Evidence for Impacted-Induced Shock Melting in Carbonaceous Chondrites

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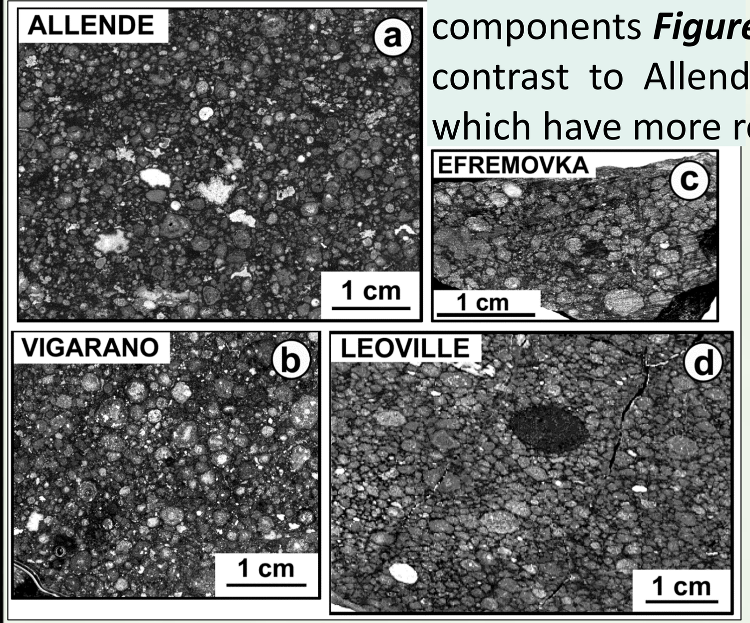
INTRODUCTION

Chondritic meteorites, or chondrites, are aggregates of pre-planetary dust that formed in the nebular disk surrounding the infant Sun. This dust included (1) silicate and metal grains, (2) melted silicate droplets called chondrules, and (3) ceramic-like assemblages – called calcium-aluminum-rich inclusions (CAIs) – that are the first solids to have formed in the solar system[1]. These 3 components slowly accreted together in the nebula to form asteroids and planets, but the asteroids from which these particular meteorites came never grew large enough to melt and destroy all traces of the original dust, forming asteroids. Their dust has been preserved in cosmic deep-freeze for 4 ½ billion years. For this reason, studying chondritic meteorites gives critical clues to how our Solar System formed and how the planets accreted.

In a previous study[2], small pockets of melted matrix were found around the edges of a large CAI and were attributed to "hot accretion"; i.e., the CAI was very hot when it accreted onto the asteroid causing the matrix it contacted to melt. Alternatively, but not considered in that earlier work, the melting might have been caused by much-later impacts of large bodies onto the asteroid; in this case, the kinetic energy of the impacting body was instantaneously converted into heat that caused local ("impact or shock-induced") melting of the asteroid. We tested the second hypothesis, by looking for evidence that can discriminate between hot-accretion and impact-induced melting. In particular, a distinctive feature of shock waves passing through a porous medium (such as chondrites) is that the effects are very heterogeneous. Large objects such as CAIs may concentrate the shockwave during an impact creating highly-localized melting.

We studied the CAI-matrix contacts around 2 CAIs from the Leoville and Efremovka carbonaceous chondrites (a sub-variety defined by being carbon rich and noted for having abundant and large CAIs). Leoville and Efremovka exhibit significant compression (flattening) of all components ***Figure 1* (left)** in contrast to Allende and Vigarano which have more rounded features. *We searched for two types of evidence: that melting occurred, and that this melting is impact-induced shock melting.*



METHODS

We used an FEI Nova NanoSEM 600 scanning electron microscope (SEM) to take backscatter electron (BSE) images of impact melt textures, generate element maps of selected areas, and conduct point-and-shoot analysis of crystals and glass. Higher precision chemical analyses of olivine and glass were collected using a JEOL 8530FPlus Hyperprobe.

RESULTS

EVIDENCE FOR MELTING

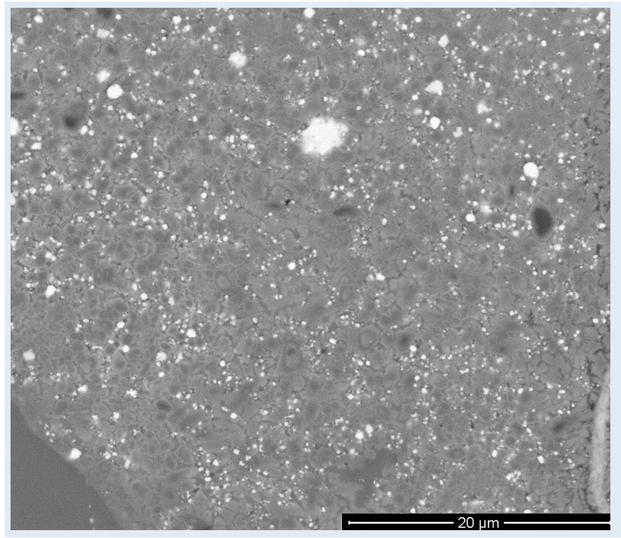


Figure 2a (above) shows **melted** matrix in Leoville 3537-1.

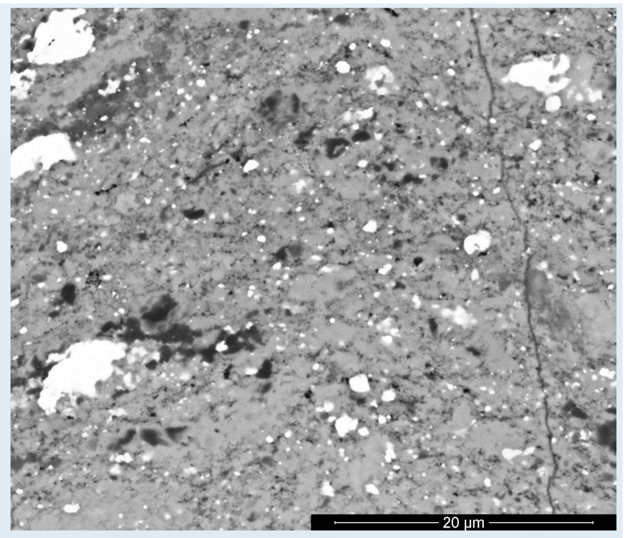
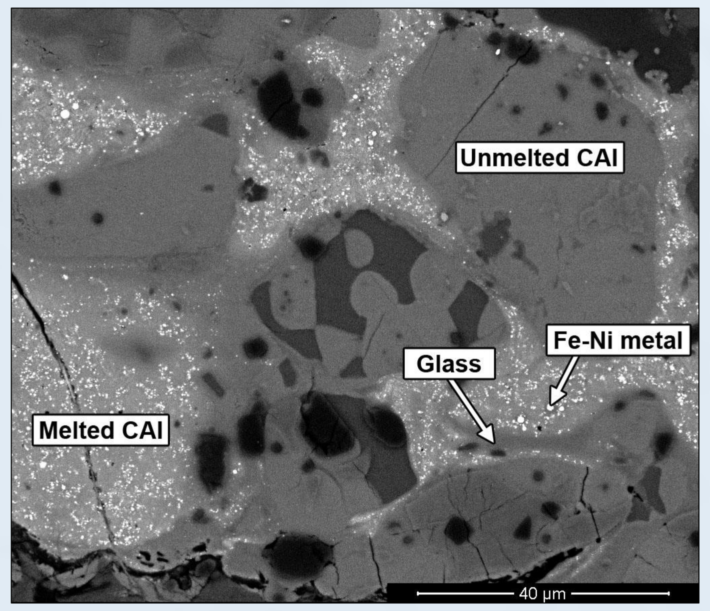


Figure 2b *(above)* shows **unmelted** matrix in Leoville 3537-1.

Evidence of melting includes rounded sulfides and iron-nickel metal grains, reduction in pore space, recrystallization, and pockets of glass. The rounded iron sulfide and iron-nickel metal grains indicate high temperatures that melted those minerals into droplets.

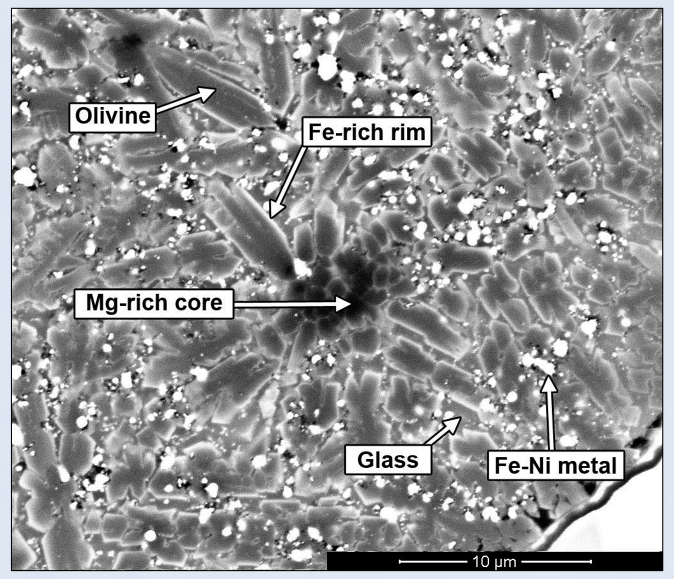
Figure 2c (right) shows melting of the CAI in Leoville 3537-1.



EVIDENCE FOR IMPACTS AS THE CAUSE FOR MELTING

RAPID CRYSTALLIZATION

Figure 3a (right) Rapidly crystallized olivine grains within Leoville 3537-1. These branching, skeletal, and "Christmas-tree" olivines with their magnesium-rich cores and iron-rich rims are the products of melting followed by very rapid crystallization. Shock melting is an extremely rapid process, but hot accretion and cooling is not.



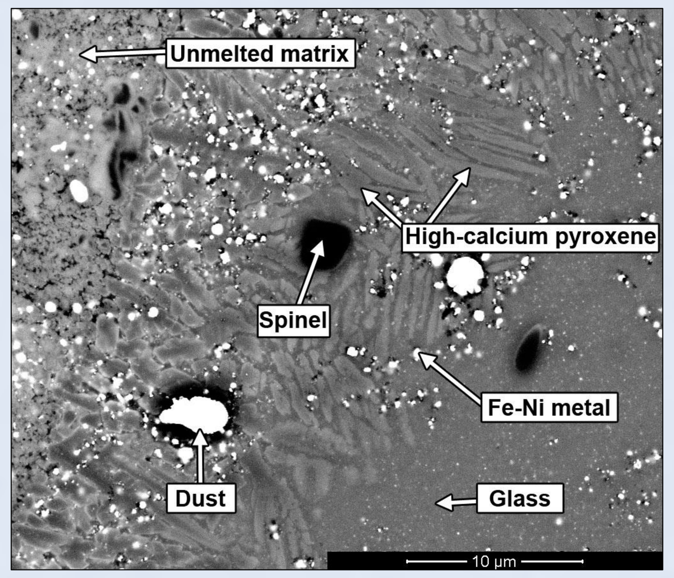
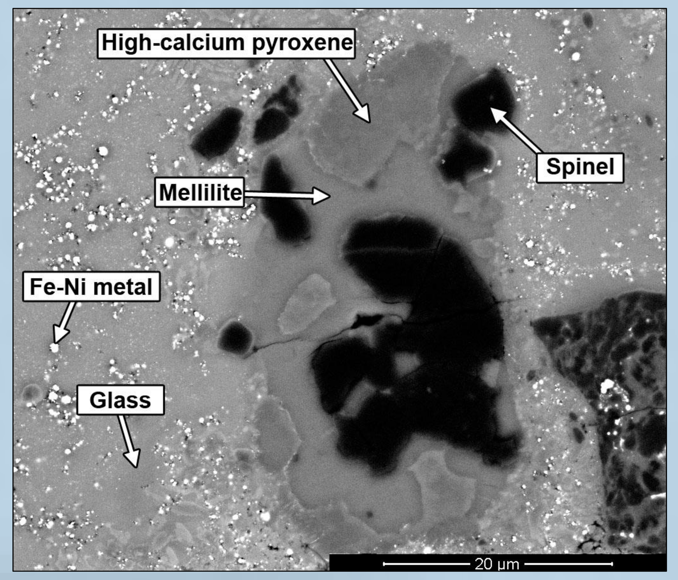


Figure 3b (left) Rapidly crystallized pyroxene grains abutting unmelted matrix and enclosing spinel from the partly melted CAI, in Leoville 3537-1. Like the skeletal olivines, these crystals do not show any evidence of deformation. Although the meteorites clearly were shocked, the undeformed crystals must have formed during, not before, the shock.

PARTIAL MELTING OF CAI

Figure 4a (right) this CAI fragment broke off of the CAI and was engulfed in the melted matrix. The rounded edges of this island indicate that it was 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).



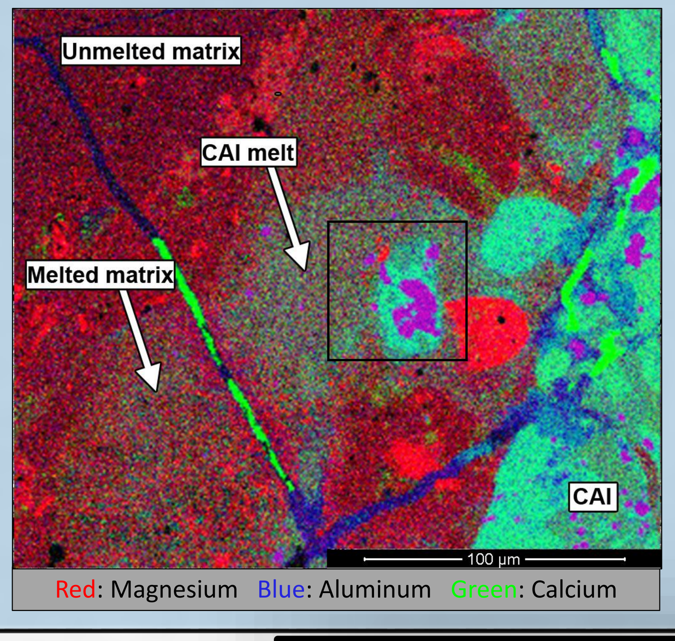
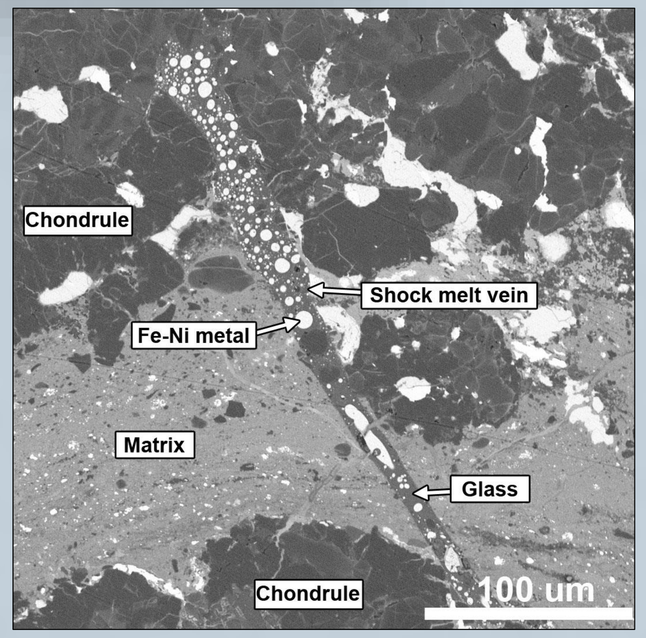


Figure 4b (left) This element distribution map encompasses the island shown in **Figure 4a** (black box). The glass near the CAI is high in calcium and aluminum, indicating this is melted CAI. In addition, spinel grains are found within the melt; if hot accretion were the reason for melting, the spinels would not have migrated out of the CAI.

SHOCK MELT VEINS IN CHONDRULES

Figure 5a (right) Shock vein found in Efremovka 27cE. Shock veins form when an impact creates a crack or opens an existing crack then fills it with molten material which rapidly cools into a glass. This is additional evidence for impact-induced melting in this meteorite.



HETEROGENEITY OF MELTING

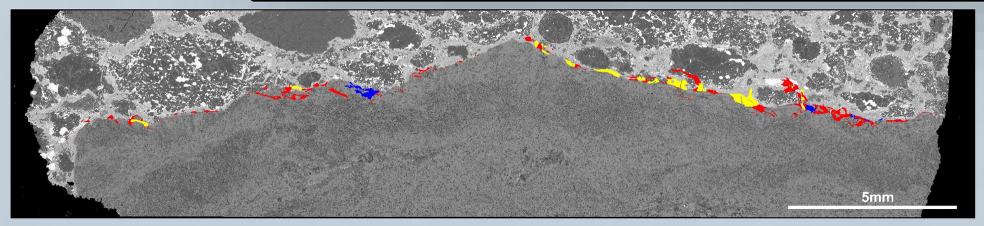
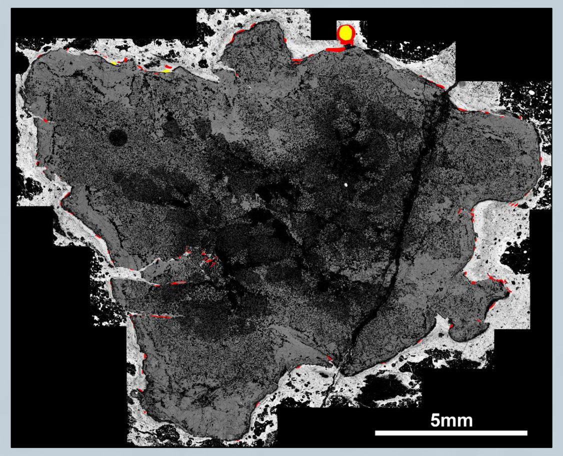


Figure 5c (below left) Efremovka 27cE also displays significant variability in melt distribution; all skeletal crystals are located along one edge of the CAI.

Figure 5b (above) Leoville 3537-1 shows melted matrix is concentrated in some areas and deficient in others. This indicates that melting was localized, as expected during shock melting.



Blue: sintered xals
Red: rounded sulfides
Yellow: skeletal xals

DISCUSSION

- The following evidence demonstrates that **melting has occurred** in the vicinity of two CAIs:
  - Pockets of glass that contain melt-grown crystals are found in and around the CAIs.
  - Iron sulfide and iron-nickel metal grains, normally irregular nuggets in the meteorite matrix, are rounded droplets in the putative melt zones. This indicates high temperatures that caused complete melting of the metal and sulfide.
- The evidence strongly indicates that the **melting is due to impact-induced shock**:
  - Skeletal and dendritic (branching) olivine and pyroxene crystals indicate very rapid crystal growth, which is a natural consequence of extremely brief and intense shock melting and cooling.
  - The melt zones are not themselves deformed, unlike the chondrules and CAIs in the meteorites. Had the melting occurred very early, during hot accretion, the later shock deformation of the meteorite would have deformed the melt zones. Melting must have occurred during, not before, the shock event.
  - Element maps reveal that some of the glass near the CAI is high in calcium and aluminum, indicating that the CAI has partially melted. In addition, spinel grains are found within the melt; if hot accretion were the reason for melting, spinels would not have migrated out of the CAI.
  - The melting is highly heterogeneous. This pattern of melting can be explained by a shock wave passing through a porous medium and melting localized regions. In hot accretion, melt would not surround the CAIs, as it does in 27cE; melt would occur homogeneously along the edge of the hot CAI.
  - One shock vein was found. Shock veins form when an impact creates a crack or opens an existing crack then fills it with molten material which rapidly cools into a glass.
- The CAIs appear to concentrate the effects of the shock, generating pockets of melt around their perimeters, possibly due to their large size relative to other objects in the meteorites. Almost all melt was found around the CAIs; very little was located around chondrules or in the matrix not adjacent to the CAI.

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REFERENCES

[1]Scott E.R.D. and Krot A.N. (2014). Chondrites and Their Components. Treatise on Geochemistry 2nd Edition. Elsevier Ltd. pp. 66-125.

[2]Caillet C., MacPherson G. J., Zinner E. K. (1993). Petrologic and Al-Mg isotopic clues to the accretion of two refractory inclusions onto the Leoville parent body: One was hot, the other wasn't. *Geochimica et Cosmochimica Acta* Vol. 57 p. 4725-4743.

MINERAL	FORMULA
Olivine	$Fe_2SiO_4 – Mg_2SiO_4$
Spinel	$MgAl_2O_4$
High-calcium pyroxene	$CaFeSi_2O_6 – CaMgSi_2O_6$
Plagioclase Feldspar	$NaAlSi_3O_8 – CaAl_2Si_2O_8$
Metal	Fe - Ni (much like magnet steel)
Sulfide	FeS with some Ni