COMPACTION BY IMPACT OF UNCONSOLIDATED LUNAR FINES*

by

Thomas J. Ahrens

Seismological Laboratory, California Institute of Technology

Pasadena, California 91109

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*Contribution No. 2626, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91109.

ABSTRACT

New Hugoniot and release adiabat data for 1.8 g/cm^3 lunar fines (sample, 70051) in the ~2 to ~70 kbar range demonstrate that upon shock compression intrinsic crystal density (~3.1 g/cm^3) is achieved under shock stress of 15 to 20 kbar. Release adiabat determinations indicate that measurable irreversible compaction occurs upon achieving shock pressures above ~4 kbar. For shocks in the ~7 to 15 kbar range, the inferred post-shock specific volumes observed decrease nearly linearly with increasing peak shock pressures. Upon shocking to ~15 kbar the post-shock density is approximately that of the intrinsic minerals. If the present data for 70051 are taken to be representative of the response to impact of unconsolidated regolith material on the moon, it is inferred that the formation of appreciable quantities of soil breccia can be associated with the impact of meteoroids or ejecta at speeds as low as ~1 km/sec.

INTRODUCTION

This is a first report on the effect of shock on the irreversible partial compaction of lunar regolith into soil breccia.

As the moon underwent the final stages of accretion the large impacts which excavated the major, now recognizable, crater basins out of the early solid crust undoubtedly produced enormous quantities of unconsolidated ejecta, most of which remained on the moon. Both visual studies of the moon, e.g. Hartmann and Wood (1971 , Baldwin (1963), McGetchen *et al*. (1972), Pike (1973), laboratory studies, e.g. Moore et al. (1963), Horz (1969) and numerical calculations, e.g. O'Keefe and Ahrens (1975), Gault and Heitowit (1963) have demonstrated that the mass of ejecta produced during a hypervelocity impact on rock ranges from as low as 15 to 10^3 times the projectile mass, depending on the detailed impact parameters and target strength. Moreover, all but a few percent of the ejecta has experienced shock stress of a few kilobars or less. Thus since the time, possibly, 3.9 AE (Tera et al., 1974), when protoregolith formed on the moon at the termination of the accretion process, the continual rain of smaller objects has on the average continually reworked the major early ejecta blankets.

For a given impact into unconsolidated regolith material, a mass of target material, comparable in mass to the meteoroid, is completely or partially vaporized. Estimates of the total amount of material which has been vaporized and melted on the surface of the moon is given by Gault et al. (1974). For all impacts of greater than several kilometers per second, considerably more regolith material is subjected to stress levels such that partial melting and irreversible compaction takes place. Field evidence both on the moon (Schmitt and Cernan, 1973) LSPET (1972, 1973) and on the earth (Moore, 1965 and 1975) as well as shock recovery experiments (Christie et al., 1973) demonstrate that the so-called soil-breccias form as a result of impact of meteoroids into the lunar regolith. Schmitt and Cernan (1973) specifically reported and photographically documented the prolific occurrence of $\sim$ 10 to 15 cm soil breccia fragments which littered the vicinity of small craters ($\lesssim$ 5 m diameter) at the Apollo 17 site. Rocks similar to the Apollo 17 soil breccias were collected at the other landing sites and were particularly noted in the Apollo 15 collection (e.g. 15145-15148, 15315-15320, 15306, 15321-15555).

Motivated by the need for both understanding the processes required to partially melt and indurate breccias into the partially recrystallized rock so prevalent on the moon (the "normal" breccias) as well as form the more friable "soil breccias" previous experiments were conducted in 20 to 120 kbar range on sample 70051 (Ahrens and Cole, 1974). It was discovered that for the loose aggregate of material represented by sample 70051, an assemblage of lithic and mineral fragments, agglutinates and glassy spherules, they were irreversibly compacted to their crystal density. Minor decreases in post-shock density between 20 and 120 kbars were attributed to increased solid-state and thermally-induced glass formation in the fines with increasing pressure. Kieffer (1975) has attributed this latter effect to the result of residual gas.

The previous experiments demonstrated that virtually complete irreversible compaction possibly corresponding to nearly complete induration into rock, resulted from shock compression to all stress levels above $\sim$20 kbar. Since by definition the soil breccia material on the moon is poorly lithified, it is of interest to place some bounds on the shock stresses required to partially irreversibly compact regolith material.

No Hugoniot and release adiabat data are previously reported relevant to the macroscopic irreversible partial compaction of terrestiral or lunar mafic fines. This report gives the results of an initial study of this phenomenon which appears to me to control the formation of soil breccias on the lunar regolith.

EXPERIMENTS

In order to measure Hugoniot and release adiabat states for a 1.8 g/cm^3 sample material (70051), assumed to be typical of the fines in the unconsolidated material of the lunar regolith (Ahrens and Cole, 1974), it is necessary to encapsulate a predetermined mass within a volume of controlled dimensions. Samples were prepared by hand pressing $\sim$ 620 mg aliquots into cylindrical containers (14 mm diameter and 2.3 mm thick) so as to achieve an initial density of $\sim$ 1.8 g/cm^3. Some irreversible damage certainly occurred to the individual grains during this procedure. The "packing pressure" is on the order of only 10^{-3}, the later applied shock stress. Thus the effect of grains interpenetrating rather than rotating so as to achieve an increased intergrain surface contact area, is believed to be insignificant.

Compacted samples, contained laterally within a carefully machined metal ring, and above and below, by 0.01 mm thick mylar foils were mounted on 1.5 mm thick 2024 Al and polycrystalline tantalum driver plates in the geometry previously described by Ahrens and Cole (1974). In addition to measurements on sample (70051) several experiments were also carried out on powdered Vacaville basalt (Ahrens and Gregson, 1964).

To achieve the very low shock stresses of the present study, solid lexan (a polycarbonate plastic) projectiles were used to impact sample assemblies in most of the experiments. Despite the wide use of this material, the low pressure Hugoniot data for lexan (measured by the Los Alamos group) has not been previously reported (Table 1).

Hugoniot states were obtained by measuring projectile velocities with the laser obscuration technique and shock velocities are measured with an electronically triggered image-converter streaking camera, a detailed description of the technique is given in Ahrens et al. (1972).

Release adiabat measurements were carried out on the same shots as the Hugoniot measurements. The technique employed was to place a series of buffer material (plastic foam) blocks on the upper (free) specimen surfaces. Upon propagating a shock into the lower impedance buffer from the samples an adiabatic rarefaction wave propagates back into the sample as a shock propagates forward in the buffer material. Upon interaction of the shock at the buffer-sample interface, the shock pressure and particle velocity in the buffer is equal to that achieved upon adiabatic release in the sample. Hence by measuring the shock state in the buffer by means of a shock velocity measurement, a release state is determined in the sample (Ahrens et al., 1969). Although in principle one can trace out a release adiabat in the pressure-particle velocity plane by this technique, the inherent scatter of data obtained from porous samples and buffers precludes obtaining the fine structure of the release adiabat. Thus although we had managed to use buffers of different shock impedance in the present experiments, the inherently large data scatter provides little opportunity but to assume a straight-line release adiabat either in the pressure particle velocity or pressure-volume planes.

Three buffer materials, plastic foams, were used in the present experiments. As previously, a 0.038 g/cm^3 polystyrene foam was utilized for most of the shots (Ahrens and Cole, 1974). Because this foam has such a low shock impedance, it provides data at nearly zero-pressure and to a good approximation provides by means of shock velocity measurement in the foam, a fairly good approximation to the sample free-surface velocity. In order to demonstrate the dependence of the present and previous results on the less well determined polystyrene foam Hugoniot, several experiments were fired using somewhat higher shock impedance polyurethane foams. Considerable Hugoniot data are reported by McQueen et al. (1970) for the foams. Blocks of polyurethane foam (30 x 15 x 5 cm) were cast (Foam Molders and Specialties, Cerritos, CA) to bulk density of 0.568 and 0.286 g/cm^3. Voids were uniformly 0.2 to 0.4 mm diameter, bubbles. The following parameterization of the fairly abundant, but also scattered, polyurethane foam, Hugoniot data was assumed in order to obtain the release adiabat states particle velocity, u_p, from the measured foam shock velocity, U_s. For foams of initial density, ρ_f, $\sim$0.5 g/cm^3

$$U_s = -1.67 + 5.27\ \rho_f + u_p\ (2.03 - 1.85\ \rho_f) \qquad (1)$$

and for foams, $\sim$0.3 g/cm^3,

$$U_s = 0.451 + 1.25\ u_p \qquad (2)$$

The density of individual carefully machined aliquots of foam employed in each experiment were determined from their mass and external dimensions and are probably accurately known to within $\sim$ 3%.

RESULTS AND CONCLUSIONS

The new low-pressure Hugoniot data for powdered Vacaville basalt and for sample 70051 (Table 2) is plotted in Figure 1. Also plotted are the results of the earlier experiments (Ahrens and Cole, 1974). Virtually all the uncertainty in the data is attributed to the observed non-uniformity of shock propagation through the granular materials (both the samples and foams).

The data for 70051 clearly demonstrate that compaction to essentially crystal density occurs for 1.8 g/cm^3 initial density material between 15 and 20 kbar and is nearly linear with shock stress. Moreover, the present results for powdered Vacaville basalt demonstrates that the effect of lower compressions (than 70051) observed in one previous experiment (at $\sim$ 54 kbar) is reproducible and was readily observed for 3 shots at pressures below 10 kbar. We attributed the earlier discrepant Vacaville point to differences in chemistry and possibly water content, with respect to 70051. On the other hand, that differences in the low pressure data set exist suggests that the difference in the Hugoniots arises from differences in mechanical interlocking of grains and possibly differences in grain size distribution and/or shapes.

The measured release adiabat data, shown in the pressure-particle velocity plane in Figures 2 and 3 demonsrate that the zero-pressure unloading particle velocity is always substantially less than twice the Hugoniot particle velocity. Thus, even though in many cases the experimental uncertainties are large, irreversible compaction is clearly indicated in all experiments except for shot 368.

Moreover, although the release adiabat data (except for shot 374) is considerably more uncertain in the case of polyurethane foams than for polystyrene foam, the results are consistent. As before the quality of the release data is such that the assumption of a straight line unloading path in the pressure-particle velocity plane, which maps into a straight line in the pressure-volume plane, appears to be appropriate. Using the linear slope of the release adiabat and the Reimann integral formula the post-shock (unloaded) zero-pressure densities, given in Table 3 are obtained. The resulting post-shock volumes for the present and previous data are plotted in Figure 4. The uncertainty in post shock specific volume both calculated and plotted represents that arising generally from the larger uncertainties in the release adiabat data and not the Hugoniot data. The present results imply that if the response of 70051 to shock is representative of the unconsolidated regolith, very low shock pressures ($\sim$ 20 kbar), achievable with meteroid projectiles having speeds as low as 1 km/sec, will induce significant irreversible compaction. Hence the soil breccias observed in the regolith could have resulted from impact of secondary objects (ejecta from larger impacts). Moreover, the present results demonstrate that dynamic stresses required for irreversible compaction of lunar fines on the moon are considerably below the ~40 kbar or ~ 50 kbar values inferred from either the limited quasistatic (Stevens and Lilley, 1969) or shock recovery experiments (Christie et al., 1973) which has been previously performed.

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Table 1. Hugoniot data for polycarbonate (lexan) - G. E. resin [a].

Initial density g/cm^3	Shock Velocity (km/sec)	Particle Veolcity (km/sec)
1.194	1.928	0
1.200	1.960	0
1.196	3.566	0.724
1.196	3.891	0.938
1.196	4.517	1.357
1.196	5.117	1.750
1.196	6.069	2.379

a) Private communication, R. G. McQueen (5/74).

Table 2. Hugoniot Data, lunar sample 70051.

Shot No.	Initial Density (g/cm3)	Flyer Plate Velocity (km/sec)	Flyer/Driver Material	Hugoniot Pressure (kbar)	Hugoniot Density (g/cm3)
367	1.863	0.505	Lexan/2024 Al	2.55 $\pm$0.04	2.268 $\pm$0.002
368[a]	1.810	0.643	Lexan/2024 Al	4.45 $\pm$0.05	2.249 $\pm$0.009
365[a]	1.800	0.918	Lexan/2024 Al	7.74 $\pm$0.08	2.434 $\pm$0.012
370	1.800	1.048	Lexan/2024 Al	8.54 $\pm$0.12	2.723 $\pm$0.029
371	1.801	1.057	Lexan/2024 Al	9.70 $\pm$0.10	2.546 $\pm$0.015
369[a]	1.813	1.07	Lexan/2024 Al	10.3 $\pm$0.2	2.512 $\pm$0.027
372	1.805	1.307	Lexan/2024 Al	13.4 $\pm$0.4	2.765 $\pm$0.061
373	1.800	1.426	Tant./Tant.	68.9[b]	3.295[b]
374	1.798	1.469	Tant./Tant.	71.8[b]	3.310[b]

a) Vacaville basalt powder, 1.8 g/cm^3.
b) Inferred values.

Table 3. Release Adiabat Data, lunar sample 70051

Shot No.	Foam Density (g/cm^3)	Foam Shock Velocity (km/sec)	Release Adiabat Pressure (kbar)	Release Adiabat Particle Velocity (km/sec)	Inferred Post Shock Density (g/cm^3)
367	0.038 PS[a]	0.429 ±0.044	0.055 ±.011	0.339 ±.041	1.97 ±0.17
368[b]	0.038 PS	0.572 ±0.044	0.102 ±.016	0.468 ±0.040	1.703 ±0.136
365[b]	0.038 PS	0.669 ± .024	0.14 ±0.01	0.556 ±0.022	2.10 ±0.05
370	0.038 PS	0.680 ±0.011	0.15 ±0.01	0.567 ±0.011	2.498 ±0.025
371	0.478 PU	1.355 ±0.023	3.02 ±0.84	0.458 ±0.097	2.445 ±0.136
369[b]	0.038 PS	0.586 ±0.042	0.11 ±0.02	0.481 ±0.038	2.473 ±0.029
372	0.286 PU	1.167 ±0.039	1.92 ±0.17	0.575 ±0.031	2.732 ±0.024
373	0.467 PU	2.69 ±0.12	20.4 ±2.2	1.62 ±0.11	3.025 ±0.160
374	0.501 PU	2.60 ±0.04	19.0 ±0.7	1.46 ±0.03	3.273 ±0.020

a) polystyrene foam
b) Vacaville basalt powder 1.8 g/cm^3.
c) polyurethane foam

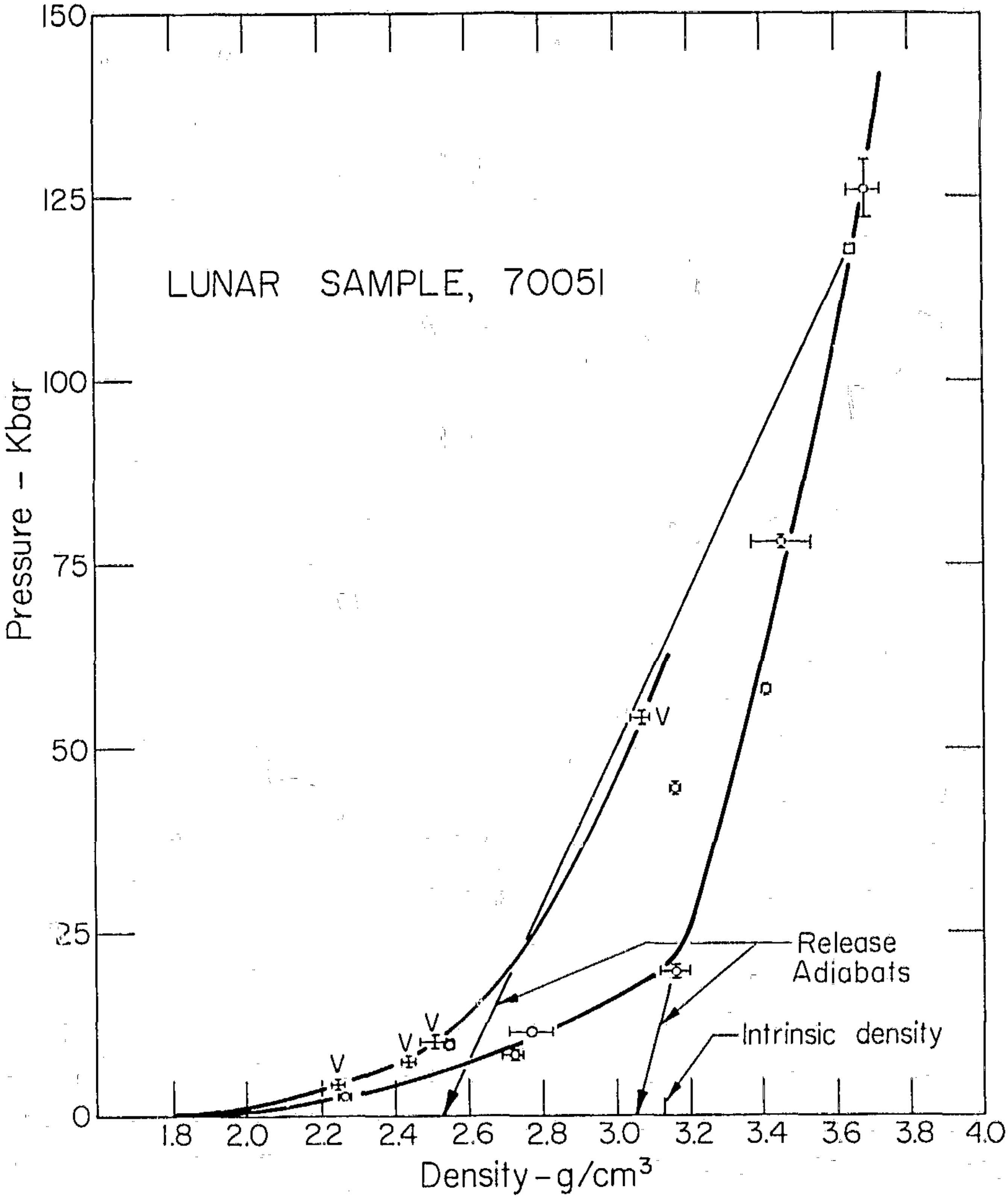
FIGURE CAPTIONS

Figure 1. Pressure-density Hugoniot data for lunar sample 70051 and powdered Vacaville basalt (indicated by V).

Figure 2. Pressure-particle velocity data for Hugoniot and release adiabat experiments for lunar sample 70051 and powdered Vacaville basalt (V).

Figure 3. Pressure-particle velocity data for Hugoniot and release adiabats in the irreversible compaction region for lunar sample 70051 and Vacaville basalt (V).

Figure 4. Post shock volume versus peak shock-pressure for lunar sample 70051 and powdered Vacaville basalt (V).



LUNAR SAMPLE, 70051
Pressure - Kbar
Density - g/cm3
150
125
100
75
50
25
0
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
4.0
V
V
V
V
V
Release Adiabats
Intrinsic density

Fig. 1

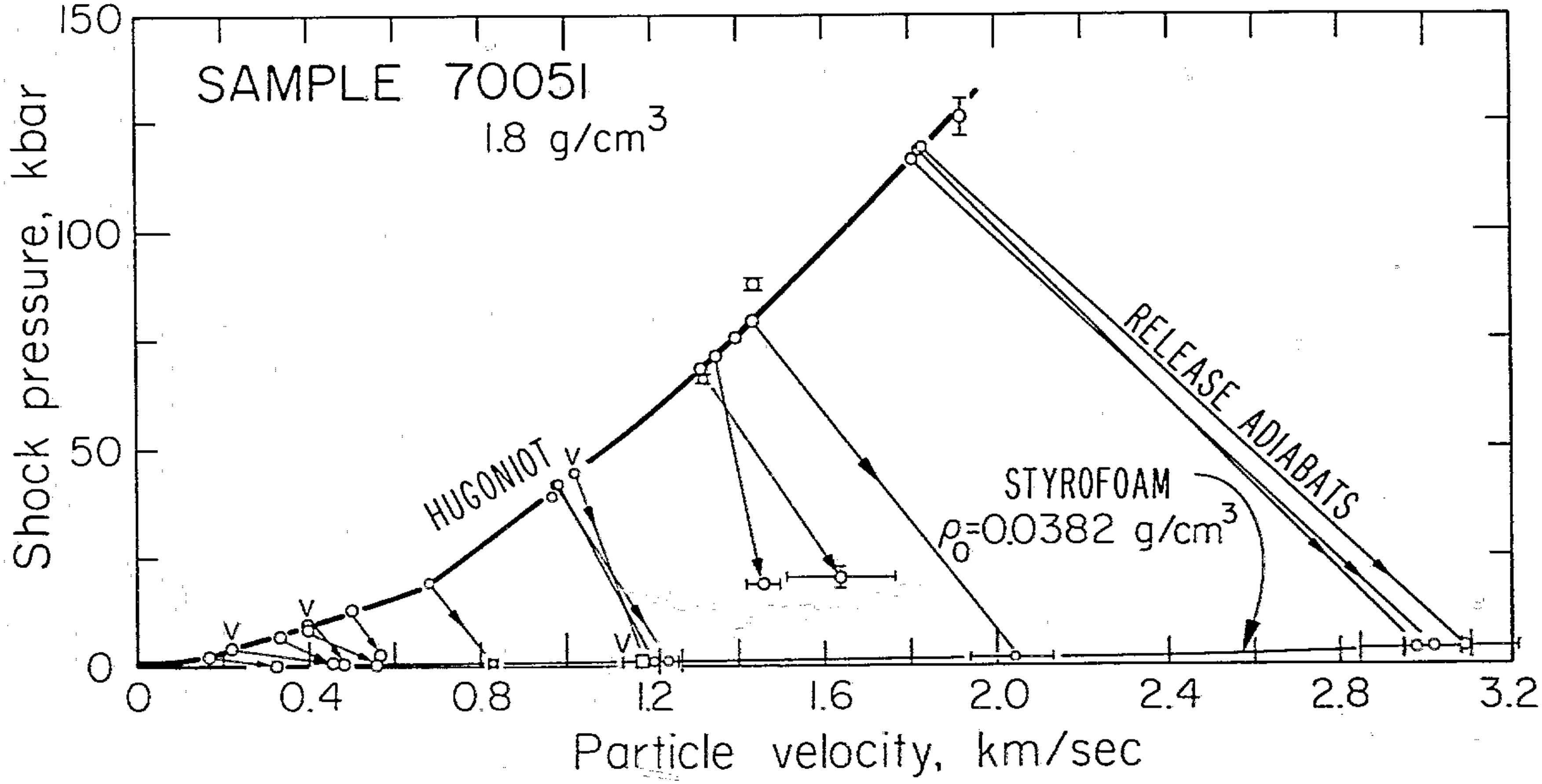
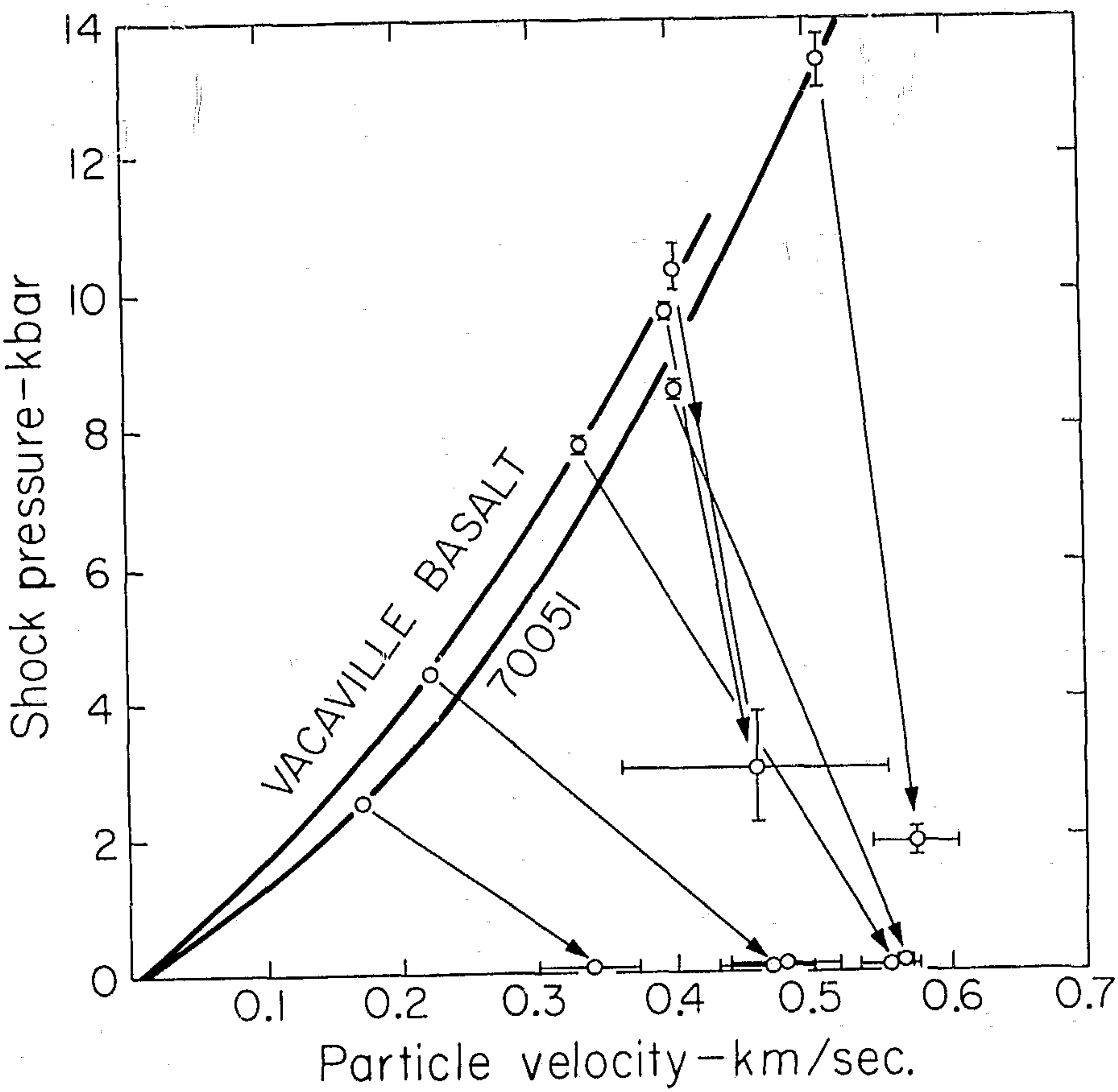

SAMPLE 70051
1.8 g/cm3
HUGONIOT
RELEASE ADIABATS
STYROFOAM
ρ0=0.0382 g/cm3
Shock pressure, kbar
Particle velocity, km/sec
0
50
100
150
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2

Fig. 2



14
12
10
8
6
4
2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Shock pressure-kbar
Particle velocity-km/sec.
VACAVILLE BASALT
70051

Fig. 3

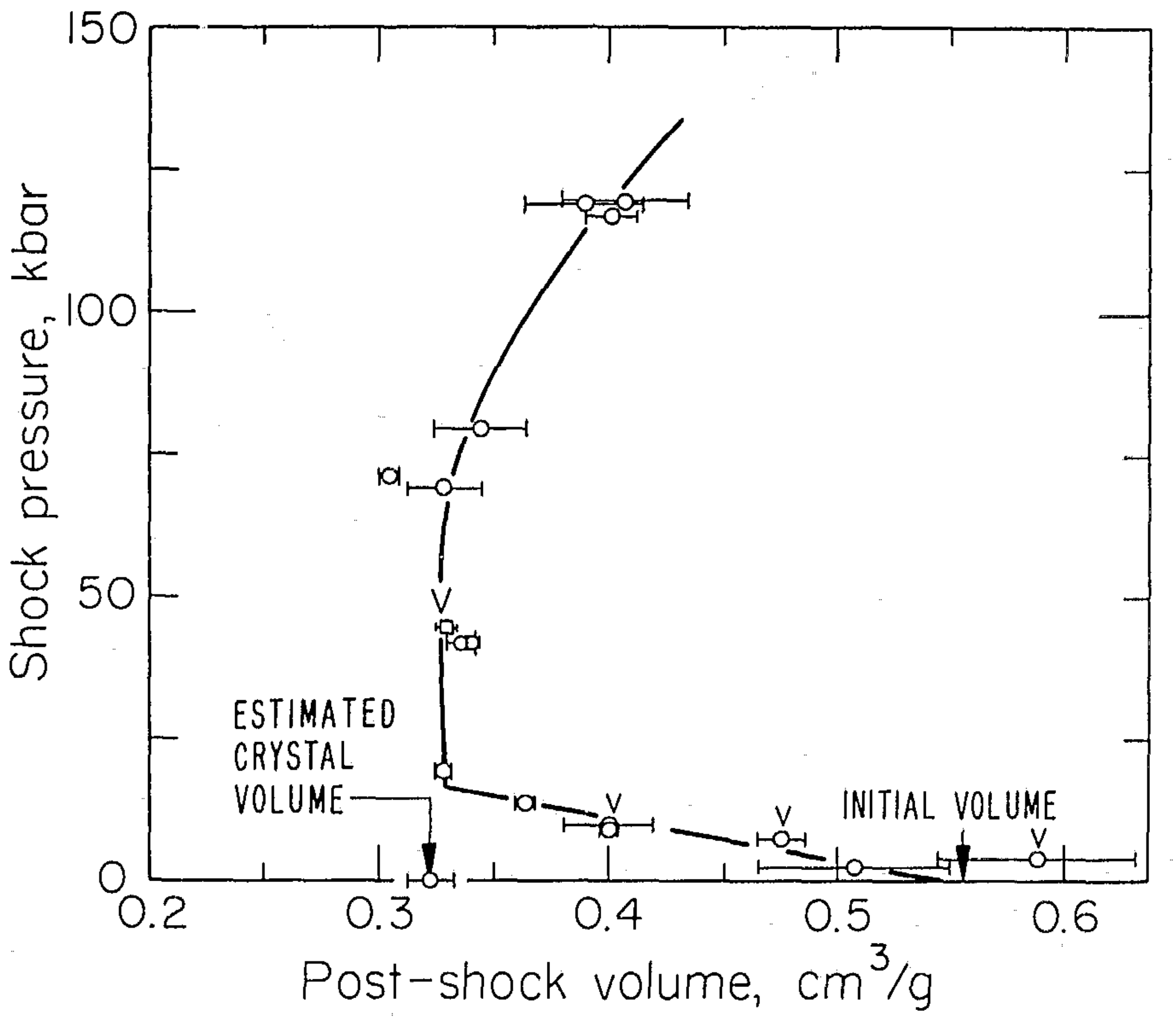

150
100
50
0
Shock pressure, kbar
ESTIMATED
CRYSTAL
VOLUME
INITIAL VOLUME
0.2
0.3
0.4
0.5
0.6
Post-shock volume, cm³/g

Fig. 4