DARK INCLUSIONS OF ALLENDE: EVIDENCE FOR NEBULA OR PARENT BODY PROCESSING?

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Introduction: Understanding the formation processes of key meteorite components, such as dark inclusions (DIs), allows for a more complete view of the host meteorites formation and evolution. Commonly found in the Allende CV3 chondrite, DIs are also observed in other carbonaceous chondrites. DIs are typically described as angular, irregular-shaped clasts that range in size from <1mm up to several centimeters [1].

Based on texture, DIs can be divided into four groups (A, A/B, B, and C, [2]), which vary in their abundance of matrix, chondrules, and fine-grained, fayalite-rich porous aggregates. These textural variations appear to represent a complex array of alteration stages [3-6].

The origin and subsequent processing of DIs is the subject of continuing debate. Various theories proposed suggest that DIs are: 1) aggregates of primary condensates that were metasomatised in the nebula [7-8]; 2) fragments of CV3 parent bodies which were processed to different degrees by reactions with the solar nebula gas prior to their incorporation into the host meteorites [1]; 3) fragments of a CV-like parent body that were aqueously altered and dehydrated locally on the parent body [e.g. 2, 3, 5].

We have combined data from three very different techniques in order to achieve a greater understanding of the formation and subsequent processing of DIs with regards the above models.

Methodology and Results: The techniques we applied to the dark inclusions of Allende were: microsource X-ray diffraction (XRD); electron backscatter diffraction (EBSD); and solution inductively coupled plasma – mass spectrometry (ICP-MS).

<u>XRD.</u> Microsource X-ray diffraction provides a quantitative modal mineralogy for fine grained components such as matrix and DIs. These two components are composed primarily of olivine, pyroxene and pentlandite. The data shows that Allende DIs and matrix form part of a mineralogical continuum (Fig. 1). The wider range in olivine compositions (Fo_{40-60} for matrix; Fo_{20-80} for DIs) coupled with the form in which pyroxene is found (augite in matrix; diopside in DIs) suggests that DIs have been processed to a greater degree than matrix [9].

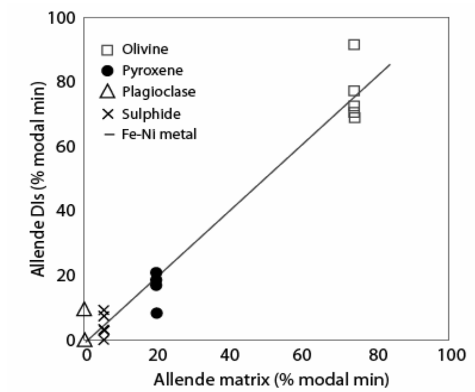

Fig. 1: Mineral abundances for 5 DIs plotted against average matrix mineralogy. The slope of the best fit line is 1.02, indicating that there is no difference in mineral abundance between matrix and DIs in Allende.

<u>EBSD.</u> Electron backscatter diffraction is a scanning electron microscopy technique which permits the measurement of the full crystallographic orientation of any point, allowing the quantification of fabrics in meteorites. EBSD analysis of fayalitic olivine grains in the matrix of Allende and its DIs reveals that the Allende matrix exhibits a three-dimenional planar fabric which persists throughout its DIs (Fig. 2) [10].

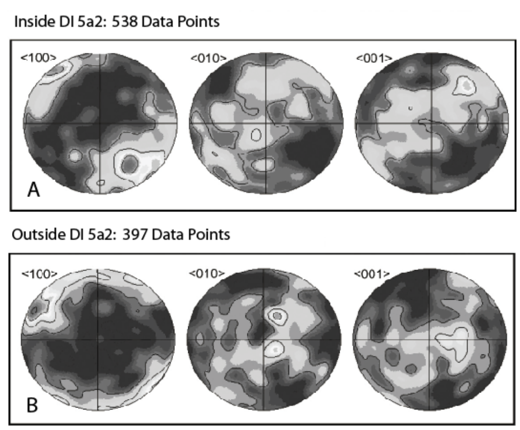

Fig. 2: Equal area, lower hemisphere pole figure plots for EBSD data from areas internal to and external to DIs. a) Pole figure plot for EBSD data obtained inside DI 5a2. b) Pole figure plot for EBSD data obtained outside of DI 5a2 (i.e. host Allende). Both figures a & b show the same short-axis alignment fabric orientation.

Solution ICP-MS. Dark inclusions have a composition similar to that of the bulk rock with regards major elements [11]. We have measured the absolute abundances for 28 trace and minor elements from sub-mg samples, as analysed via solution ICP-MS. This analysis reveals a DI composition enriched in refractory elements and depleted in moderately volatile elements relative to CI values. Matrix is typically regarded as the most similar component to DIs, yet this dataset shows that they differ greatly with regards to chemical composition, with DIs being enriched in refractory elements and depleted in volatile elements relative to matrix (Fig. 3).

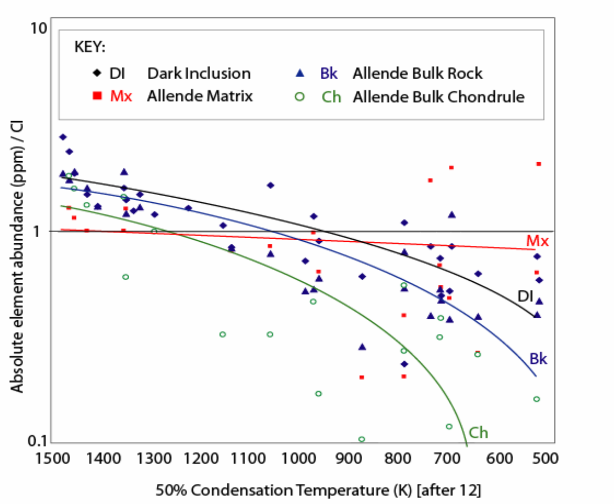

Fig. 3: Absolute element abundances collected via solution ICP-MS for Allende DIs, matrix, chondrules and bulk rock. All data is normalized to CI values and plotted against the element condensation temperature as defined by [12].

Discussion: The presence of a uniform, planar fabric throughout the matrix of Allende and its DIs (as evident from the EBSD analyses) is likely to be the result of gravitational compaction on the parent body. It would imply that this process has affected both Allende matrix and DIs, whilst the DIs were in their present orientation. This would suggest that DIs are unlikely to represent lithic fragments from another part of the asteroid that have experienced locallised aqueous alteration, dehydration and subsequent incorporation into the Allende host. If they were in fact fragments from another lithified part of the asteroid, we would not expect them to preserve the same fabric orientation as the material that surrounds them. In addition, both DIs and Allende matrix are highly porous (~25% [13]), and it is probable that their porosities were significantly greater prior to the deformational shortening, responsible for the fabrics we observe. Mobilising a highly porous DI during an impact brecciation event, without imposing a fabric, and incorporating it into a highly porous matrix, whilst maintaining high porosities in all of the affected materials, is improbable. Instead it is likely that DIs were processed in the nebula and accreted at the same time as the Allende matrix material, therefore experiencing the same mild, compactional events.

XRD data indicates that a mineralogical and chemical continuum exists between Allende matrix and DIs. In addition, the ICP-MS data reveals that DIs and matrix are compositionally very different. This can be interpreted as the result of a nebula condensation phenomenon or secondary processing of Allende matrix-like material. If the latter is the case then this would suggest that DIs are the product of a more processed/altered Allende matrix, therefore agreeing with the XRD data. The fact that aqueously mobile elements are not specifically affected may suggest a nebular, rather than a parent body location for this alteration.

Conclusions: By combining XRD, solution ICP-MS and EBSD analyses of Allende matrix and DIs we have provided a strong argument for a nebula location for the formation and secondary alteration of DIs. We can also infer that the primary, precursor material to DIs may have been Allende matrix-like material.

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