The Distribution and Significance of Shock-Induced High-Pressure Minerals in Chondrite Skip Wilson

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Introduction: The mineralogy and textures preserved in chondritic melt veins allow us to interpret the shock and post-shock conditions of meteorites. High-pressure minerals occur within shock-induced melt veins as products of crystallization (igneous) and of solid-state transformation (metamorphic) processes [1,2]. A thorough investigation of the igneous and metamorphic petrology of these melt veins can give us a better understanding of the pressure and temperature conditions associated with shock metamorphism and the formation of melt veins in chondrites.

Black veins in chondrites were first interpreted as shock-induced melting in 1963 [3]. Since then, much emphasis has been placed on the presence of high-pressure mineral phases in the veins. Minerals such as ringwoodite ($(Mg,Fe)_2SiO_4$-spinel), majorite ($(Mg,Fe)SiO_3$-garnet), akimotoite ($(Mg,Fe)SiO_3$-ilmenite), and $NaAlSi_3O_8$-$CaAl_2Si_2O_8$-hollandite are commonly found in shock veins, either as polycrystalline products of solid-state polymorphic transformations, or as the black vein matrix, representing the product of melt-vein crystallization at high pressure (Fig. 1) [2].

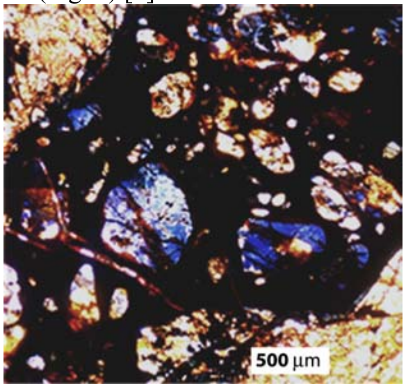

Figure 1. *The melt vein in Skip Wilson contains two textural units: a black, finely crystalline matrix and polycrystalline host rock inclusions. Plane polarized light.*

The olivine polymorph ringwoodite, which can be easily recognized in plane polarized light by its deep blue color, is a common indicator of shock stage S6. Based on the calibration of shock effects by Stöffler et al. [4], the presence of ringwoodite implies a shock pressure of at least 45-55 GPa. It was recognized that using the crystallization assemblage in the vein matrix, determined with TEM, along with results of static high-pressure experiments, the conditions of melt-vein crystallization could be estimated [1,2]. The crystallization pressures for S6 samples such as Tenham, Sixiangkou, Umbarger [1,5] and Skip Wilson are 25-30 GPa, lower than the 45-55 GPa calibrated for S6 [1,2], suggesting that the calibration is too high. In order to explain the heterogeneous distribution of ringwoodite and other shock metamorphic effects, melt veins have been described as the result of local pressure and temperature excursions [4]. In order to explain the heterogeneous distributions of blue ringwoodite within melt veins, [6] proposed a cavitation mechanism to generate localized extremes in pressure and temperature within melt veins.

The goals of this study are to 1) use the igneous melt-vein assemblages to constrain the P-T conditions of crystallization during shock, 2) determine the distribution of high-pressure minerals associated with shock-induced melt veins, 3) determine if the transformed polycrystalline inclusions in the melt vein can be explained in terms of the localized high temperatures rather than localized pressure and temperature excursions.

Analytical Method: Thin section analysis of L6 S6 W2 Chondrite Skip Wilson, was conducted using the following techniques: Optical petrography; SEM with a JEOL JSM-840 and attached Energy Dispersive System (EDS), used primarily in back scattered mode (BSE) for mineral identification, imaging and x-ray mapping; Electron Microprobe analysis with a JEOL JXA-8600 superprobe, used to attain quantative mineral compositions; Raman Spectroscopy, used to identify and map the distribution of high-pressure mineral phases in and adjacent to the melt vein; and Transmission Electron Microscopy (TEM) with a Philips CM200-FEG, used to determine the crystallization assemblage in the melt vein matrix.

Observations: Skip Wilson contains a large melt vein, ranging in thickness from 100 µm to 4 mm. The black vein matrix contains large, irregular polycrystalline host rock inclusions with diameters from ~15 µm to 2mm. Many of these inclusions observed in plane polarized light appear blue, indicating the presence of ringwoodite. Orthopyroxene, clinopyroxene, Fe-oxides, Fe-sulfides and a plagioclase polymorph, likely maskelynite or hollandite structure, are also present as melt vein inclusions.

The crystallization assemblage in Skip Wilson, determined with TEM, consists of majorite garnet, magnesiowüstite and magnetite throughout the veins.

The magnetite is an alteration product of magnesiowüstite. The garnets are commonly large (10-15 μm), euhedral grains or dendritic laths. The euhedral garnets are located in the vein centers whereas the dendritic garnets occur only at the melt vein margins. Other notable textures include reaction rims or chill margins surrounding most large inclusions and at the vein edges (Fig. 2).

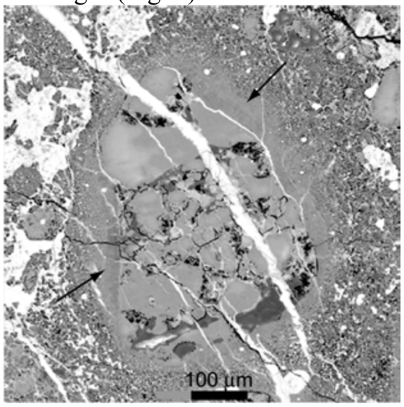

Figure 2. *BSE image of host rock inclusion with a finely crystalline reaction rim.*

Raman analysis of the entrained fragments in the melt vein was used to identify high-pressure minerals and distinguish olivine from ringwoodite (Fig. 3).

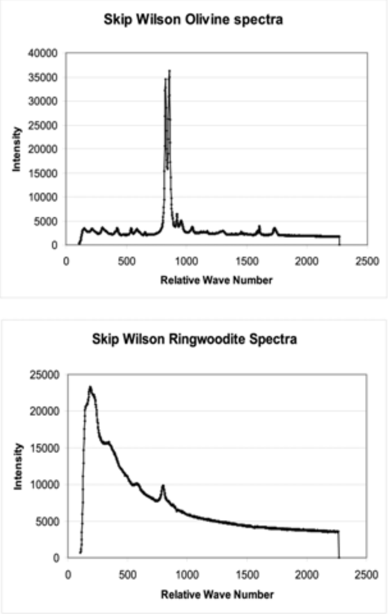

Figure 3. *Raman spectroscopy identifies differences between low-pressure olivine found outside the vein and the high-pressure ringwoodite, found inside the vein.*

Ringwoodite and maskelynite are the only high-pressure phases preserved in the inclusions. All entrained fragments with ($(Mg,Fe)_2SiO_4$) composition are ringwoodite. Despite its common blue color, ringwoodite spectra were also obtained from white and yellow mineral fragments. Raman analysis of material with compositions similar to plagioclase was inconclusive due to radiation damage during collection. Therefore, the presence of hollandite, the high-pressure crystalline form of plagioclase has not yet been confirmed.

Discussion: Crystallization of majorite plus magnesiowüstite throughout the vein matrix indicates crystallization pressures ~23-25 GPa [7], which is significantly lower than that calibrated for S6 (> 45-55 GPa) [4]. The transition from large euhedral majorites in the vein center to dendritic majorites at the vein margins is consistent with the melt vein cooling by conduction to the surrounding chondrite. The fact that the dendritic chill-margin has the same assemblage as the vein center indicates the pressure remained constant through the crystallization of this thick melt vein. This demonstrates that crystallization did not occur during pressure release, but rather occurred at an equilibrium shock pressure of about 23-25 GPa. Thermal modeling of melt-vein quench [8] provides an estimate of solidification times as a function of thickness. The thick, 1.3-mm vein we characterized with TEM would have crystallized in several hundreds of μs, which is a minimum value for the pressure-pulse duration.

The distribution of polycrystalline ringwoodite after olivine within the melt veins is homogeneous in spite of the heterogeneous distribution of optically observed blue ringwoodite. The heterogeneous distribution of blue ringwoodite in other samples has been used to argue for local pressure and temperature heterogeneities caused by cavitation during shock [6]. Cavitation, which is caused by the collapse of bubbles during pressure release [6], could not have happened in Skip Wilson because the vein was solidified prior to pressure release. Because ringwoodite has variable color, it is essential that its distribution be determined by a method such as Raman spectroscopy.

Conclusions: The melt veins in Skip Wilson crystallized at an equilibrium shock pressure of ~23-25 GPa during a pressure pulse lasting several hundred μs. The homogeneous distribution of ringwoodite inclusions within the melt vein can be explained by local high-temperatures associated with the melt vein, instead of localized pressure excursions.

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