DARK INCLUSIONS: CLASTS OF CM-TYPE MATERIAL WITHIN ALLENDE. S. H. Gordon[1,2], S. J. Hammond[2], L. E. Howard[3], P. A. Bland[1]. [1]IARC, Dept. Earth Sci. & Eng., Imperial College, South Kensington Campus, Exhibition Road, London SW7 2AZ, UK (s.h.gordon05@imperial.ac.uk), [2]Dept. of Earth Sci., CEPSAR, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK. [3]IARC, Dept. Min., Natural History Museum, London SW7 5BD, UK.

Introduction: Dark inclusions are irregular, cm-sized clasts of fine grained material found within chondrites such as Allende. They can be classified into 4 groups (A, A/B, B, and C) based primarily on the presence of components such as small scale chondrules [e.g. 1-2]. Alteration is prevalent with many dark inclusions being composed entirely of secondary minerals [3] and often surrounded by a complex, three-layered rim [4]. Any record of the dark inclusion precursor has been masked by this complex alteration. Investigation of the trace and minor element signature of these components allows an insight to the precursor dark inclusion characteristics together with an indication of where and when – be it nebula or parent body – the subsequent alteration took place.

Origin(s) of dark inclusions: Theories on the origin and subsequent processing of dark inclusions postulate that they may be anything from aggregates which accreted and were subsequently processed within the nebula [e.g. 5-6] to fragments of CV3 parent bodies processed to a different extent to that of the surrounding host rock [e.g. 1-2, 7-8]. Problems arise when attempting to explain the variation in dark inclusion lithologies via a nebula origin, whilst a CV clast origin does not explain issues such as why dark inclusion components are so much smaller than those located in the surrounding host rock.

Alteration of dark inclusions: All CV3's have been altered. Dark inclusions within these rocks also display evidence for extensive alteration. Chondrule pseudomorphs [9], fibrous fayalitic olivine thought to be representative of dehydrated phyllosilicates [1], and extensive secondary mineralogy [10], are all indicative of aqueous alteration. This observation is supported by evidence for the movement of fluids by the presence of nepheline veins [11], together with a depletion in 16O relative to the surrounding meteorite [2]. Evidence for heating is also prevalent in the form of Ca, Fe-rich aggregates (CFA's) [e.g. 12], and high temperature rims [4] (which indicate heating too great to have occurred within the Allende parent body [13]). Where and when this alteration took place is still debated.

The determination of trace and minor element absolute abundances (ppm) from selected dark inclusions of Allende allows for the extent of element movement by fluids (ie. aqueous alteration) to be assessed, together with the composition of Allende dark inclusion precursor to be found.

Methods: 10 samples taken from 4 Allende dark inclusions were picked by hand using a tungsten-carbide mill tip, viewed through a reflected light microscope. Each sample was weighed in a pre-cleaned aluminium-foil weighing vessel using a 5 figure Sartorius ultra-micro balance before being transferred to a 25ml Teflon beaker. Typical HF : HNO_3 digestion followed, including an additional HCl stage to account for any unwanted fluorides which may have formed during the HF dry-down. Each sample was diluted by ~2,000 fold with 2% UPA HNO_3 prior to being analysed with a quadrupole Agilent 7500s ICP-MS, housed at the Open University, Milton Keynes.

Results: Data corresponds well with published literature and has good reproducibility. Each dark inclusion shows a degree of individuality, however, when plotted in order of increasing volatility and normalized to CI values, most show a steady refractory element pattern until Sr at which point they begin to deplete in abundance.

The element composition determined for dark inclusions is very different to that of the other components found within Allende (e.g. Chondrules, CAI's, matrix) [14] and is remarkably different to that of Allende bulk.

Discussion: The trace and minor element abundances determined here for Allende dark inclusions most closely resemble those abundances defined for CM bulk meteorites (see Fig. 1). A CM-type material can therefore be proposed as the precursor for Allende dark inclusions.

CM meteorites and dark inclusions do differ in composition for some elements, however the majority of these can be explained through various episodes of aqueous and thermal alteration.

CM-like xenoliths have been reported within a range of meteoritic groups [e.g. 15-16] and have been linked to dark inclusions within other CV meteorites such as Leoville.

Oxygen isotopes also support this finding with dark inclusions of Allende lying on the peripheries of Allende and CM bulk determinations on a three isotope plot ($\delta^{18}O$ versus $\delta^{17}O$) [e.g. 2].

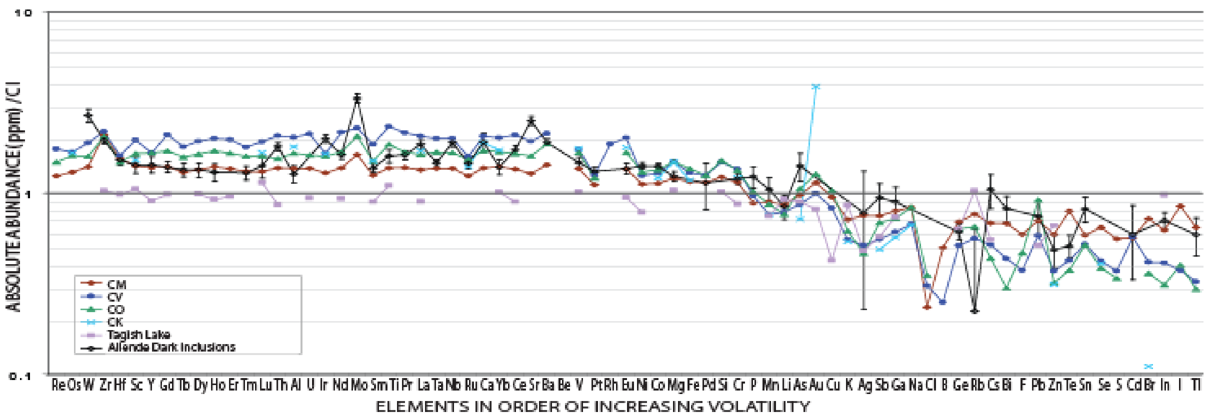

Fig.1 Comparison of trace and minor element abundances for bulk carbonaceous chondrites normalised to CI. CM; CV; and CO bulk compositions determined via INAA and obtained from Wasson and Kalleymeyn (1988). CK bulk composition determined via INAA as reported in Kalleymeyn et al. 1990. Tagish lake matrix composition was obtained via LA-ICP-MS as reported by Bland et al. 2005.

Components such as chondrules located within dark inclusions and CM meteorites are of a similar size range (~100µm in diameter). The appearance of these components and interstitial texture is very different however, with the dark inclusions displaying evidence of high levels of alteration and mineral replacement.

Dark inclusion alteration: Previous studies have shown prolific aqueous alteration within dark inclusions [e.g. 1]. However, there is little compositional evidence for exchange of aqueously mobile elements between dark inclusion and surrounding matrix. Deviations in abundances of aqueously mobile elements such as Ca, Sr, and Ba from CM composition are noted in the dark inclusions, but these are not mirrored by corresponding depletions of these elements in the surrounding Allende matrix.

CM matrix is abundant in phyllosilicates which is in contrast to the dominantly lath shaped fayalitic olivine matrix found within Allende dark inclusions. If the dark inclusions were indeed CM in origin, dehydration of these phyllosilicates must have taken place at some point in their history. The lack of exchange of aqueously mobile elements between matrix and dark inclusions seen in this trace and minor element study suggests that dehydration took place prior to the incorporation of dark inclusions within the Allende host rock. This finding supports the discrepancy in I-Xe ages determined for dark inclusions and components within the surrounding host rock [3], which implied that the age recorded for dark inclusions was not reset by aqueous alteration recorded by the remainder of the host rock components.

The lath-shaped fayalitic olivine grains of the dark inclusions are intergrown with those of the host matrix. This implies that some fayalitic olivine growth must have taken place after the two components had come into contact. Compression of the dark inclusion and surrounding host rock post lithification is also likely, allowing the uniform planar fabric within the dark inclusions and surrounding matrix to form [17]. This subsequent alteration of the Allende host serves to mask some of that which occurred pre-lithification of the CM-type material dark inclusion.

Conclusions: Dark inclusions located within chondrites such as Allende (CV3) have a very similar trace and minor element composition to that of the CM meteorites. This not only implies that dark inclusions were initially CM-type material, but that this material was present in the solar nebula prior to that of Allende. The majority of the aqueous and thermal alteration necessary to transform the CM-type material into Allende dark inclusions appears to have taken place prior to their incorporation into the host body.

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