Estimating Shock Pressures from High-Pressure Minerals in Shock-induced Melt Veins of the Chondrites.

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Introduction: Shock metamorphism, resulting from hypervelocity collisions, is a fundamental process in the early solar system [1-6]. Shock-induced melt veins contain two lithologies [2]. One consists of poly-crystalline grains that transformed from host rock fragments by solid-state mechanisms. The other consists of quenched silicate and metal-sulfide grains that crystallized from shock-induced melts. Both lithologies commonly contain high-pressure mantle minerals such as ringwoodite, majorite and akimotoite. The crystallized mineral-assemblages can be used to constrain the crystallization pressure of the melt based on the phase equilibrium data [2, 5-6]. If a melt vein in a given sample quenched during the equilibrium shock pressure pulse, the crystallization pressure is the shock pressure. Based on a simple thermal model for the cooling of a dike, melt-vein quench times can be estimated as a function of vein thickness [7]. Thus the duration of the pressure pulse can be constrained by the size of the shock veins [8].

The purpose of this study is to test the hypothesis [2] that melt-vein crystallization can be used to estimate shock pressure. We have examined melt veins in chondrites of shock stage S3 to S6 to determine crystallization pressures and see how these pressures are related to the shock pressures inferred from the calibration of Stöffler et al [1]

Sample and Method: 7 L5-L6 chondrites were investigated, ranging from shock stage S3 to S6. These chondrites are Roy (S3), La lande (S4), Kunashak (S4), Nakhon Pathon (S4), Ramsdorf (S4), Umbarger (S4-S6*), and Tenham (S6).

Transmission electron microscopy (TEM) is the primary tool for determining the crystallization assemblages in shock-induced melt veins because most of the crystals are extremely fine grained (sub-μm to several μm). TEM imaging techniques were employed to characterize the micro-texture of the veins and the microstructures of the vein minerals. Mineral phases were identified on the basis of selected area electron diffraction (SAED) and quantitative energy dispersive X-ray spectroscopy (EDS) microanalyses

Result:

1) Roy S3. Roy was previously classified as S3 [1], but abundant maskelynite, consistent with S5 was found adjacent to the shock-induced vein. This maskelynite suggests that the transformation of plagioclase to maskelynite is temperature dependent and only occurs where temperatures are highest. TEM study reveals that majorite ($En_{77}Wo_8Fs_{15}$) and ringwoodite (Fa_{27}) occur in the melt vein, indicating melt-vein crystallization at ~18 GPa.

2) Kunashak S4. SEM data shows that the melt vein contains fine silicate crystals. TEM show these fine crystals consisting of olivine (Fa_{22}) and albite ($Ab_{95}An_2Or_3$), indicating crystallization at low pressure after pressure release.

3) La lande S4. The texture of the melt vein and mineral assemblages in La Lande are similar to these in Kunashak. Olivine (Fa_{22}), low-Ca pyroxene ($En_{77}Wo_1Fs_{22}$) and albite ($Ab_{96}An_2Or_2$) occur in the melt vein, indicating low pressure crystallization after pressure release

4) Nakhon Pathon S4. Pyroxene ($En_{80}Wo_5Fs_{15}$) and olivine (Fa_{25}) grains occur in the melt vein. Based on this assemblage, this vein could have crystallized at pressure up to about 15 GPa.

5) Ramsdorf S4. As in Nakhon Pathon, the melt vein of Ramsforf contains olivine (Fa_{21}) and pyroxene ($En_{78}Wo_4Fs_{19}$), indicating crystallization pressure up to 15 GPa.

6) Umbarger S4-S6.* Umbarger was previously classified as S4 [1], but blue ringwoodite grains were found in the melt veins under optical microscope indicating shock stage of S6 [1]. Melt-vein crystallization produced two mineral assemblages. Akimotoite (En_{11}), ringwoodite (Fa_{30}) and Ca-rich clinopyroxene ($En_{42}Wo_{33}Fs_{25}$) constitute most of the silicate matrix in the melt vein. However, Fe_2SiO_4-spinel, stishovite, and altered SiO2-rich glass occur in localized FeO-SiO$_2$ rich melt. The Akimotoite-ringwoodite-pyroxene assemblage and the spinel-stishovite assemblage are consistent with crystallization at ~18 GPa.

7) Tenham S6. SEM data shows the melt vein has different textures between the vein edge and vein center. TEM study reveals that the vein-edge assemblage consists of vitrified silicate-perovskite ($En_{81}Wo_4Fs_{15}$), ringwoodite (Fa_{35}), akimotoite (En_{12}) and majorite. The vein center consists of majorite ($En_{78}Wo_7Fs_{15}$) plus magnesiowüstite ($(Mg_{0.69}Fe_{0.31})O$). Both mineral assemblages are consistent with crystallization at ~22 to 25 GPa.

The crystallization pressures for the melt veins in these samples are summarized in Figure 1 on a simplified version of the Allende phase diagram of Agee et al [9]. The diagram is the most complete phase diagram relevant to chondritic composition currently available. Our samples are grouped into three P-T areas based on mineral assemblages: (1) Tenham (S6), Roy(S3-S5*) and Umbarger (S4-S6*) represent the highest pressure crystallization at 18 to 25 GPa. It is interesting that the lowest shock stage sample Roy (S3) is in this highest pressure group. (2) Ramsdorf (S4) and Nakhon Pathon (S4) may have crystallized at pressures up to 15 GPa.

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(3) Kunashak (S4) and La Lande (S4) crystallized at pressure less than 3 GPa after pressure release.
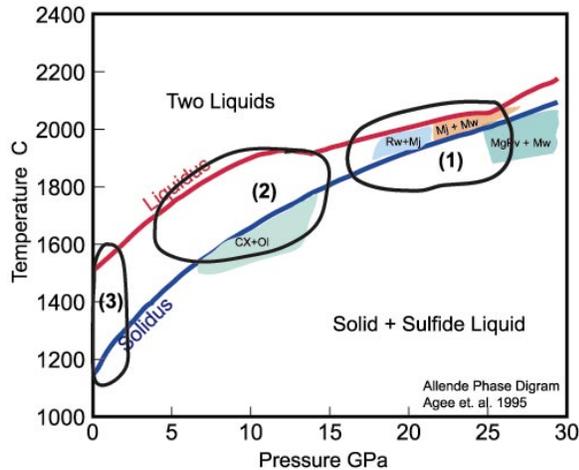

Figure. Three crystallization-pressure regions illustrate on a simplified version of the Allende phase diagram [9]. Ol, olivine; CX, Clino-pyroxene; Rw, ringwoodite; Mj, Majorite; Mw, magnesiowüstite; MgPv, (Mg,Fe)SiO3-perovskite.

Discussion: The crystallization of high-pressure minerals in melt veins implies that the vein was quenched at high pressure. The fact that two of our samples contain low-pressure assemblages indicates that melt-vein quench also can occur after pressure release. Albite indicate crystallization pressure less than 2.5 GPa at ~700 K [10].

The presence of akimotoite in Umbarger and in Tenham is a result of metastable crystallization, probably as a result of very rapid quench. This is consistent with it only occurring in the chilled margins of the veins in Tenham. The pressure of akimotoite crystallization is not constrained by the Allende phase diagram [9]. Akimotoite is a subsolidous phase and it occurs together with ringwoodite between 18 and 25 GPa in the enstatite-forsterite system [11]. Ca-rich clinopyroxene is stable up to about 18 GPa, like akimotoite, Ca-pyroxene is metastable relative to majorite garnet [12].

According to Stöffler's shock classification [1], the meteorites studied range from S3 (15-20 GPa) to S6 (>55 GPa). The present study indicate the shock pressure was less than ~25 GPa for all of these meteorites and that the melt vein in Roy (S3), the sample with the lowest shock stage (S3), crystallized at a pressure not greatly different from the S6 samples. The discrepancy between the crystallization pressures and the shock pressure calibration of Stöffler et al [1] has been inferred to be a result of crystallization occurring during pressure release. However, the tempreature drop that results from adiabatic decompression is small relative to the total temperature drop of the vein caused by thermal conduction to the cooler chondrite matrix [8].

If crystallization occurs during adiabatic pressure release, the crystallization pressure inferred from the mineralogy should decrease from the melt-vein margins to the vein center. Although it is possible that Umbarger crystallized during pressure release from about 25 to 18 GPa, there is no apparent difference in the mineral assemblages between the vein edge and the vein center. The presence of high-pressure phases in the veins of S6 chondrites constrains the peak shock pressure in the matrix to be less than about 35 GPa. If peak pressures were much higher, the post-shock temperature would be too high to permit survival of metastable high-pressure phases [8].

Conclusion: Mineral assemblages of the melt veins can be used to infer both the crystallization pressure of the melt vein and shock pressure when high-pressure phases are present. If crystallization occurred during adiabatic pressure release, the pressure change during crystallization should result in observable variations in the crystallization assemblages.

Stöffler's pressure calibration for chondrites [1] appears too high by at least a factor of two for highly shocked (S5-S6) samples.

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