeds are therefore in the range 5.04 to 5.99 km/sec. All three anorthosite experiments release to zero stress with sound speeds in this range, indicating that shear strength is lost upon shock above 6 GPa and never regained upon release.

Stress-density release paths for shocked anorthosite show a net densification from the mean initial density of 2.654 Mg/m^3. The density change is an increasing function of shock stress. Because strength effects are not important according to sound-speed data, a possible interpretation is polymorphic phase transition of albite to jadeite and quartz or coesite. This is analogous to the behavior of quartz under shock pressure, which loses

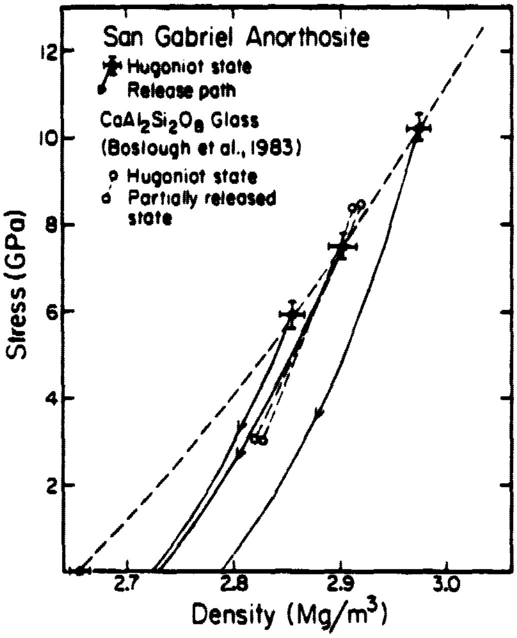

Figure 4: Hugoniot states and release paths of San Gabriel anorthosite. Included are two Hugoniot states of anorthite glass[8], with respective partial release states.

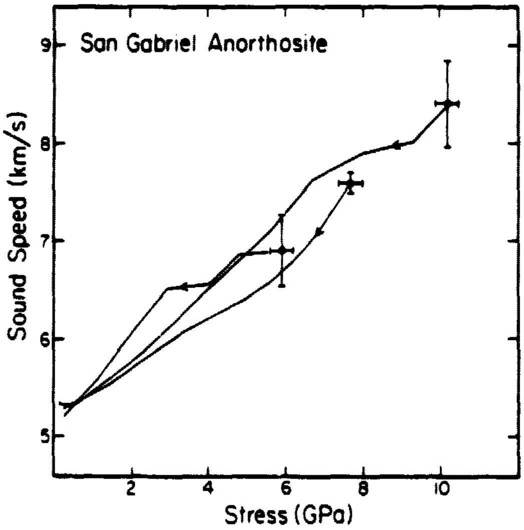

Figure 5: Eulerian sound speeds along release paths of shocked San Gabriel anorthosite.

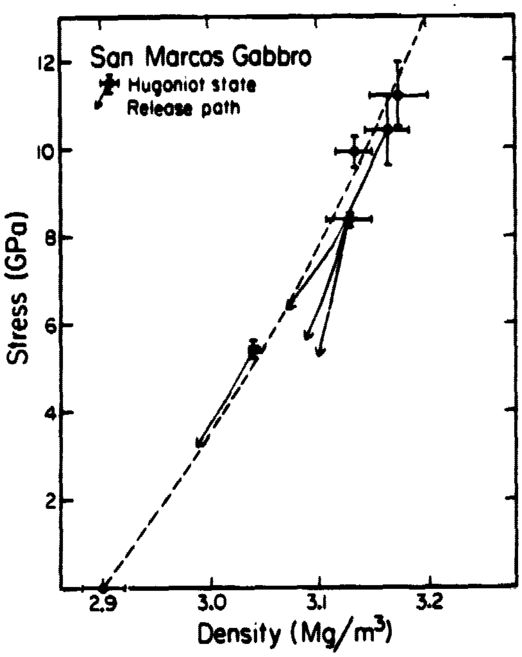

Figure 6: Hugoniot states and release paths of San Marcos gabbro. Noisy particle velocity records precluded determination of release to zero stress.

strength and transforms to stishovite[6,7]. Similar densification upon release has been observed in shocked anorthite glass[8] (Fig. 4), for which the composition is An_{100}, and the density increase must be attributed to strength effects, annealing, or irreversible compaction of the amorphous material.

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