

TITANIUM ISOTOPE COMPOSITIONS OF REFRACTORY INCLUSIONS: IMPLICATIONS FOR NEBULAR MIXING. Z. A. Torrano¹, V. K. Rai¹, and M. Wadhwa¹, ¹Center for Meteorite Studies, School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA (ztorrano@asu.edu)

Introduction: Calcium-aluminum-rich inclusions (CAIs) in chondritic meteorites are the first solids to form in the early Solar System, and thereby record the earliest conditions and processes in the solar nebula [1]. CAIs exhibit mass-independent anomalies in a variety of isotope systems, and these anomalies are thought to represent formation in an isotopically distinct reservoir when compared to subsequently formed objects such as chondrite parent bodies and terrestrial planets ([2] and references therein).

Most previous studies of the mass-independent variations in the Ti isotope compositions of CAIs have focused almost exclusively on inclusions from the Allende CV chondrite (e.g., [3] and references therein), which is known to have been extensively altered by secondary processes on its parent body [4]. In particular, very few CAIs from other CV, CO, and ordinary chondrites have been analyzed thus far for their Ti isotope compositions with modern high precision techniques [5-7]. It is therefore important to determine whether these previously analyzed CAIs are representative of the broader CAI-forming region in the early Solar System (as represented by CAIs in other chondrites and chondrite groups).

This study is part of a larger, ongoing project to determine the high-precision, mass-independent Ti isotope compositions of CAIs from primitive meteorites other than Allende, with the goal of providing a more rigorous assessment of the degree of isotopic heterogeneity in the broader CAI-forming region in the early Solar System. The suite of CAIs from chondrites other than Allende that we have reported on previously include the following 12 inclusions: “Bart” from CK3 Northwest Africa (NWA) 6254; “Homer” from CK3 NWA 4964; “Marge” from CV3 NWA 6619; “ZT1” and “ZT2” from CV3 Leoville; “Lisa” and “ZT3” from CV3 NWA 6991; “ZT4” and “ZT5” from CV3 NWA 7891; and “ZT7”, “ZT8”, and “ZT9” from CV3 NWA 3118 [8-10]. In this work we have extended the sample list to 5 additional CAIs from several other CV3 chondrites: “Saguaro” from NWA 5508, “ZT6” from NWA 2900, “ZT10” from NWA 6991, and “ZT13” and “ZT14” from Axtell. We report here the high-precision, mass-independent Ti isotope compositions for these 5 new inclusions and discuss the implications of our dataset as a whole.

Samples and Methods: All sample handling and chemical processing was conducted in the Isotope Cosmochemistry and Geochronology Laboratory (ICGL) at Arizona State University (ASU). Each CAI was carefully extracted from its meteorite slab using

clean dental tools. Extracted fractions were digested in Parr bombs, followed by multiple treatments with aqua regia. A small fraction of each sample solution (typically 5-10%) was reserved for determining the concentrations of elements, including the rare earth elements (REE), with the iCAP-Q quadrupole ICPMS in the Keck Laboratory at ASU. The remainder of the sample solutions were processed for Ti purification.

Ti was purified using procedures adapted from [11] and modified by [10]. Purified Ti samples and standards were analyzed on the Thermo Neptune Multicollector Inductively Coupled Plasma Mass Spectrometer (MC-ICPMS) in the ICGL using methods similar to those described previously [8-10]. Samples and standards (1 ppm concentration) were introduced using an Aridus II desolvating nebulizer with a 100 μ L/min flow rate. Data were collected by switching between two different cup configurations. The intensities of ⁴⁴Ca, ⁴⁶Ti, ⁴⁷Ti, ⁴⁸Ti, and ⁴⁹Ti were measured in the first cup configuration, followed by measurement of ⁴⁷Ti, ⁴⁹Ti, ⁵⁰Ti, ⁵¹V, and ⁵²Cr intensities with the second cup configuration. Measurements of ⁴⁴Ca, ⁵¹V, and ⁵²Cr were used to correct for isobaric interferences on the Ti masses. Ti isotopic data are reported relative to the NIST Ti standard after internal normalization to ⁴⁹Ti/⁴⁷Ti (=0.749766; [12]) using an exponential fractionation law. Samples of homogenized Allende powder and BCR-2 rock standard were chemically processed and analyzed alongside the samples to assess the accuracy and precision of our analyses.

Results and Discussion: The 17 CAIs from chondrites other than Allende in this sample suite (5 of which are reported here for the first time) represent a diversity of petrologic and geochemical types. The REE compositions of these CAIs indicate that this sample set includes samples with unfractionated Group I REE patterns (Lisa, ZT1, ZT4, ZT6, ZT7, ZT13, Saguaro), fractionated Group II patterns (Homer, ZT2, ZT3, ZT5, ZT9, ZT10, ZT14), and somewhat fractionated Group III patterns (Marge, Bart, ZT8).

The 17 CAIs in the sample set studied here show resolvable variation in their mass-independent Ti isotope compositions, suggesting that the CAI-forming region of the early Solar System preserved isotopic variability (Fig. 1). The range of $\epsilon^{50}\text{Ti}$ values for CAIs from CV and CK chondrites in our sample set falls within the range observed in previously analyzed CAIs from CV, CO, and ordinary chondrites. In particular, the $\epsilon^{50}\text{Ti}$ values measured in the 5 new samples range from 8.95 ± 0.20 to 10.45 ± 0.17 and they, along with the 12 previously measured samples, define a single

population with a median $\epsilon^{50}\text{Ti}$ value of ~ 9 , similar to the median value for all previously analyzed CAIs [3,5-7,12-21]. This implies that CAIs from CV, CK, CO, and ordinary chondrites originated in a common nebular source reservoir characterized by mass-independent isotopic variability in Ti (and other select elements), consistent with the observations of [7,10].

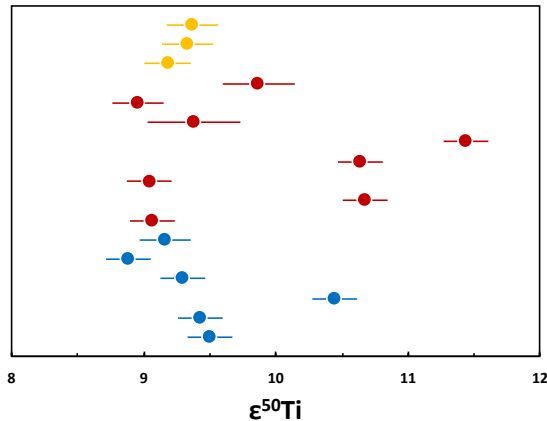


Figure 1. Plot of $\epsilon^{50}\text{Ti}$ values for the 17 CAIs from chondrites other than Allende in our sample suite, including the 5 new CAIs analyzed in this study. Blue symbols represent CAIs with unfractionated (Group I) REE patterns, red symbols represent CAIs with fractionated (Group II) REE patterns, and orange symbols represent CAIs with slightly fractionated REE (Group III) patterns.

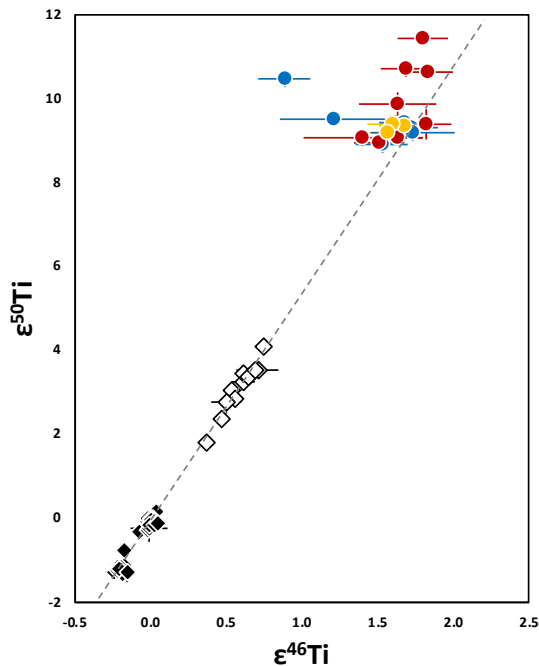


Figure 2. Plot of $\epsilon^{50}\text{Ti}$ values versus $\epsilon^{46}\text{Ti}$ values for the 17 CAIs from chondrites other than Allende in our sample suite (colored symbols, same as in Fig. 1); data for bulk samples of a variety of Solar System materials (white diamonds are carbonaceous meteorites and black diamonds are non-carbonaceous meteorites) from [6,11] are also shown. The dashed gray line is the correlation line based on the previously reported mass-independent Ti isotope compositions of bulk samples of Solar System materials.

Interestingly, several CAIs studied here do not fall on the $\epsilon^{50}\text{Ti}$ vs. $\epsilon^{46}\text{Ti}$ correlation line defined by previous data for bulk meteoritic materials [6, 11] and some CAIs [3, 6] that is thought to reflect mixing between a ^{46}Ti - and ^{50}Ti -poor reservoir and a ^{46}Ti and ^{50}Ti -rich reservoir [e.g., 3] (Fig. 2). Instead, these CAIs appear to be either enriched in ^{50}Ti or depleted in ^{46}Ti relative to the correlation line. Many hibonite-rich inclusions such as PLACs (platy hibonite crystals) and SHIBs (spinel hibonite inclusions), which can have $\epsilon^{50}\text{Ti}$ values ~ 100 times larger than the CAIs studied here, do not display any correlation between $\epsilon^{46}\text{Ti}$ and $\epsilon^{50}\text{Ti}$ [22, 23]. PLAC-like CAIs with smaller isotopic anomalies ($|\delta^{50}\text{Ti}| \leq 25\%$) fall on the correlation line, while those with larger anomalies do not [23]. This could suggest that hibonite-rich inclusions with smaller anomalies formed after the ^{46}Ti and ^{50}Ti components were coupled, and after the objects with larger anomalies had already formed.

Together, these data suggest that the ^{46}Ti and ^{50}Ti components that were incorporated into the early Solar System were initially decoupled and heterogeneously distributed. Refractory inclusions that do not fall on the bulk Solar System correlation line may represent an incomplete stage of the mixing processes responsible for homogenizing initially heterogeneously distributed presolar carrier phases and for the coupling of ^{46}Ti and ^{50}Ti .

References: [1] MacPherson (2014), *Treatise on Geochemistry (2nd Ed.)*, 139. [2] Dauphas and Schauble (2016), *Annu. Rev. Earth Planet. Sci.* 44, 709-783. [3] Davis et al. (2018) *Geochim. Cosmochim. Acta.*, 221, 275-295. [4] Krot et al. (1998) *Meteoritics & Planet. Sci.*, 33, 748-775 [5] Leya et al. (2009) *Astrophys. J.* 702, 1118-1126. [6] Trinquier et al. (2009) *Science*, 324, p. 374-376. [7] Ebert et al. (2018) *Earth Planet. Sci. Lett.*, 498, 257-265. [8] Torrano et al. (2017) *LPSC 48*, #3045. [9] Torrano et al. (2017) *MetSoc 80*, #6318. [10] Torrano et al. (submitted) *Geochim. Cosmochim. Acta*. [11] Zhang et al. (2011) *J. Anal. Atom. Spect.*, 26, 2197-2205. [12] Niederer et al. (1981) *Geochim. Cosmochim. Acta*, 45, 1017-1031. [13] Heydegger et al. (1979) *Nature* 278, 704-707. [14] Niederer et al. (1980) *Astrophys. J.* 240, L73-L77. [15] Niederer et al. (1985) *Geochim. Cosmochim. Acta* 49, 835-851. [16] Niemeyer and Lugmair (1981) *Earth Planet. Sci. Lett.* 53, 211-225. [17] Niemeyer and Lugmair (1984) *Geochim. Cosmochim. Acta* 48, 1401-1416. [18] Loss et al. (1994) *Astrophys. J.* 436, L193-L196. [19] Chen et al. (2009) *Terr. Atmos. Ocean. Sci.* 20, 703-712. [20] Williams et al. (2016) *Chem. Geol.* 436, 1-10. [21] Simon et al. (2017) *Earth Planet. Sci. Lett.* 472, 277-288. [22] Kööp et al. (2016) *Geochim. Cosmochim. Acta* 184, 151-172. [23] Kööp et al. (2016) *Geochim. Cosmochim. Acta*, 189, 70-95.