CONSTRAINING PRESSURE-TEMPERATURE HISTORIES OF SHOCKED METEORITES FROM THE FORMATION AND DESTRUCTION OF HIGH-PRESSURE MINERALS.

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Introduction: Shock metamorphic effects in meteorites provide a record of impact events and processes in the Solar System. The key to interpreting this record is understanding the shock conditions and relating these to impact processes [1, 2]. A major challenge in understanding shock effects in meteorites is the interpretation of heterogeneous shock effects in a given sample. For example, high-pressure minerals almost exclusively occur in close association with shock-melt veins and pockets in S6 samples, yet samples with large amounts of shock melt generally lack high-pressure minerals. These shock-melt breccias, with abundant quenched shock melt, clearly experienced high pressures yet they are commonly not classified as S6 [1, 3]. High shock temperatures are needed to form high-pressure minerals, but high post-shock temperatures destroy them. In this study we look at the mineralogy associated with shock melt in three highly shocked L chondrites to better understand shock conditions necessary to form and preserve high pressure minerals. Similarly, we address the lack of high-pressure minerals in a sample that has abundant shock melt.

Samples and Methods: We examined the textures and mineralogy associated with shock melting in L5/6 chondrites Mbale (S6), Acfer 040 (S6) and Chico (melt breccia). We used transmitted and reflected polarizing light microscopy, Raman spectroscopy and synchrotron micro-diffraction to classify samples and identify high-pressure polymorphs. We used FE-SEM and EDS to characterize nano-textures and compositions of minerals in and around shock veins. We also used FIB lift-out and TEM to characterize the nano-mineralogy of the shock veins and transformation effects in associated minerals. Finally, we used transformation kinetics and thermal modeling to interpret the conditions required to destroy high pressure minerals.

Results:

Acfer 040 (S6). Acfer 040 is a highly shocked L chondrite with abundant shock veins and pockets. The shock melt crystallized to form assemblages of bridgmanite, akimotoite and ringwoodite. In both assemblages, the bridgmanite was pervasively back-transformed to a pyroxene glass. XRD results indicate that traces of bridgmanite survived in the quenched shock melt. Entrained olivines were pervasively transformed to polycrystalline ringwoodite whereas entrained enstatites consist of a granular mixture of enstatite-composition glass, ringwoodite, magnesiowüstite and stishovite. We infer that the pyroxen class was bridgmanite at high pressure. This sample experienced a sustained shock pressure of > 24 GPa throughout the quench of the shock melt.

Mbale (S6). Mbale is a highly shocked L5-6 chondrite fall with prominent shock veins that contain recrystallized olivine. The shock vein matrix consists of majoritic garnet, wadsleyite and ferro-periclase-magnetite oxides, suggesting a crystallization pressure of 14 to 16 GPa. The recrystallized olivines consist of nanocrystalline aggregates that have strongly heterogeneous fayalite contents on the scale of 10s of micons. Minor wadsleyite and ringwoodite in these aggregates indicates that they are back-transformed ringwoodite and wadsleyite aggregates.

Chico L6-S6 (melt breccia). Chico L6-S6 is black and nearly opaque, as a result of finely disseminated sulfides throughout the sample. Chico contains abundant shock melt veins and pockets as well as textures suggesting pervasive post-shock recystallization and melting. The shock veins crystallized a low pressure assemblage that includes olivine, pyroxene and plagioclase and there is no evidence of surviving high-pressure minerals.

Discussion: Shock classification of these samples is problematic because they do not all have shock deformation and transformation effects that are commonly used in classification [1]. Chico has the least direct evidence of high pressure and is classified as S6, based on recrystallized olivine, and S4, based on crystalline plagioclase, respectively. However, if one considers the extent of shock melting as a proxy for shock intensity, Chico is the most highly shocked of the three samples and Mbale (S6) is the least shocked.

The formation and survival of metastable high-pressure minerals provides valuable insight into the pressure-temperature histories of the samples. Formation of high pressure minerals in S6 samples requires super adiabatic temperature associated with localized melting. Mineral clasts within the melt are heated to near melting in the superheated melt. At these temperatures, transformation of olivine to ringwoodite is rapid. The survival of abundant high-pressure minerals, including trace amounts of bridgmanite, implies that Acfer 040 remained at high pressure through the rapid quench of its melt veins and pockets. Survival of perovskite required cooling to below ~ 400 K before complete release of the shock pressure. This suggests a steep decompression trajectory through pressure-teperature space, followed by cooling (Fig. 1).

Mbale provides an example of partial annealing and back-transformation. The polycrystalline olivine in Mbale did not form by direct recrystallization, but rather by back transformation of ringwoodite-wadsleyite aggregates formed by transformation of olivine fragments in the shock melt. The presence of majoritic garnet and wadsleyite in the quenched melt confirms the formation of high-pressure minerals and indicates shock-melt quench at high pressure. Back-transformation kinetic data for ringwoodite and wadsleyite [4-5], combined with thermal modeling of shock veins and entrained clasts indicate that back transformation, as seen in Mbale, requires temperatures > 1200 K for seconds after decompression. This implies that Mbale had a relatively short shock-pressure pulse relative vein quench or a shallower trajectory in pressure-temperature space (Fig. 1) that left the melt-vein regions relatively hot after pressure release.

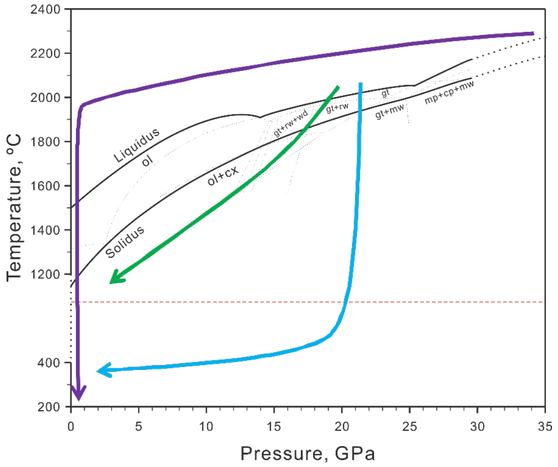

Figure 1. Schematic pressure-temperature phase diagram showing the liquidus and solidus for a chondritic melt. The blue P-T tragectory corresponds to that of shock melt in Acfer 040, which experieced rapid quench before pressure release. The dashed red line corresponds to the temperature at which ringwodite readily transformed back to olivine. The purple path correspnts that of shock melt in an melt breccia that crystallized after decompressure. The green tragectory corresponds to a sample such as Mbale that remained relatively hot after decompression. The phase relation is from [6]. Abbreviations: ol-olvine, cpx-clinopyroxene, gt-garnet, rw-ringwoodite, wd-wadsleyite, mw-magnesiowüstite, mp-bridgmanite.

Chico was more pervasively heated and melted and remained at high temperatures longer that the other samples. Crystallization of a low-pressure assemblage from shock melt implies that the melt remained above the liquidus until after pressure release. This implies that the shock melt experienced a very shallow and high-temperature trajectory through pressure-temperature space (Fig. 1). Extensive recrystaalization and melting indicates that non-melted regions also followed a shallow pressure-temperatre trajectory that resulted in some material crossing the melting curve at low pressure.

In summary, very high temperatures are required to form high pressure minerals in shocked chondrites, but survival also requires rapid quench during the shock pulse. This implies that bulk shock temperature of S6 samples, containing high-pressure mineral, is relatively low. This is consistent with modest shock pressures of ~20 to 25 GPa for S6 samples. Samples that experience significantly higher pressure shocks are more pervasively melted such that their quench time exceeds the shock pulse. These samples have shallow high-temperature P-T paths through shock decompression that prevent the direct crystallization of high-pressure minerals from the melt and cause pervasive back-transformation and recrystallization of transformed minerals. Mbale is an example of an intermediate path where high-pressure minerals were formed, both by crystallization of melt and transformation of entrained mineral clasts, with subsequent partial back transformation and recrystallization of transformed olivine.

References: [1] Stöffler D. *et al.* 1991. *Geochim. Cosmochim. Acta* 55, 3845–3867. [2] Sharp T. G. and DeCarli P. S. 2006. In Meteorites and the Early Solar System II, Univ. Arizona Press, Tucson. pp. 653–677. [3] Heymann, D. 1967. *Icarus* 6, 189-221. [4] Reynard B., *et al.* 1996. Am. Mineral. 81, 585–594. [5] Ming L. C., *et al.* 1991. *Phys. Chem. Miner.* 18, 171–179. [6] Agee C. B. et al. 1995. *JGR* 100, 17725-17740.