EVIDENCE FOR IMPACT-INDUCED SHOCK MELTING IN CARBONACEOUS CHONDRITES.
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Introduction: Impact-induced shock melting, melting caused by impacts, in carbonaceous chondrites was first observed in CK chondrites, which are heavily shock-metamorphosed [1]. It has only recently been observed in relatively unmetamorphosed CV and CM carbonaceous chondrites [2]. In CV chondrites, this shock melting appeared as distinct clasts surrounded by matrix [2]. In contrast, we have studied the heavily-shocked Leoville and Efremovka CV3 chondrites and found abundant melt pockets not as distinct clasts, but in contact with several calcium-aluminum-rich inclusions (CAIs). Some of these pockets of melted matrix were previously identified in the Leoville carbonaceous chondrite and were attributed to hot accretion of CAIs [3]. Alternatively, but not considered in that earlier work, the melting might have been caused by much-later impacts of large bodies onto the asteroid as suggested by [4]; in this case, the kinetic energy of the impacting body was rapidly converted into heat that caused local impact-induced shock melting of the asteroid.

Materials & Methods: In this study, we analyzed polished sections of Leoville and Efremovka (CV3) from the U.S. National Meteorite Collection. We used the FEI Nova NanoSEM 600 scanning electron microscope (SEM) at the Smithsonian Institution (SI) to take backscatter electron (BSE) images of impact melt textures, generate element maps of selected areas, and conduct point-and-shoot EDS analysis of crystals and glass. Higher precision chemical analyses of olivine and glass were collected using the JEOL 8530FPlus Hyperprobe at SI.

Results: Leoville 3537-1 is a CAI ~3 cm in length sampled as a circular thin section. It is composed mostly of pyroxene, with smaller amounts of fassaite, anorthite, melilite, and spinel [5]. The inclusion takes up about half of the thin section, yet the entire perimeter of the inclusion is not visible due to its size and the sampling. Its visible edge borders both unmelted matrix and small pockets of melted matrix, which also fill some cracks in the CAI. Within the matrix are many smaller, mostly olivine-rich chondrules.

Efremovka 27cE is a CAI ~1 cm across, sampled as a circular thick section. Its mantle is composed mostly of melilite with small spinel crystals, while the core is melilite, pyroxene, anorthite, spinel, and FeNi metal [6]. The entire perimeter of this inclusion is visible. Like Leoville 3537-1, it borders mostly unmelted matrix but pockets of melted matrix are found.

Evidence for Impact Melting: Evidence for impact-induced shock melting was inferred from several textures and chemical signatures, disproving the former “hot accretion” hypothesis.

Evidence for Melting Evidence of melting includes the presence of sulfide and iron-nickel metal globules, reduction in pore space, recrystallization, and pockets of glass. The rounded sulfides and iron-nickel metal grains indicate high temperatures that melted those minerals into rounded globules. Prior to melting, the iron-sulfide and iron-nickel metal grains occur in a variety of shapes and are rarely spherical.

Evidence for Rapid Crystallization: Rapidly crystallized olivine grains were identified within both Leoville 3537-1 (Fig. 1) and Efremovka 27cE. These branching, skeletal, and “Christmas-tree” olivines, with magnesium-rich cores and iron-rich rims, are products of melting followed by very rapid crystallization (aka quench growth). Shock melting is an extremely rapid process, but hot accretion and cooling are not. These crystals display no evidence of deformation. Although the meteorites were clearly shocked, the undeformed crystals must have formed during, not before, the shock. In addition, rapidly crystallized pyroxene grains abutting unmelted matrix and enclosing spinel from the partly melted CAI were identified in Leoville 3537-1. Like skeletal olivines, these pyroxene crystals do not show evidence of deformation and therefore formed during, not before shock.

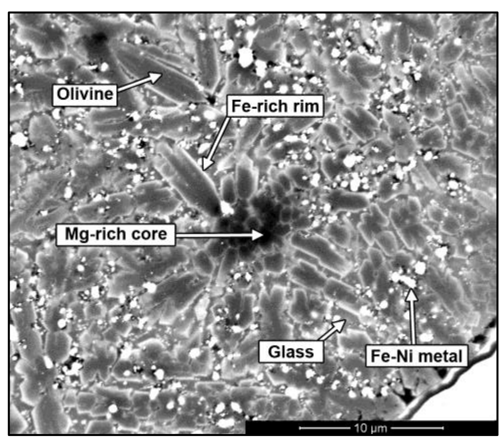

Figure 1: Rapidly crystallized olivine crystals in Leoville 3537-1. These crystals have magnesium-rich

cores and iron-rich rims and are surrounded by glass and rounded iron sulfides and iron-nickel metal.

Partial Melting of CAI: Glass in one region near the CAI in Leoville 3537-1 (Fig. 2) is high in Ca and Al, indicating this is melted CAI. This glass contrasts with adjacent glass from the melted matrix, which is enriched in Mg and depleted in Ca and Al due to the matrix consisting mostly of olivine. In addition, spinel grains are found within the melt; if hot accretion were the reason for melting, the spinels would not have migrated out of the CAI. The CAI "islands" which broke off from the CAI during melting are engulfed in the melted matrix and melted CAI. The rounded edges of these islands indicate that they were dissolving into the surrounding melt, which would not be the case if the CAI was itself the source of the heat for melting (hot accretion).

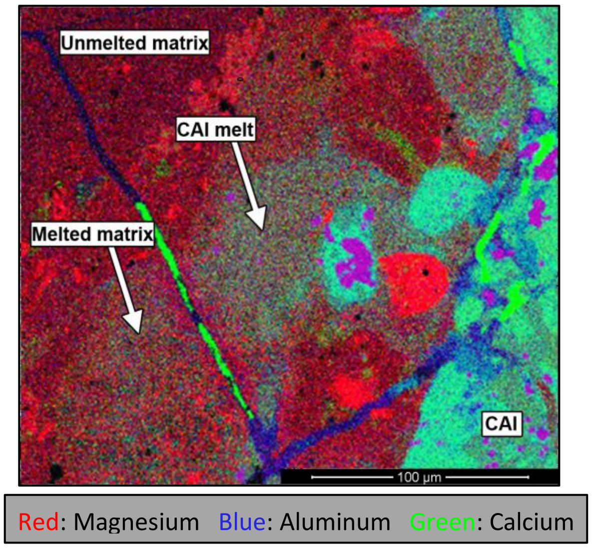

Figure 2: Partial melting of CAI in Leoville 3537-1. CAI melt is mixed with matrix melt and pieces of the CAI have broken off and migrated into the melt.

Spatial Heterogeneity of Melting: Both Leoville 3537-1 and Efremovka 27cE display significant variability in melt distribution; all skeletal crystals are located along one edge of the CAI in Efremovka 27cE, and there are regions in both meteorites where melting is concentrated and other regions where melting is nonexistent.

Discussion: Evidence of melting was found in the form of glass and rounded iron sulfides and iron-nickel metal. We argue that this melting was impact-induced due to the presence of undeformed skeletal and branching olivine and pyroxene crystals, melting of the CAI in Leoville, shock melt veins, and the heterogeneity of melting around the CAIs. The heterogeneity of melting is the strongest indicator of impact-induced shock melting. In the "hot accretion" scenario, it is likely that an object as small as the CAI would have had a uniform temperature and therefore melted all the material it came into contact with. However, the melting in the two meteorites is clearly not homogenously distributed around the CAIs. This suggests shock as the source of melting, as shock waves can create heterogeneous melting. Numerical simulations of impact-induced compaction within CV chondrites demonstrate variable temperatures and pressures around chondrules. These indicate localized temperatures reaching >3000 K and varying by >1000 K, and localized pressures as high as 30 GPa varying by >10 GPa [4].

We hypothesize that melting is only observed along the largest CAIs, and not smaller CAIs and chondrules, because these larger CAIs (up to ~ 3 cm in CV3) act to focus impact energy locally in the porous medium, or due to the insulating (ceramic) nature of their compositions and chemistry, or both. The fact that the melting straddles the borders of CAIs could be explained by differences in porosity. The shockwaves likely concentrated along the edges of CAIs because these are large, nonporous objects surrounded by porous matrix and much smaller chondrules. When the shockwaves hit these nonporous CAIs, the porous matrix material was pressed against the edge of the CAI, creating a high-pressure zone where melting occurred.

It should be noted that both Leoville and Efremovka display significant chondrule flattening, and the amount of flattening in CV3 chondrites has been shown to correlate with the intensity of shock metamorphism. This is believed to be due to the collapse of pore space due to shock pressure [7].

Conclusions: Several textures, such as the heterogeneity of melting, presence of quench crystals, and melting of the CAI support that this melting was caused by impact-induced shock that occurred long after accretion, and not by hot accretion of the CAIs. The cause of the melting and its heterogeneous distribution around CAIs is likely due to pore compression being concentrated around these nonporous CAIs as a shockwave passed through the medium.

Acknowledgements: I would like to thank the NSF (REU site 1560088) for funding this research.

References: [1] Rubin A. (1992) Geochim. Cosmochim. Acta, 56, 1705-1714. [2] Lunning N. et al. (2016) Geochim. Cosmochim. Acta, 189, 338-358. [3] Caillet C. et al. (1993) Geochim. Cosmochim. Acta, 57, 4725-4743. [4] Bland P. et al. (2014) Nature Comms. 5:5451. [5] Mao X.. et al. (1990) Geochim. Cosmochim. Acta, 54, 2121-2132. [6] Ivanova M. et al. (2010) 41st LPSC. [7] Scott E. et al. (1992) Geochim. Cosmochim. Acta, 56, 4281-4293.