

## THE SIGNIFICANCE OF SLOPE 1 VARIATION IN EARLY SOLAR SYSTEM SOLIDS

R. C. Greenwood<sup>1</sup>, I. A. Franchi<sup>1</sup>, C. M. O'D. Alexander<sup>2</sup>, M. E. Zolensky<sup>3</sup>, P. C. Buchanan<sup>4</sup> <sup>1</sup>The Open University, Milton Keynes MK7 6AA, UK (Email: r.c.greenwood@open.ac.uk), <sup>2</sup>DTM, Carnegie Institution, Washington DC 20015, USA <sup>3</sup>ARES, Johnson Space Center, Houston TX, USA. <sup>4</sup>Kilgore College, Kilgore, Texas 75662 USA.

**Introduction:** As originally demonstrated by Clayton and co-workers, primitive meteorites and their components commonly display mass-independent oxygen isotopic variation [1-3]. As a tool to understand this behaviour, a number of reference lines have been defined, with slopes of  $\sim 1$  [2-5]. The Carbonaceous Chondrite Anhydrous Mineral (CCAM) line, derived predominantly from analyses of components in the Allende (CV3) meteorite, is the most widely used reference and has a slope of  $0.94 \pm 0.01(2\sigma)$  [2,3]. However, the fundamental significance of the CCAM line has been questioned [4]. Based on the results of a UV laser ablation study of an Allende CAI, it was suggested that a line of exactly slope 1 (Y&R line) was of more fundamental significance [4]. SIMS analysis of chondrules from primitive CRs and related chondrites define a third, distinct slope 1 line, known as the Primitive Chondrule Minerals (PCM) line [5,6]. Here we discuss the results of bulk oxygen isotope analysis of CO, CV and CR chondrites and various separated components, with the aim of better understanding the origin of slope 1 behaviour in early Solar System materials.

**CV chondrites and dark inclusions:** Allende dark inclusions (DIs) plot on a well-defined linear trend with a slightly shallower slope than the CCAM line [7]. Compared to Allende DIs, inclusions from the CV3 reduced subgroup plot define a shallower trend similar to that seen in CM2 chondrites. Thus, DIs in the less altered CV3 reduced subgroup preserve clearer evidence for aqueous alteration than those from the more thermally altered Allende meteorite. Analysis of organic matter suggests that Allende has a metamorphic grade  $>3.6$ , whereas Efremovka, Leoville and Vigarano are 3.1. to 3.4 [8]. In contrast to the DIs, Allende chondrules plot to the left of the CCAM line [7,9]. Thus, oxygen isotope analyses of Allende chondrules and DIs indicate that the CCAM line may not be of primary significance [4,7]; a conclusion supported by SIMS data for chondrules from Kaba (CV3) [10].

**CO chondrites:** Based on a range of parameters (presolar silicate contents, bulk H, C and N abundances, C and H isotopic compositions), a small group of Antarctic CO3s have been identified as amongst the most primitive meteorites yet recognized [11,12]. In particular, DOM 08006 has the highest matrix-normalized presolar silicate abundance of any chondrite so far studied [11]. However, Antarctic meteorites, including COs, have experienced variable degrees of terrestrial weathering [13]. Antarctic COs are displaced from the CCAM line due to exchange with Antarctic precipitation, whereas CO3 falls plot on it. The effects of this alteration can be mitigated using a leaching treatment. Following leaching, Antarctic COs define an array along the CCAM line, but displaced to more  $^{16}\text{O}$ -rich compositions relative to falls [12]. These relationships might be interpreted to suggest that the CCAM line has primary significance. However, this seems unlikely in view of the CV3 DI and chondrule data. However, it is possible that multiple slope 1 lines are required to define the primordial composition of early Solar System materials.

**CR chondrites:** SIMS analysis of chondrules from various CR and ungrouped chondrites indicate that the PCM line may be of primary significance [5,6]. Laser fluorination analysis undertaken at the Open University on separated chondrules from the CR chondrite LAP 02342 define a trend which is coincident with the PCM. In addition, bulk analyses of DIs from MIL 090001 (CR2) also plot close to the PCM, as do DIs from the H3 ordinary chondrite Sharps. However, at the  $^{16}\text{O}$ -rich end of the CR mixing line [14] whole-rock compositions diverge from the PCM line towards the Y&R line. In contrast, chondrules within the same samples plot on the PCM line (e.g. QUE 99177). We are currently investigating this feature, which may reflect Antarctic weathering, in a similar manner to the COs.

**Conclusions:** Understanding the process(es) that resulted in oxygen isotope mass independent variation in Solar System materials remains a fundamental problem in planetary sciences. There is no doubt that reference lines such as the CCAM [2,3], Y&R [4] and PCM [5] are useful tools in this endeavour. However, whether a unique slope 1 line can be used to define the primordial oxygen isotope variation in early Solar System materials remains unclear.

**References:** [1] Clayton R. N. et al. (1973) *Science* 182, 485-488. [2] Clayton R. N. et al. (1977) *Earth and Planetary Science Letters* 34, 209-224. [3] Clayton R. N. and Mayeda T. K. (1999) *Geochimica et Cosmochimica Acta* 63, 2089-2104. [4] Young E. D. and Russell S. S. (1998) *Science* 282, 452-455. [5] Ushikubo T. et al. (2012) *Geochimica et Cosmochimica Acta* 90, 242-264. [6] Tenner T. J. et al. (2015) *Geochimica et Cosmochimica Acta* 148, 228-250. [7] Greenwood R. C. et al. (2016) LPSC 42, abstract #2153. [8] Bonal L. et al. (2006) *Geochimica et Cosmochimica Acta* 70, 1849-1863. [9] Clayton R. N. et al. (1983) in *Chondrules and their origins* LPI, 37-43. [10] Hertwig A. T. et al. (2018) *Geochimica et Cosmochimica Acta* 224, 116-131. [11] Nittler L. R. et al. (2013) LPSC 44, abstract, #2367. [12] Alexander C. M. O'D. et al. (2018) *Geochimica et Cosmochimica Acta* 221, 406-420. [13] Brearley A. J. In *Treatise on Geochemistry* (Second Edition) Elsevier (2014). [14] Schrader D. L. et al. (2011) *Geochimica et Cosmochimica Acta* 75, 308-325.