PARTICLE VELOCITY EXPERIMENTS IN ANORTHOSITE AND GABRO

Mark B. Binslough and Thomas J. Ahrens

Seismological Laboratory
California Institute of Technology
Pasadena, California 91125

Shock wave experiments have been conducted in San Gabriel anorthosite and San Marcos gabro to 15 GPa using a 40 mm-bore propellant gun. Particle velocities were measured directly at several points in each target by means of electromagnetic gauges. Anorthosite 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 celsite, with the amount of material transformed increasing as a function of shock stress. Electrical interference effects in the gabro precluded the determination of accurate release paths for that rock.

1. INTRODUCTION

In most shock-wave experimental work, only one sample—the Hugoniot state—is demanded 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 gabro are two rocks present in the terrestrial and lunar crusts, and effects of impacts into these 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 above 1,500 m/sec. Three U-shaped copper gauges were sandwiched between four 1/4-in-thick slices of rock with one gauge on the free surface. A uniform magnetic field of 1.8 kOe was applied tangentially 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-y 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, where the shock velocity is determined from the shock-transit times taken from the particle-velocity records, and the known polycarbonate Hugoniot2 and projectile-velocity characteristics. Elastic 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-strain-release paths by numerically integrating the equations for conservation of mass and linear momentum

\[
\frac{\rho}{\rho h} = \frac{a_0}{a_0^2(a_0)}
\]

where \(\rho\) is the density, \(\rho h\) is the initial density, \(\rho_0\) is the stress, \(a_0\) is the particle velocity, and \(h\) is the Lagrangian space coordinate. \(a_0^2(\rho_0)\) 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 pin
J. Pneumatic pulse generator
K. Particle velocity gauge

Figure 2: x-t diagram representing experimental event. Projectile approaches stationary target from left and impacts at ‘B’.

Figure 3: Gauge records for experiment 40-571: anorthosite shocked to 10 GPa.
Table 1
San Gabriel Anorthosite Hypopion Data

<table>
<thead>
<tr>
<th>Shot number</th>
<th>Pressure (GPa)</th>
<th>Density (Mg/m³)</th>
<th>Sound speed (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40-372</td>
<td>5.9</td>
<td>2.66</td>
<td>8.9</td>
</tr>
<tr>
<td>40-310</td>
<td>7.5</td>
<td>2.80</td>
<td>7.6</td>
</tr>
<tr>
<td>40-371</td>
<td>16.2</td>
<td>3.97</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Table 2
San Marcos Gabbro Hypopion Data

<table>
<thead>
<tr>
<th>Shot number</th>
<th>Pressure (GPa)</th>
<th>Density (Mg/m³)</th>
<th>Sound speed (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40-169</td>
<td>5.4</td>
<td>3.04</td>
<td>8.5</td>
</tr>
<tr>
<td>40-573</td>
<td>0.4</td>
<td>3.13</td>
<td>8.5</td>
</tr>
<tr>
<td>40-585</td>
<td>2.9</td>
<td>3.14</td>
<td>7.0</td>
</tr>
<tr>
<td>40-536</td>
<td>10.4</td>
<td>3.17</td>
<td>7.0</td>
</tr>
<tr>
<td>40-574</td>
<td>15.2</td>
<td>3.18</td>
<td>6.7</td>
</tr>
</tbody>
</table>

\[
\frac{\Delta h}{\Delta t} = \frac{1}{\rho V} \frac{dV}{dt}
\]

where \(\Delta h\) is the initial distance between gauge, and \(\Delta t\) is the transit time for a disturbance with particle velocity \(V\). Eulerian sound speeds, equal to \(\frac{\rho V}{\rho g}\), were calculated for the release paths. Results of these calculations for the two rocks are plotted in Figs. 4-5. The anorthosite data are significantly better than those for gabbro because of the relative weakness 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 in anorthosites of similar composition 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 2.65 GPa/m³. 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 cordierite. This is analogous to the behavior of quartz under shock pressure, which loses

Figure 4: Hypopion states and release paths of San Gabriel anorthosite. Included are two Hypopion states or anorthosite glass, with respective partial release states.

Figure 5: Eulerian sound speeds along release path of shocked San Gabriel anorthosite.
strength and transforms to stishovite\cite{2,3}. Similar densification upon release has been observed in unsealed amorphous glass\cite{2,3} (Fig. 4), for which the composition is Al2O3, and the density increase must be attributed to strength effects, annealing, or irreversible compaction of the amorphous material.


4. REFERENCES

