

**A COMMON SOURCE OF REFRACTORY INCLUSIONS IN DIFFERENT CARBONACEOUS CHONDRITE CLASSES? INSIGHTS FROM TITANIUM ISOTOPIC SIGNATURES.** J. Render, G.A. Brennecke, S. Ebert, C. Burkhardt and T. Kleine, Institut für Planetologie, University of Münster, Wilhelm-Klemm Str. 10, 48149 Münster, Germany (jan.render@wwu.de)

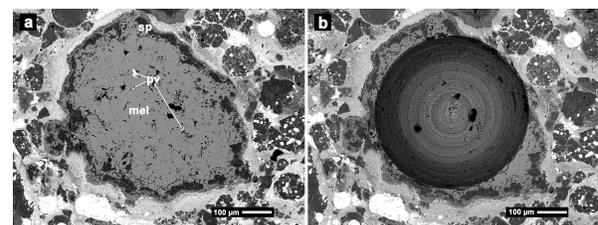
**Introduction:** As the first solids to form from a gas of solar composition, Ca-Al-rich inclusions (CAIs) are prime samples to investigate the earliest stage of our Solar System. Previous studies have shown that ‘normal’ CAIs—*i.e.* excluding hibonite-rich grains like PLACs and SHIBs and the enigmatic population of FUN-CAIs—display distinct and broadly uniform nucleosynthetic isotope anomalies in a variety of elements relative to later formed meteoritic components and terrestrial standards (see review by [1]). However, because meteorites of the CV class tend to have the highest abundances and largest sizes of normal CAIs (hereafter just referred to as ‘CAIs’) there has previously been an overwhelming bias towards isotopic information about CAIs from this group, and in particular the chondrite Allende. This begs the question whether CAIs from CV chondrites are indeed representative for those of other chondritic meteorites and whether all CAIs derive from one single reservoir of the protoplanetary disk. Recently, this issue was addressed by investigations of nucleosynthetic isotope signatures in a couple of CAIs from CK chondrites [2-4], that exhibit isotopic compositions indistinguishable from CV CAIs. However, with the exception of the aforementioned FUN-CAIs [1] and hibonite-rich objects in CM chondrites [5-6], nucleosynthetic isotope anomalies of refractory inclusions from any other chondrite class remain largely unexplored. Here, we aim to better constrain the isotopic signature of CAIs from the CO chondrite class. The considerably smaller size compared to their analogs from CV chondritic meteorites requires the element of interest to be present in wt% levels, making titanium (Ti) an attractive target for the type of study. Furthermore, Ti has five stable isotopes ( $^{46}\text{Ti}$ ,  $^{47}\text{Ti}$ ,  $^{48}\text{Ti}$ ,  $^{49}\text{Ti}$ , and  $^{50}\text{Ti}$ ), that are formed in different nucleosynthetic environments, potentially providing additional information about the origin of nucleosynthetic isotope anomalies in CAIs.

Previous investigations of the Ti isotopic composition of CAIs from CV chondrites have reported consistently positive anomalies in the neutron-rich isotope  $^{50}\text{Ti}$ , covering a range from roughly 2 to 14  $\epsilon$  (parts per ten thousand relative to terrestrial), with a main peak at  $\sim 9 \epsilon$  [7-8]. Interestingly, these excesses appear to be correlated with less pronounced anomalies in the neutron-poor isotope  $^{46}\text{Ti}$  in both CAIs [7] and in other Solar

System materials [9-10]. In a previous study, we presented  $^{50}\text{Ti}$  isotope data for two CO CAIs [11], whereas here, we investigate a more extensive set of CAIs from different CO chondrites and also report the first  $\epsilon^{46}\text{Ti}$  isotopic signatures for such samples.

**Methods:** Ten CAIs from five different CO3 chondrites (DaG 005, DaG 025, DaG 027, DaG 083 and NWA 2187) with diameters of several hundred  $\mu\text{m}$  were identified and characterized using a JEOL 6610-LV SEM at the University of Münster. The CAIs consist primarily of melilite with additional Mg-rich spinel, Ca-rich pyroxene, perovskite, and occasional fassaite and anorthite. Following the method of [12], these CAIs were removed using a *New Wave Research Micro Mill*. Digestion ensued in  $\text{HNO}_3$ -HF and subsequently in aqua regia. This sample set was accompanied by the terrestrial rock standard BCR-2 following the same digestion and chemical procedures.

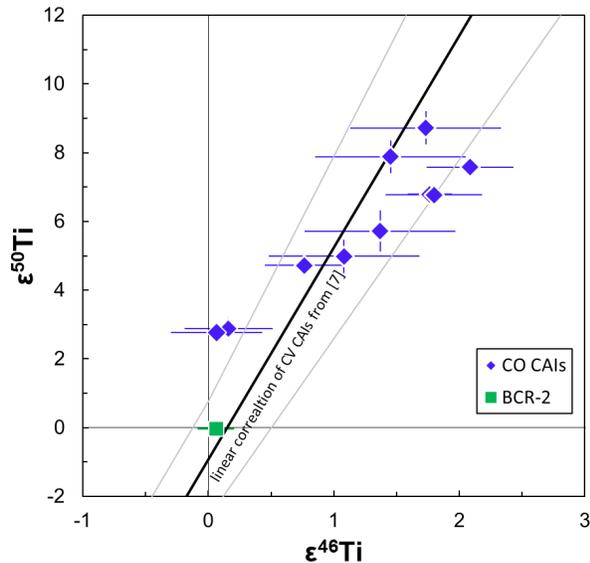
Chemical purification of Ti was achieved using a two-stage ion exchange chromatography following the method of [13] and measurements were performed as outlined in [14], using the Neptune Plus MC-ICPMS in Münster and internally normalizing to  $^{49}\text{Ti}/^{47}\text{Ti} = 0.749766$ . Procedural blanks from this wet chemistry treatment are usually  $\approx 5 \text{ ng Ti}$  [13-14]. Due to limited total Ti contents of the CAIs, solutions were measured at 100 ppb, resulting in an external reproducibility of  $\pm 0.6$  and  $\pm 0.5$  for  $\epsilon^{46}\text{Ti}$  and  $\epsilon^{50}\text{Ti}$ , respectively. Due to a more severe Ca interference on mass 48 than mass 46, we are unable to reliably report  $\epsilon^{48}\text{Ti}$  in all samples, however, anomalies in  $^{48}\text{Ti}$  are generally less pronounced and more difficult to resolve even under ideal sample conditions [7].



**Figure 1:** Secondary electron image before (a) and after (b) the drilling procedure of one CAI sample. mel: melilite; pv: perovskite; sp: spinel

**Results:** As expected, values for both  $\epsilon^{46}\text{Ti}$  and  $\epsilon^{50}\text{Ti}$  are in agreement with previously published work on the terrestrial basalt standard BCR-2, with  $0.06 \pm 0.15$ , and  $-0.02 \pm 0.10$ , respectively. In contrast,

all CAIs from CO chondrites investigated here show clearly resolved positive anomalies in  $^{50}\text{Ti}$ , ranging from 2.8 to 8.7  $\epsilon$ -units. Additionally, eight out of ten CAIs show resolved anomalies for  $\epsilon^{46}\text{Ti}$ , covering a range from 0.1 to 2.1. Similar to prior studies, we observe a positive correlation in the two isotopes, although some scatter might be present.



**Figure 2:**  $\epsilon^{50}\text{Ti}$  vs.  $\epsilon^{46}\text{Ti}$  plot, showing the individual CO CAIs analyzed here. The solid line represents the best-fit correlation defined by the array of CV CAIs from [7]. Whereas most samples are in agreement with this linear correlation, one sample is clearly deviating.

**Discussion:** Whereas CAIs from CV chondrites have been shown to exhibit broadly uniform isotopic compositions for most elements [1], the CAIs from CO chondrites analyzed here are clearly variable in their Ti isotopic compositions. This is, however, analogous to the range in Ti isotopes reported for CAIs from CV chondrites [7], suggesting that such isotopic heterogeneity of Ti isotopes is a feature of all CAIs, regardless of their host meteorite.

In contrast to the much larger CV CAIs, however, the small volumes and the correspondingly low total Ti contents of these CO CAIs make their Ti isotope anomalies more susceptible to possible contamination of foreign Ti. Since the CAI-hosts of this study are desert finds, terrestrial weathering is a possible source of non-CAI derived Ti. Any such contamination with terrestrial Ti would dilute isotope anomalies in both Ti isotopes towards  $\epsilon^{\text{Ti}} = 0$ . Although occasionally alteration products (ilmenite, Fe-rich spinel and Na-rich assemblages) were observed in some of the CAI samples during SEM investigations, there is no obvious association between the magnitude of the Ti isotope anomaly and the degree of alteration, likely because of the immobile and refractory character of Ti. Nonetheless, combination of Ti from the CAIs with material from the surrounding bulk chondrite ( $\epsilon^{50}\text{Ti} \sim$

3 [9-10]) cannot be excluded, as the exact three-dimensional shape of each individual CAI is not known, inevitably resulting in variable input of non-indigenous Ti during the drilling procedure. Considering, however, that the concentration of Ti in CAIs is usually much higher compared to the bulk meteorite, this renders a significant impact from surrounding bulk chondrite material on the isotope anomaly rather unlikely. Consistent with this expectation, most CAIs in this study contained >200 ng Ti, whereas the application of our drilling procedure to a chondrule yielded a total Ti content of only 20 ng. As such, we assume that the measured isotope anomalies largely reflect the pristine isotopic signatures of the CAIs themselves.

The Ti isotopic compositions of the CAIs from CO chondrites analyzed in this study are within the range of previously reported values for CV and CK CAIs [7, 9]. This good agreement with literature data in addition to the fact that most samples analyzed here plot on or close to the correlation line defined by CAIs from CV CAIs [7] indicates a strong genetic relationship between refractory inclusions from these carbonaceous chondrite classes. Taken together with similar conclusions drawn from  $^{50}\text{Ti}$  isotope data [11], oxygen isotopics [16], and  $^{26}\text{Al}$  abundances [17] of CAIs from non-carbonaceous chondrites, this suggests that CAIs from carbonaceous (CV, CK, and CO) and non-carbonaceous chondrites likely derived from a single reservoir and, thus, presumably formed contemporaneously in the same region of the protoplanetary disk.

**References:** [1] Dauphas and Schauble (2016) *Annu. Rev. Earth Planet. Sci.* 44, 709. [2] Shollenberger et al. (2017) *GCA*, in review. [3] Torrano et al. (2017) *LPSC 48*, #3045. [4] Render et al. (2017) *ApJ*, in submission. [5] Kööp et al. (2016) *GCA* 189, 70-95. [6] Kööp et al. (2017) *GCA* 221, 296-317. [7] Davis et al. (2017) *GCA* 221, 275-295. [8] Brennecka et al. (2017) *GCA*, in revision. [9] Trinquier et al. (2009) *Science* 324, 374. [10] Zhang et al. (2012) *Nat. Geosc.* 5, 251. [11] Ebert et al., (2017) *80th MetSoc Abst.* #6250. [12] Charlier et al. (2006) *Chem. Geol.* 232, 114. [13] Zhang et al. (2011) *J. Anal. At. Spectrom.* 26, 2197. [14] Gerber et al. (2017) *ApJL* 841, L17. [15] Brennecka et al. (2013) *PNAS* 110, 17241. [16] McKeegan et al. (1998) *Science* 280, 414. [17] Russell et al. (1996) *Science* 273, 757.