Oxygen isotope variation in CV and CR dark inclusions and chondrules: Evidence for a possible genetic relationship between CV3 dark inclusions and CM chondrites

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Carbonaceous chondrites comprise a complex assemblage of components (e.g. calcium aluminium-rich inclusions (CAIs), amoeboid olivine aggregates (AOAs), multiple generations of chondrules, dark inclusions (DIs) and matrix) which formed in unique environments early in Solar System history [e.g. 1]. The study of such components has the potential to furnish a wealth of important information about conditions that prevailed in the first few million years of Solar System evolution. However, secondary processes, such as thermal metamorphism and aqueous alteration, that likely took place on asteroidal parent bodies, have obscured, to a variable extent, these earliest signatures. Here we discuss the results of an oxygen isotope and mineralogical study of chondrules and dark inclusions in CV3 and CR2 chondrites. The principal aim of this study was to determine, as precisely as possible, the respective slopes of the oxygen isotope lines for these components, in order to disentangle their nebular and parent body histories.

Intact chondrules were extracted from whole-rock fragments of Allende (CV3) (n=32) and LAP 02342 (CR2) (n=13) using stainless steel tools. Material from DIs was analysed from the following meteorites: Allende (CV3ox-A) (n=12), Efremovka (CV3reduced) (n=1) (DI E-80), MIL 090001 (CR2) (n=2). Backscattered electron (BSE) imaging and energy dispersive X-ray spectrometry (EDS) on Allende chondrules, LAP 02342 chondrules and MIL 090001 DIs was undertaken at the Open University using an FEI Quanta 200 3D SEM. Electron microprobe analysis of Allende DIs was undertaken at the Johnson Space Center. Oxygen isotopic analysis of chondrules, DIs and bulk samples of LAP 02342 and MIL 090001 was carried out at the Open University (OU) using an infrared laser fluorination system [2, 3].

DIs from four CV3s were analysed in this study (Allende, NWA 2140, NWA 2364, Efremovka). Samples from Allende cover all categories of the four-fold DI classification scheme [4, 5] (inclusion numbers analysed in brackets). Type A clasts (1a1, 4b1, 25s-1-tw1) contain chondrules, inclusions and matrix, but are significantly finer grained than normal Allende material. Type A/B clasts (MZB, AMHH 4301) are transitional between Types A and B. Type B clasts (12b1, All-AF) contain opaque matrix and olivine-rich aggregates and may have experienced a hydration-dehydration cycle [6]. Type C clasts (5a1, ekpb4b1, MZ15, USNM 3876) consist of fine-grained, opaque material similar to Allende matrix. DI material from NWA 2140 analysed for this study is Type A/B and that from NWA 2364 is Type A. Phyllosilicates in DIs from CV3 reduced subgroup chondrites are more abundant than in Allende DIs, in which they are rare. Only one inclusion from a reduced CV3 was analysed as part of this study. The petrography of E-80 from the Efremovka chondrite is described in detail by [7]. Material from two cm-sized DIs in the CR2 chondrite MIL 090001were also analysed in this study. Chondrules extracted from Allende show a diverse range of textures, with porphyritic olivine and porphyritic olivine pyroxene types being particularly well represented. Chondrules extracted from LAP 02342 are predominantly coarse-grained Mg-rich olivine and pyroxene-bearing types. The majority of the chondrules in LAP 02342 contain abundant grains of sub-angular to sub-rounded Ni-poor metal (Ni contents 5 to 6 wt %).

Allende DIs analysed in this study plot on a well-defined linear trend, which has a slope and y axis intersect given by $y = -4.22 + 0.87x$ ($R^2 = 1.00$) and therefore somewhat shallower in slope than the CCAM line, which can be defined as $y = -4.08 + 0.94x$. With respect to mineralogical types A, A/B and B, there appears to be no consistent trend with oxygen isotope composition. In contrast, type C DIs show relatively restricted variation with respect to their oxygen isotope compositions. DIs from the CV3 reduced subgroup (data: [8] and this study: E-80) are shown in Fig. 1 in relation to the combined DI data for Allende ([8] and this study). Reduced CV3 DIs define a distinct linear trend in Fig. 1 with a shallower slope than the Allende DIs. The slope and y axis intercept of the reduced CV3 DIs is given by $y = -3.97 + 0.76x$ ($R^2 = 0.98$). Also shown in Fig. 1 are analyses for CM2 falls (data: [8]; Met. Bull. 85), which define a trend with a similar slope to that of the reduced CV3 DIs.

In contrast to Allende DIs, Allende chondrules define a steeper slope than the CCAM line (Fig. 2). Our Allende chondrule data are compared with that of [9, 10] in Fig. 2. It was pointed out by [9] that barred chondrules in Allende appear to plot on a distinct trend compared to that of the porphyritic chondrules, having oxygen isotope compositions that deflect towards the ordinary chondrites (not shown in Fig. 2). Support for this observation comes from this study with barred olivine chondrules ("sub-TFL") plotting away from the main chondrule trend (Fig. 2). If the barred chondrule data in the studies of [9, 10] are excluded, the remaining analyses have a slope and y axis intercept of $y = -3.61 + 0.98x$ $R^2 = 0.97$. This is essentially indistinguishable from that given by our data: $y = -3.60 + 0.96x$ $R^2 = 0.98$, again excluding three barred chondrule analyses

that plot close to the TFL (Fig. 2). As is clear from Fig. 2, chondrules from Allende plot between the CCAM and PCM (Primitive Chondrule Minerals) [10] lines, which is broadly consistent with chondrule mesostasis having been affected by secondary alteration. Analyses of separated chondrules from the LAP 02342 (CR2) chondrite display a well-developed linear trend with a slope and y axis intercept given by y = -2.84 + 0.99x R^2 = 0.89, which is essentially coincident with PCM line [11]. Bulk analysis of LAP 02342 and DIs from MIL 090001 (CR2) also plot close to the PCM line. These relationships suggest that both LAP 02342 and MIL 090001 have experienced very low degrees of secondary alteration.

In contrast to the CR2 DIs, oxygen isotope analyses of CV3 DIs show evidence for a complex sequence of thermal and aqueous alteration processes. In particular, Allende DIs define a more limited and steeper trend than DIs from the less altered CV3 reduced samples (Fig. 1). Paradoxically, CV3 reduced DIs appear to preserve clearer evidence of aqueous alteration than DIs from the more heavily altered Allende meteorite. Analysis of organic matter suggests that the CV3 chondrites experienced a significant range in thermal metamorphism, with Allende graded >3.6 and Efremovka, Leoville and Vigarano 3.1 to 3.4 [12]. One possibility is that the more intense thermal metamorphism experienced by Allende resulted in relatively rapid expulsion of pore fluid and hence less intense hydrothermal alteration than CV3reduced DIs. However, this appears to be at odds with mineralogical observations from Allende DIs indicating that they experienced prolonged aqueous alteration and dehydration [13]. Such processes would have produced heavy oxygen isotope shifts [14], which are not seen in the Allende DIs. One possibility is that following hydrothermal alteration these DIs experienced a phase of partial oxygen isotope re-equilibration after their emplacement within heated Allende matrix.

The CV3 reduced DIs also show a possible genetic link to CM2 chondrites. The best fit line through the CV3 reduced DIs is close to that defined by CM fall data [8] (Fig.1), suggesting either a close similarity in the aqueous alteration processes that took place on their respective parent bodies, or possibly that both are derived from the same parent body.

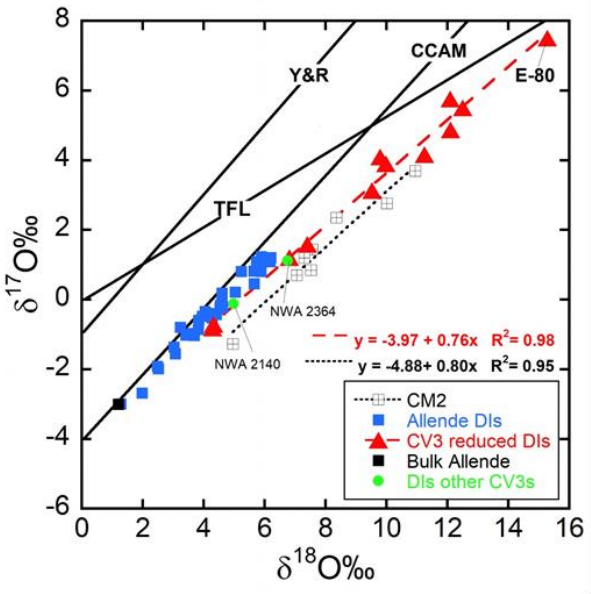

Fig.1 Oxygen isotopic composition DIs in CV3 chondrites

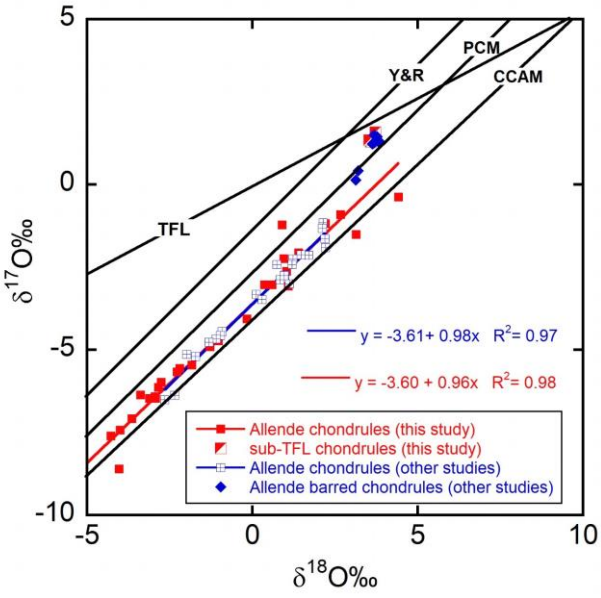

Fig 2 Oxygen isotopic composition of Allende (CV3) chondrules

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