

# **HIGH-PRESSURE QUENCH OF SHOCK MELT IN METEORITES: IMPLICATOINS FOR THE S6 SHOCK CLASSIFICATION** T. G. Sharp<sup>1</sup>, and J. Hu<sup>2</sup>, <sup>1</sup>School of Earth and Space Exploration, Arizona State University, Tempe AZ, 85287-1404 (tom.sharp@asu.edu), <sup>2</sup>Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, USA (jinping@caltech.edu).

**Introduction:** Many meteorites considered highly shocked have shock melt veins and pockets that contain high-pressure (HP) minerals such as ringwoodite and majorite [1]. These HP minerals are in exclusive association with shock melt veins and pockets and form by either transformation of entrained fragments or by direct crystallization of shock melt at high pressure, which defines the regions classified as shock-stage S6 [2]. However, the 15 to 25 GPa pressures inferred from HP mineral crystallization are far lower than the 75-90 GPa estimates for shock stage S6, with the later pressure being solely based on deformation and corresponding shock recovery experiments [2]. As a result, there is confusion about the shock conditions needed to form “S6” shock veins and HP minerals in meteorites. Formation and preservation of HP minerals requires localized shock melting followed by rapid quench. Here we review new calculations of shock temperatures and adiabatic cooling paths [3] that provide constraints on the P-T-t paths experienced by HP minerals and their usefulness of shock classification in shocked meteorites.

## **Results:**

**Shock Temperature Calculations.** In order to quantitatively constrain the P-T histories and quench of “S6” HP mineral assemblages in meteorites, one must estimate the bulk shock temperatures and P-T release paths for appropriate sample compositions. Shock temperatures were calculated using two methods: a Birch-Murnaghan and Mie-Grüneisen equation of state (EOS) method and an integral approximation along the Hugoniot. The details of these calculations are presented in [3]. The results of the integral method for the Bruderheim L chondrite (Fig. 1) along with melting curves for Allende show that the shock temperatures remain about 1500 K below the melting curve to pressures up to 50 GPa.

**Release Path Calculations.** Post-shock temperature has a significant effect on annealing high-pressure signatures in shocked meteorites. Although the bulk post-shock temperature for a given shock pressure can be calculated from the amount of waste heat added to the system, the final post-shock temperature is not sufficient to interpret P-T release paths of continuous decompression. We calculated release paths as isentropes from points on the Hugoniot using the Riemann equation of release and Mie-Grüneisen EOS. Release paths from the chondrite P-T Hugoniot are shown for 25, 40 and 50 GPa (Fig.

1). These concave-downward release paths define the minimum bulk shock temperatures in a shocked chondrite sample during pressure release. P-T release paths for shock melt were calculated assuming it is isentropic along the density-volume path of shock melt [4]. The shock-melt release paths from 25, 40 and 50 GPa (Fig. 1) show moderate temperature drop with a slope similar to that of the chondrite solidus curves. These paths indicate that adiabatic cooling alone cannot quench shock melt veins at high pressure and that crystallization of high-pressure minerals requires transfer of heat from shock melt to the much cooler solid host-rock material (Fig. 2).

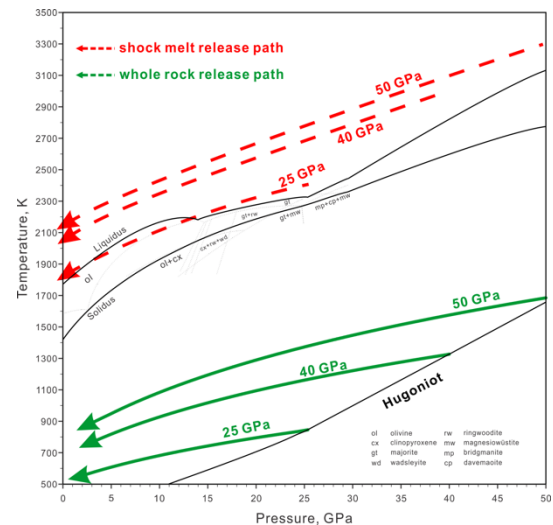


Figure 1. The adiabatic release paths of L chondrite bulk rock (blue) and shock melt (orange) at 25, 40 and 50 GPa superimposed on the phase diagram Allende [12].

## **Discussion:**

**Constraints from HP Mineral formation and survival.** The formation and preservation of HP minerals in shocked chondrites requires a large deviation from the Hugoniot conditions in the form of localized melting. This melting is required to heat host-rock fragments sufficiently to transform minerals, such as olivine and pyroxene, to their HP polymorphs on a timescale of hundreds to thousands of milliseconds. The formation of shock veins through pore collapse and localized deformation produces local pressure spikes somewhat above the equilibrium shock pressure, but these pressure variations “ring down” to the equilibrium shock pressure in 10s on nanoseconds [5], a very short time relative to the duration of the shock pulse and the formation of HP

minerals. The observation that many shock veins in L chondrites contain nearly uniform crystallization assemblages indicates that cooling path from super-liquidus conditions is steep at near-constant pressure and that the driving force for melt-vein quench in these samples is rapid heat transfer to the relatively cool host rock.

For HP minerals to survive in the sample after pressure release, they must be cooled below a critical temperature. At ambient pressure, ringwoodite and wadsleyite break down at temperatures above 900 K and back-transform to olivine within seconds at  $T > 1200$  K [6]. The critical temperatures for breakdown of akimotoite and bridgmanite are significantly lower at 700 and 400 K, respectively [7, 8]. In P-T space, the conditions HP mineral destruction is illustrated as a grey region with the minimum breakdown temperature corresponding to akimotoite breakdown. The P-T paths followed by HP minerals, from superliquidus or near liquidus conditions must end below this breakdown region after pressure release in order to preserve HP minerals. This constraint demonstrates the importance rapid heat transfer to the surrounding cool sample, resulting in a steep concave upward P-T paths. Samples without sufficiently cool material will not preserve HP minerals.

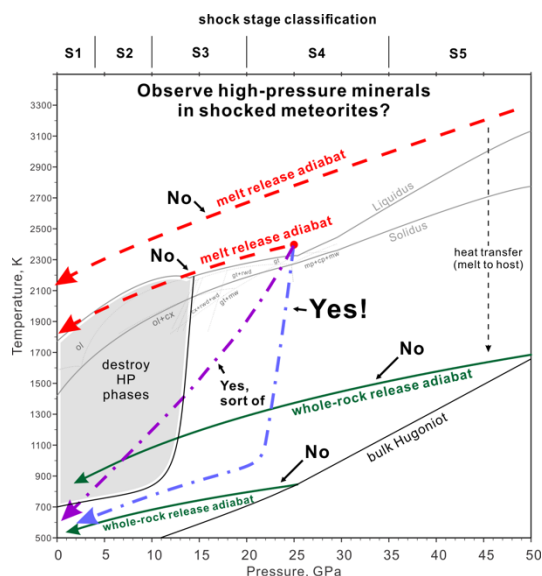


Figure 2. Shock temperature, release paths and the melting curve are used to illustrate P-T paths (blue and purple) that form and preserve HP minerals. The region of HP mineral destruction is illustrated as a gray. Shock stages of [2] are shown above the graph.

**Constraints on S6 pressure estimates.** Shock recovery experimentation is an important technique for calibrating the shock pressures of many features [2] but 80-90 GPa estimates of ringwoodite formation are not supported by shock recovery experiments. If

samples were shocked to pressures even as high as 50 GPa, the host-rock temperature, defined by the 50 GPa release adiabat, would be too high to sufficiently cool the HP minerals for post-shock survival (Fig. 2). Even if S6 features and HP minerals correspond to large pressure excursions during compression, the transitory high-pressure state would quickly reduce to the equilibrium shock pressure where most HP mineral crystallization and transformation occurs. The crystallization of the shock melt, which happens after pressure equilibration, is useful in constraining equilibrium shock pressure and pressure evolution during pressure release. Crystallization at pressures above 25 GPa should produce assemblages that are rich in bridgmanite. Although bridgmanite crystallization has been inferred in Acfer 040 and Tenham [9,10] from vitrified “grains” in the crystallization assemblage, relatively few shocked meteorites have evidence of bridgmanite.

**How to interpret S6 features.** The reconciliation of S6 conditions in shocked meteorites comes from the heterogeneous nature of shock effects and shock stage in these samples. More than 70% of the ringwoodite-bearing chondrites shock classified by [11] were classified as shock stage S4 away from the S6 shock veins. Even the iconic S6 chondrite Tenham has melt-vein free material that was classified as S4 [11]. These results indicate that the S6 classification based on HP minerals is not a valid part of a progressive series of shock effects, but rather the result of local hot zones in samples shocked to moderate pressures, typically corresponding to S4 conditions.

**Conclusion:** The presence of ringwoodite in many chondritic samples, which is commonly considered as evidence of shock stage S6, is not an indication of extreme shock pressure, but rather an indication of shock pressures consistent with shock state S4.

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