

SHOCK-MELTING AND VAPORIZATION OF ANORTHOSSITE AND IMPLICATIONS FOR AN IMPACT-ORIGIN OF THE MOON, Mark B. Boslough and Thomas J. Ahrens, Seismological Laboratory, California Institute of Technology, Pasadena, California 91125.

New shock wave data for lunar gabbroic anorthosite (15418) and a synthetic glass of anorthite composition ($\text{CaAl}_2\text{Si}_2\text{O}_8$) allow calculation of the critical shock-pressures required for incipient melting (IM), complete melting (CM), and incipient vaporization (IV), as well as the amount of impact-induced vaporization as a function of shock pressure. The pressures required for IM, CM, and IV can be used with models of the spatial attenuation of peak shock-pressures in a planetary surface due to hypervelocity impact, such as given by Ahrens and O'Keefe (1), in order to calculate the quantities of shock-melted and shock-vaporized material.

Shock-temperature experiments were conducted with optical pyrometers at Livermore (2) and Caltech (Table 1). The two lowest pressure points agree well with the calculated temperature-pressure Hugoniot of the high-pressure phase of anorthite based on the thermal equation of state of Jeanloz and Ahrens (3) (Figure 1). The two highest pressure points agree well with the curve calculated for an inferred high pressure $\text{CaAl}_2\text{Si}_2\text{O}_8$ liquid using a melting energy of the high-pressure phase of about 500 KJ/mol. The intermediate point lies between the curves, and is interpreted to be on the melting curve in the mixed-phase region. Pressures were determined by an impedance-match solution using a fit to single-crystal anorthite data (3, 4) with a thermal correction.

Entropy-gain calculations, as described by Ahrens and O'Keefe (5), were used to determine Hugoniot pressures required to melt and vaporize shocked anorthite upon release. We used melting entropies from Robie et al. (6) and inferred vaporization entropies (5). The Hugoniot pressure required for IM is 46.2 GPa, 52.4 GPa for CM, and 92.4 GPa for IV. The mass fraction of vaporized material as a function of shock pressure was calculated similarly, and is shown in Figure 2.

Hugoniot experiments on anorthite glass (Table 2) were carried out to insure that the thermal equation used in reducing the temperature experiments was appropriate. These points, along with the calculated Hugoniot, are shown in Figure 3. Two release states are also shown. Because these points are in the liquid/vapor regime one would expect them to release shallower than the Hugoniot, as does the lower-pressure point. The dense state to which the higher pressure point releases is not explained, but similar behavior has been observed in porous anorthosite (3). The release data for gabbroic anorthosite (Figure 4), however, indicate that vaporization occurs above 120 GPa, in agreement with the entropy-gain calculations.

Finite-difference calculations (1) show that for a gabbroic anorthosite object impacting a gabbroic anorthosite surface at 15 km/s, about 50 times the mass of the impacting object will reach a pressure above 125 GPa, where 10% of the mass of the material is vaporized. This gives a simply obtained lower bound of 5 meteoroid masses for the quantity of material vaporized in such a collision. Similarly, 100 times the mass of the impacting object will reach a peak pressure above 52 GPa, and will be completely melted upon release. These estimates are over an order of magnitude greater than previous calculations (7, 8), apparently due to the inadequacy of equation of state models used by these workers.

As a result, impact models of lunar origin (9, 10) become much more plausible. Because a planetesimal smaller than 0.2 lunar masses impacting at 15 km/s can vaporize 1.0 lunar mass, constraints on the planetesimal composition (9) can be relaxed. The necessity to invoke an impact into a magma ocean (10) in order to minimize the contribution of undifferentiated planetesimal material also becomes less important. Because the shocked anorthite is incongruently vaporized, the molten material left behind is devolatilized. It is this material which, if carried into earth-orbit, will determine the bulk composition of the moon.

Table 1

CaAl₂Si₂O₈ Shock-Temperatures

SHOT	T _H (°K)	P _H (GPa)
*	4930	110.3
*	3800	90.4
*	2890	68.2
LGG 131	2715	57.0
LGG 132	2455	50.3

*Experiments carried out at
Lawrence Livermore Laboratory

Table 2

CaAl₂Si₂O₈ Glass Hugoniot and Release States

SHOT	P _H (GPa)	ρ _H (g/cm ³)	P _R (GPa)	ρ _R (g/cm ³)
LGG 124	97.0	4.883	82.1	4.651
LGG 129	123.5	5.154	101.0	5.095
LGG 133	111.3	4.936	-	-

Table 3

Lunar Gabbroic Anorthosite Hugoniot and Release States

SHOT	P _H (GPa)	ρ _H (g/cm ³)	P _R (GPa)	ρ _R (g/cm ³)
LGG 118	125.5	5.183	63.9	3.813
LGG 119	122.6	5.149	101.2	4.998

Boslough, M.B. and Ahrens, T.J.

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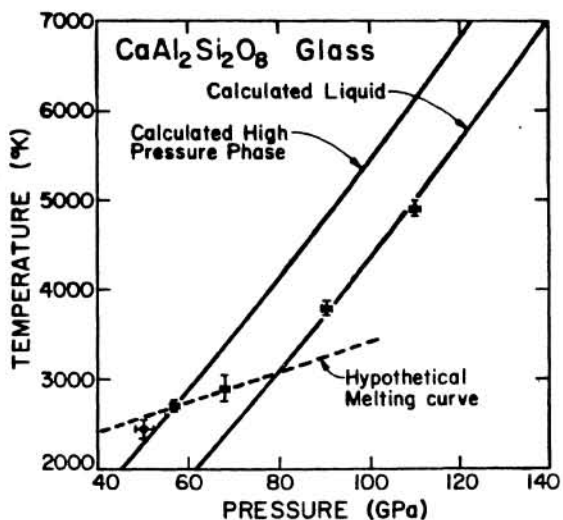


Fig. 1 Calculated and experimental shock temperatures showing evidence for melting of the high pressure phase of CaAl₂Si₂O₈, and supporting the thermal equation used for the high pressure phase.

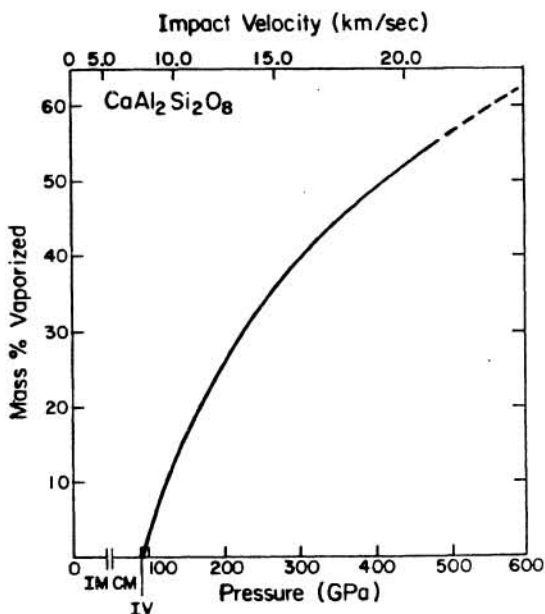


Fig. 2 Curve showing the mass % of CaAl₂Si₂O₈ vaporized as a function of shock pressure (and impact velocity for a one-dimensional collision). Also shown are pressures required for incipient melting (IM), complete melting (CH) and incipient vaporization (IV).

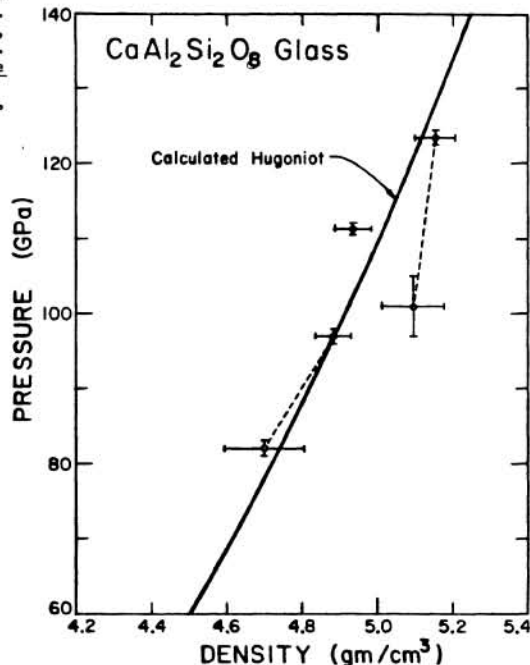


Fig. 3 Experimental Hugoniot and release states and Hugoniot calculated using same equation of state used to determine melting and vaporization levels.

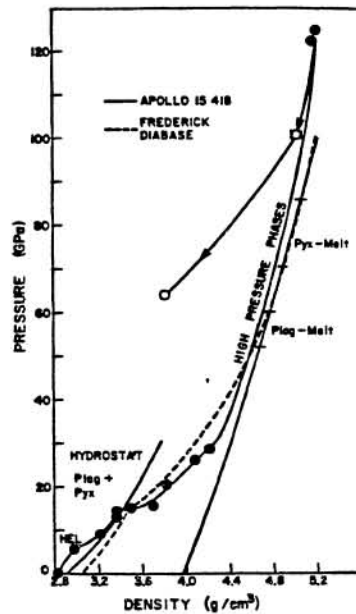


Fig. 4 Experimental and theoretical Hugoniot for 15,418, gabbroic anorthosite (solid), and Frederick diabase (dashed). Both are pyroxene- and plagioclase-bearing rocks. New release adiabat data for gabbroic anorthosite demonstrates incongruent vaporization upon shocking to 125 GPa, 1.25 Mbar (Ahrens, 1982, unpublished).