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## The origin and significance of the CCAM line: Evidence from chondrules and dark inclusions in Allende (CV3)

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**THE ORIGIN AND SIGNIFICANCE OF THE CCAM LINE: EVIDENCE FROM CHONDRULES AND DARK INCLUSIONS IN ALLENDE (CV3).** R. C. Greenwood<sup>1</sup>, I. A. Franchi<sup>1</sup>; M. E. Zolensky<sup>2</sup>, P. C. Buchanan<sup>3</sup>. <sup>1</sup>Planetary and Space Sciences, The Open University, Milton Keynes MK7 6AA, UK (r.c.greenwood@open.ac.uk). <sup>2</sup>ARES, Johnson Space Center, Houston TX, USA. <sup>3</sup>Kilgore College, Kilgore, Texas 75662 USA.

**Introduction:** The process responsible for the mass independent oxygen isotope variation observed in Solar System materials remains poorly understood. While self-shielding of CO, either in the early solar nebula [1,2], or precursor molecular cloud [3], appears to be a viable mechanism, alternative models have also been proposed [e.g. 4].

An important aspect of this problem relates to the interpretation of various reference lines on oxygen three-isotope diagrams. The Carbonaceous Chondrite Anhydrous Mineral (CCAM) line, derived predominantly, but not exclusively, from analyses of components in the Allende (CV3) meteorite, is the most widely used reference and has a slope of  $0.94 \pm 0.01(2\sigma)$  [5,6]. However, the fundamental significance of the CCAM line has been questioned by [7]. Based on the results of a UV laser ablation study of an Allende CAI, it was suggested that a line of exactly slope 1 was of more fundamental significance. As pointed out by [7], almost all Solar System materials, with the exception of the R chondrites, plot to the right of the slope 1 line. This variation could be explained if the primitive oxygen isotope composition of the Solar System was represented by a line of exactly slope 1, with subsequent mass fractionation, or isotopic exchange, shifting compositions to the right [7]. The fact that a highly  $^{17,18}\text{O}$ -enriched phase ( $\delta^{18}\text{O}$  and  $\delta^{17}\text{O} \sim +180\text{‰}$ ) within the matrix of the primitive chondrite Acfer 094 plots on the extension of the slope 1 line lends additional support to the primordial significance of this reference line [8]. With the aim of understanding the relationship between the CCAM and other reference lines we have undertaken a detailed study of chondrules and dark inclusions (DIs) from Allende.

**Materials and methods:** As part of this study intact chondrules (n=30) were extracted from Allende (CV3) whole-rock fragments under a binocular microscope. Adhering matrix was abraded from the chondrules using stainless steel tools. Material from well characterized Allende DIs (n=11) have also been analyzed. Preliminary results of the DI work were reported in [9]. In addition to Allende DIs, we have also analyzed material from the Efremovka (CV3reduced) inclusion E-80 [10].

Oxygen isotope analysis was performed by infrared laser-assisted fluorination [11]. All analyses were obtained on untreated whole rock samples (~2 mg). Sys-

tem precision, as determined by replicate analyses of our internal obsidian standard, is:  $\pm 0.05\text{‰}$  for  $\delta^{17}\text{O}$ ;  $\pm 0.09\text{‰}$  for  $\delta^{18}\text{O}$ ;  $\pm 0.02\text{‰}$  for  $\Delta^{17}\text{O}$  ( $2\sigma$ ).

**Results:** Allende DIs plot on a well-defined linear trend with a somewhat shallower slope than the CCAM line [9] (Fig. 1). The Allende DI analyses of [6] plot on a similar trend (Fig. 1). Compared to Allende DIs, inclusions from the CV3 reduced subgroup define a shallower slope (Fig. 2) (All analyses [6, 10], except E-80 (this study)). This trend is similar to that seen in CM2 chondrites (Fig. 2), to which DIs have sometimes been compared [12].

In contrast to the DIs, Allende chondrules (Fig. 3) plot to the left of the CCAM line. This feature is also seen in the Allende chondrule data of [13]. If the small cluster of chondrules plotting close to the TFL are excluded, the remaining points define a distinct linear array ( $y = -3.45 + 1.01x$   $R^2 = 0.98$ ) between the CCAM and PCM lines [14,15] (Fig. 3).

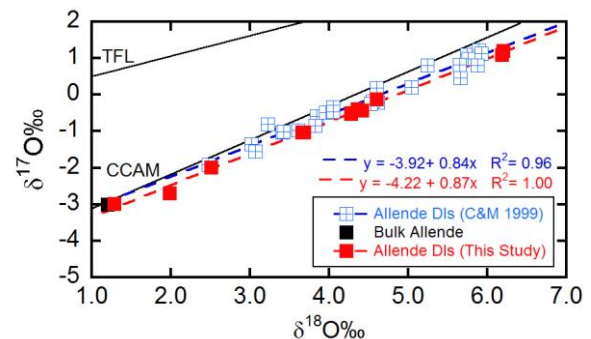


Fig. 1 Oxygen isotopic composition of Allende DIs.

**Discussion:** In its original formulation the CCAM line was calibrated using analyses not only from Allende CAIs, but also Allende chondrules and dark inclusions [5]. In addition, a limited number of analyses of non-Allende carbonaceous chondrite components were also included [5]. The CCAM line includes materials with distinct formational and secondary histories. It is therefore not surprising that individual components in Allende, such as chondrules and dark inclusions, will display systematic deviations from it.

DI analyses from Allende present an interesting paradox in that they define a more limited and steeper trend than is displayed by inclusions from the less altered CV3 reduced samples (Fig. 2). Thus, CV3 reduced DIs appear to preserve clearer evidence of aque-

ous alteration than those 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 [16]. 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 CV3-reduced DIs. However, this is at odds with mineralogical observations from Allende DIs which suggest that they experienced prolonged aqueous alteration and dehydration [17, 18, 19], processes that would have produced heavy oxygen isotope shifts [20, 21]. It appears more likely that following hydrothermal alteration Allende DIs experienced a phase of partial oxygen isotope reequilibration.

There is growing evidence that chondrules from relatively pristine carbonaceous chondrites (Afer 094, MET 00426 and QUE 99177) define a distinct trend termed the PCM line, that lies between the CCAM and Y&R lines (Fig. 3) [14, 15]. Compared to the PCM line essentially all of the chondrules in Allende are shifted to the right on an oxygen three-isotope diagram (Fig. 3). This may reflect mass fractionation in response to secondary alteration [7].

**Conclusions:** Allende chondrules and DIs demonstrate that the CCAM line, while useful for reference purposes, is not of primary significance. In agreement with previous studies, we conclude that the primary oxygen isotope distribution is better represented by a line of steeper slope than the CCAM [7]. However, this does not preclude the possibility that multiple slope 1 lines may be valid. And raises the question as to what is controlling the slope of these different mixing lines. Additional detailed work using components from pristine samples is required to evaluate further the processes that produced the mass-independent oxygen isotope variation observed in early Solar System materials.

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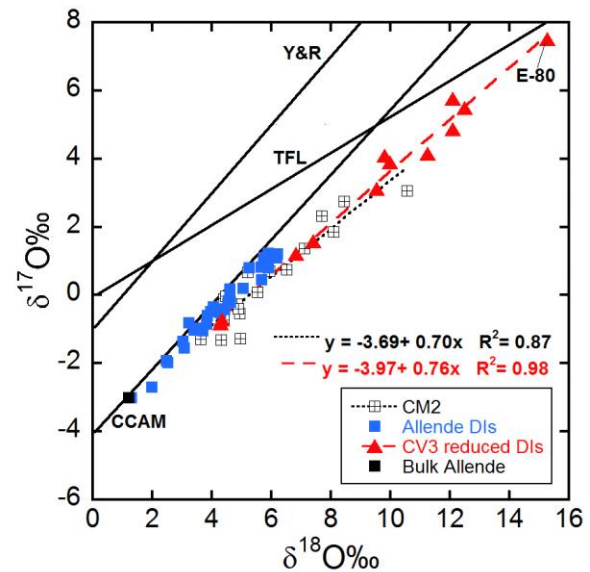


Fig. 2 Oxygen isotopic composition of Allende DIs (This study) [6]; CM2 falls and finds (all data OU); CV3 reduced DIs [6, 10] (E-80: this study).

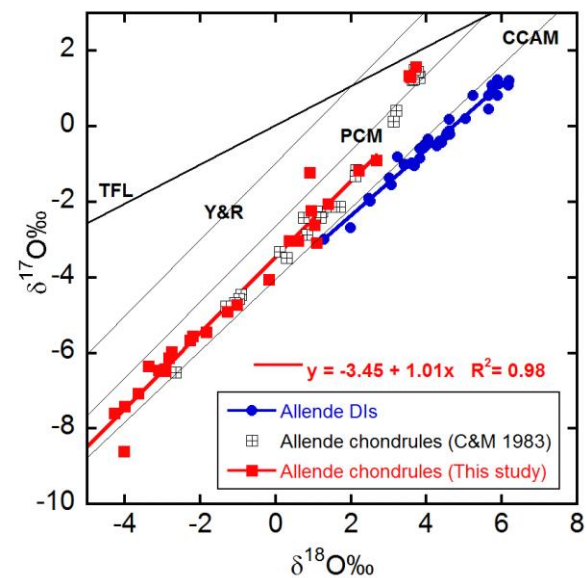


Fig. 3 Oxygen isotopic composition of Allende chondrules and DIs. PCM = Primitive Chondrule Minerals line [14, 15].