

PRESSURE- TEMPERATURE HISTORIES OF SHOCK-INDUCED MELT VEINS IN CHONDRITES.

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Introduction: It is generally accepted that the melt veins observed in many chondrites were formed by shock loading [1]. Possible mechanisms of vein formation include shock collisions, adiabatic shear, and the collapse of previously existing porosity. Melt veins commonly contain newly crystallized grains of silicate, oxide, sulfide and metal that are sometimes accompanied by silicate glass or altered silicate glass. These minerals may comprise low-pressure minerals in some occurrences; or metastable high-pressure phases such as ringwoodite, majorite, and hollandite that crystallized from the melt at high pressure [2-5]. Those portions of the chondrite that are more than a few vein widths from the nearest vein do not appear to have been strongly heated or as highly shocked as the material adjacent to the melt vein. In addition to crystallization from the melt, high-pressure minerals form in highly shocked samples by solid-state transformation of chondrite silicates that are entrained in the melt veins or occur at the melt-vein margin [6, 4, 7, 8]. These transformations only occur in materials that are in contact with melt, suggesting that such transformations are only kinetically possible in the highest temperature regions of the sample. Although it has been argued that the solid-state transformation to high-pressure minerals, requires local pressure as well as temperature anomalies [6, 7], the distribution of high-pressure minerals around melt veins is consistent with melt veins quenching by conduction to the surrounding cooler chondritic material. Thermal quench of melt veins was first investigated in Zagami by Langehorst and Poirier [9], who demonstrated that melt veins quench quickly by conduction to the surrounding chondrite matrix. They also demonstrated that the quench times are strongly dependent on the thickness of the melt vein and can range from nanosecond to second time scales for μm to mm thick veins.

We are using the mineralogy associated with melt veins combined with shock physics and thermal modeling to investigate the pressure-temperature histories of melt veins in chondrites. We have calculated synthetic Hugoniot for the L6 S6 chondrites Tenham and Skip Wilson so that we can estimate the shock and post-shock temperatures of the chondrite hosts for thermal modeling. Using crystallization pressure to constrain the pressure history of the sample and the survival of metastable phases to constrain the post shock temperature, we are able to evaluate possible pressure-temperature histories for melt veins and surrounding chondrite matrices.

Results:

Synthetic Hugoniot. Synthetic Hugoniot were calculated from measured the modal mineralogy of Tenham (37% olivine, 44% pyroxene, 10% maskelynite, 4.5% troilite, 4.5% FeNi metal) and Skip Wilson (45% olivine, 31% pyroxene, 10% maskelynite, 9% troilite, 5% FeNi metal). We used the best available Hugoniot data to calculate Hugoniot for each constituent. The bulk P-V Hugoniot is the sum of the volumes of constituents at pressure (0-50 GPa). For Tenham, Hugoniot were calculated assuming zero porosity and 7% porosity. Assuming a shock pressure of 25 GPa and a nonporous release path, waste heats were calculated for the porous and nonporous models.

Shock and post shock Temperatures. Post-shock temperatures were calculated from waste heat assuming $C_p = 1\text{J/gK}$. Shock temperatures were calculated from post-shock temperatures using adiabatic compression $T_s \approx T_o e^{\Gamma(V_o-V)}$, where T_s and T_o are the shock and post shock temperatures, respectively, Γ is the Gruneisen parameter which was assumed to be 2, and V_o and V are the post-shock and shock volumes respectively. The choice of $\Gamma = 2$ is an upper bound that results in a maximum adiabatic cooling and therefore maximum shock temperature. The results for Tenham are shown in Figure 1. For a shock pressure of 25 GPa and porosities of 0% and 7%, the shock temperatures are 432 and 687 K and the post-shock temperatures are 383 and 622 K, respectively. Note that the adiabatic cooling is only 50 to 65 K.

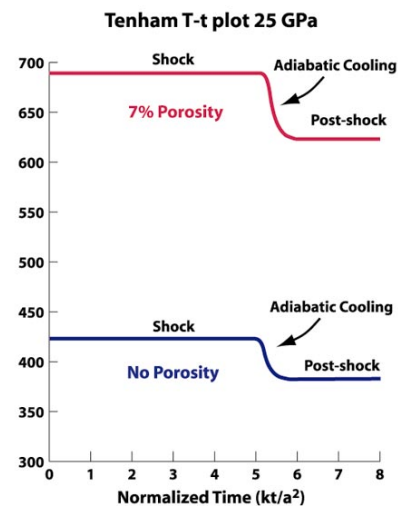


Figure 1. Plot of shock and post shock temperatures (K) versus normalized time for Tenham shocked to 25 GPa. The time of adiabatic release here is arbitrary.

Quenching of melt veins. Based on the mineral assemblages that one observes in the crystallized melt veins, one can estimate the crystallization pressure and try to relate this to the shock pressure. The key question is; when do melt veins quench? If they quench during the pressure pulse (i.e. equilibrium shock pressure) the crystallization pressure is the shock pressure. Conversely, if the vein quenches during or after shock release, the crystallization pressure will be lower than the shock pressure. Crystallization pressures have been estimated for a variety of shocked chondrites from S3 to S6 [10]. For all highly shocked S6 samples, the crystallization pressures do not exceed ≈ 25 GPa, which is about half the value of the 45-55 GPa pressure onset for S6 in Stöfflers [6] calibration. Either, the S6 pressure calibration is too high, or all S6 samples studied so far have crystallized during adiabatic release.

We can model the quench of melt veins as a function of time, using the solution for a hot slab in a cool infinite half space [11]. For Tenham, which crystallized at ≈ 25 GPa [10] we will assume that the melt vein started out at 2500 K, which is approximately 300 K above the liquidus, and the matrix was at the shock temperatures shown above. Figure 2 shows a plot of temperature versus normalized time assuming the pressure release occurred after five time steps (arbitrary). It is important to note that the temperature drop caused by adiabatic release is small relative to the total cooling of the melt vein by conduction to the surrounding matrix. Although the pressure release could coincide with crystallization, pressure release does not drive quench.

Survival of metastable phases. The high-pressure minerals that form by crystallization or solid-state transformation are metastable at low pressure and invert rapidly to stable low-pressure phases if they remain at high temperatures after pressure release. The presence of metastable high-pressure minerals in a vein thus implies that the vein was quenched to below the inversion temperature by the time the pressure was released. In the case of Tenham, (Mg,Fe)SiO₃-perovskite has been found to replace enstatite in melt veins [12]. Although we have not found (Mg,Fe)SiO₃-perovskite in our sample, we can use its 750 K thermal breakdown temperature [13] to constrain the thermal history of Tenham. In order for (Mg,Fe)SiO₃-perovskite to survive in a melt vein, the melt vein temperature must be below 750 K by the time the pressure is released. Based on Figure 2, this is only possible if the pressure pulse duration was at least five time steps and the surrounding matrix was without porosity and quite cool (≈ 425 K). Such a cool matrix limits the shock pressure of Tenham to a maximum of 25 GPa. For a melt-vein thickness of one mm, which is not uncommon in Tenham, the pressure pulse duration for cooling below 750 K would be at least 1.25 seconds. Further refinement of melt-vein quench histories are

currently being investigated with finite element modeling. This approach will allow us to model the histories of specific locations within or adjacent to melt veins.

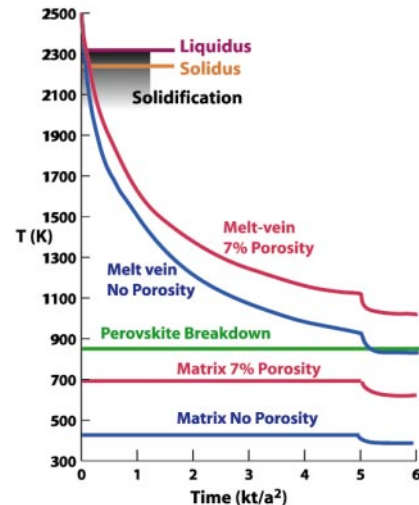


Figure 2. Plot of melt-vein and matrix temperatures versus normalized time assuming zero and 7% porosity in the matrix.

Conclusions: Shock veins cool by thermal conduction into the surrounding matrix rather than by adiabatic cooling associated with pressure release. Solidification is fast and strongly dependent on vein thickness. Survival of metastable phases requires thermal quench below the breakdown temperature before pressure release is complete. In the case of Tenham, which contains (Mg,Fe)SiO₃-perovskite, the matrix must be relatively cool, constraining the shock pressure to a maximum of ≈ 25 GPa. It also required a long pressure pulse (≥ 1.25 s). Shock physics and thermal modeling will allow us to use melt-vein mineralogy to estimate shock pressure and pulse durations for many samples.

References:

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