

MAGNESIUM, TITANIUM AND CHROMIUM ISOTOPE COMPOSITIONS OF REFRACTORY INCLUSIONS FROM SEVERAL CV3 AND CK3 CHONDRITES: IMPLICATIONS FOR NEBULAR HETEROGENEITY. 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 chondrites are the first solids formed in the early Solar System and thus preserve a record of the earliest processes and conditions in the solar nebula [1]. CAIs show mass-independent anomalies in a variety of isotope systems relative to terrestrial standards, and these anomalies have been attributed largely to incomplete homogenization of distinct nucleosynthetic components in the nebular reservoirs sampled by these objects [2]. In recent years, the isotopic compositions of an unprecedented number of elements in a single, large suite of normal (non-FUN) Allende CAIs have been reported [3-7]. This past work has shown that these normal Allende CAIs have uniform isotopic compositions (within the analytical precision) for elements ranging from Sr to Dy; these compositions, however, are distinct from terrestrial or bulk chondritic compositions, suggesting that these CAIs originated from an isotopically homogeneous nebular reservoir which was distinct from the one from which the remainder of chondritic components originated.

It is important to expand these studies to investigate the isotope compositions of additional CAIs from other primitive chondritic meteorites to ascertain the degree of isotopic heterogeneity in the broader CAI-forming region in the early Solar System. Recently, [8] reported the Sr, Ba, Nd, Sm isotope compositions of four CAIs from four different CV3 and CK3 chondrites and [7] reported the Cr and Zr isotope compositions of these same four CAIs. In this work, we expand the analyses of these same CAIs to include Ti, and additionally report Ti and Cr isotopic compositions of two additional CAIs from two other CV3 chondrites, Northwest Africa (NWA) 7891 and NWA 3118.

Another objective of the present study is to determine the ²⁶Al-²⁶Mg systematics of a range of CAIs from a variety of carbonaceous chondrites. The goal is to evaluate recent suggestions of possible heterogeneity in Mg isotopes and/or ²⁶Al in the early Solar System (e.g., [8]).

Samples and Analytical Methods: Data from six samples are presented here. We analyzed Ti isotope compositions of four CAIs that were previously studied [7, 9]: “Marge” (from CV3 NWA 6619), Lisa (from CV3 NWA 6991), “Bart” (from CK3 NWA 4966), and “Homer” (from CK3 chondrite NWA 6254). We additionally measured Mg, Ti, and Cr isotope compositions of two additional CAIs that have not

been previously studied: “ZT4” (from CV3 anomalous NWA 7891), and “ZT9” (from CV3 NWA 3118). For the CAIs ZT4 and ZT9, interior (labelled as “A”) and rim (labelled as “B”) material from each CAI was extracted and processed separately.

All sample handling and chemical processing of these CAIs was conducted in the Isotope Cosmochemistry and Geochronology Laboratory (ICGL) at Arizona State University (ASU). The interior and rim fractions from the two CAI samples from NWA 7891 and NWA 3118 were digested in Parr bombs, followed by multiple treatments with aqua regia. Subsequently, a ~5% aliquot of each fraction was reserved for elemental analyses, and the remainder of the solutions were processed for the separation of Mg, Ti, and Cr using ion chromatography methods adopted from those in [10], [11], and [12] respectively. Titanium was additionally purified from unprocessed solutions of the 4 CAIs that were previously studied by [7,9].

Magnesium, chromium, and titanium isotopes were measured on the Neptune Multicollector Inductively Coupled Plasma Mass Spectrometer (MC-ICPMS) in the ICGL using methods similar to those described previously [4,6,7]. The Al/Mg ratios were obtained using a Thermo Scientific iCAP-Q quadrupole ICPMS in the Keck Laboratory at ASU.

Purified magnesium samples and standards were analyzed at a concentration of 200 ppb. Samples were introduced using an Elemental Scientific Apex-Q with a 50 μ L/min flow rate. The non-mass dependent effects on ²⁶Mg/²⁴Mg were calculated relative to DSM-3 Mg standard after internal normalization to ²⁵Mg/²⁴Mg (=0.12663; [13]) using an exponential fractionation law.

Purified titanium samples and standards were analyzed at a concentration of 1 ppm. Samples were introduced into the mass spectrometer using an Aridus II desolvating nebulizer with a 60 μ L/min flow rate. We used a dynamic Faraday cup configuration to measure the intensities of ⁴⁴Ca, ⁴⁶Ti, ⁴⁷Ti, ⁴⁸Ti, and ⁴⁹Ti before switching the magnet to measure ⁴⁷Ti, ⁴⁹Ti, ⁵⁰Ti, ⁵¹V, and ⁵²Cr. Signals for ⁴⁴Ca, ⁵¹V, and ⁵²Cr were used to correct for isobaric interferences. Ti isotopic data are reported relative to an in-house SPEX Ti standard after internal normalization to ⁴⁹Ti/⁴⁷Ti (=0.749766; [14]) using an exponential fractionation law.

Purified chromium samples and standards were analyzed at a concentration of 800 ppb. Samples were

introduced using an Aridus II desolvating nebulizer with a 60 $\mu\text{L}/\text{min}$ flow rate. Measurements were done in high resolution mode to avoid polyatomic interferences [15]. The intensities of ^{50}Cr , ^{52}Cr , ^{53}Cr , and ^{54}Cr were measured, along with ^{49}Ti , ^{51}V , and ^{56}Fe to monitor and correct for isobaric interferences. The Cr isotopic data are reported relative to the NBS 979 standard after internal normalization to $^{50}\text{Cr}/^{52}\text{Cr}$ ($=0.051859$; [16]).

Samples of homogenized Allende powder and the BCR-2 terrestrial rock standard were chemically processed and analyzed alongside the samples studied here to assess the accuracy and precision of our analyses.

Results and Discussion: Chromium and Titanium Isotopic Systematics. The Ti isotopic compositions determined here for the six CAIs measured here are shown in Fig. 1. $\epsilon^{50}\text{Ti}$ shows a range from 7.89 ± 0.36 to 11.43 ± 0.30 . While these values are generally consistent with the $\epsilon^{50}\text{Ti}$ values reported previously for the Allende CAIs (determined via Laser ablation ICPMS) [17], they do indicate resolvable variation in Ti isotope compositions.

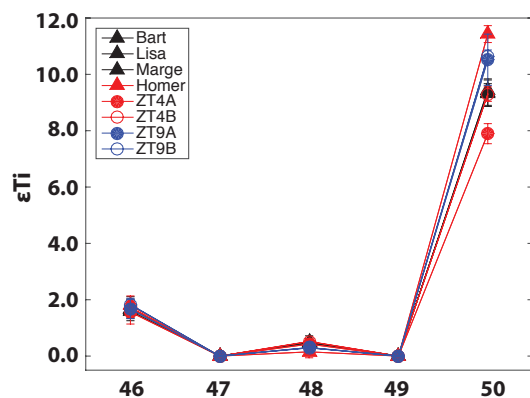


Figure 1. Mass-independent Ti isotopic compositions of the 6 CAIs analyzed here.

The Cr isotope measurements were completed for the two fractions from the CAI ZT9A; we are currently in the process of analyzing the compositions of the two CAI ZT4 fractions. The $\epsilon^{53}\text{Cr}$ values for CAI ZT9A and ZT9B show a range from -0.47 ± 0.12 to -0.56 ± 0.12 , and the $\epsilon^{54}\text{Cr}$ values show a range from 5.73 ± 0.27 to 5.86 ± 0.29 . Some variation in $\epsilon^{53}\text{Cr}$ may be due to the presence of radiogenic ^{53}Cr from the decay of ^{53}Mn . As such, we subtracted a radiogenic ^{53}Cr component that was estimated using the initial Solar System $^{53}\text{Mn}/^{55}\text{Mn}$ value of $(6.28 \pm 0.66) \times 10^{-6}$ [18] and the Mn/Cr ratios measured in these samples, but the corrected compositions are the same as those reported above (within the errors). As discussed by [6], it

is plausible that the variation $\epsilon^{53}\text{Cr}$ and $\epsilon^{54}\text{Cr}$ in CAIs could be due to addition of Cr to the CAIs from their host matrix, but this two-component mixing model is not consistent with the Cr isotope compositions of Homer and for the ZT9 CAI fractions (Fig. 2).

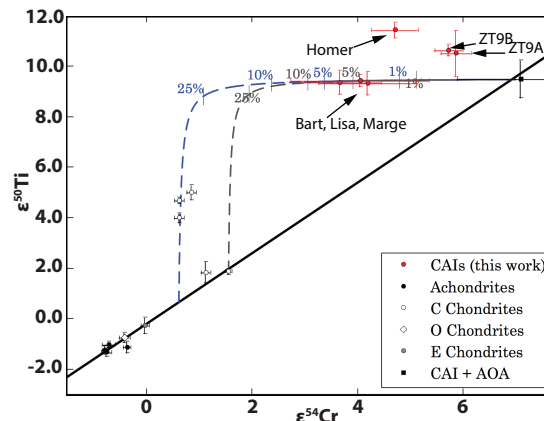


Figure 2. Data for several achondrites, chondrites, and CAIs reported by [18], along with our data for six non-Allende CAIs. Figure and model parameters after [6, 18].

Al-Mg Systematics. Al-Mg systematics for the all cuts of CAIs ZT4 and ZT9 were analyzed. These four fractions have a range of $^{27}\text{Al}/^{24}\text{Mg}$ ratios from 2.27 to 11.25. The internal isochron yields an initial $^{26}\text{Al}/^{27}\text{Al}$ ratio of $(6.3 \pm 3.7) \times 10^{-5}$, which is within error of the canonical value of $\sim 5 \times 10^{-5}$ (e.g., [19,20]). These preliminary results are consistent with a homogeneous distribution of ^{26}Al in the early Solar System, but will need to be more rigorously evaluated with high precision Al-Mg systematics in more CAIs from a variety of carbonaceous chondrites.

References: [1] MacPherson (2014), *Treatise on Geochemistry (2 Ed.)*, p. 139. [2] Meyer and Zinner in *Meteorites and the Early Solar System II*, (U. Arizona Press, 2006). [3] Brennecka et al. (2013) *PNAS*, 110, 17241. [4] Mane et al. (2014) *MetSoc 2014*, #5403. [5] Williams et al. (2014) *Goldschmidt 2014*, #2712. [6] Mercer et al. (2015) *LPSC 46*, #2920. [7] Mane et al. (2016) *LPSC 47*, #2778. [8] Larsen et al. (2011) *ApJ*, 735, L37. [9] Shollenberger et al. (2015) *LPSC 46*, #2593. [10] Bouvier et al. (2011) *GCA*, 75, 5310-5323. [11] Zhang et al. (2011) *J. Anal. Atom. Spect.*, 26, p. 2197. [12] Yamakawa et al. (2009) *Anal. Chem.*, 81, p. 9787. [13] Catanzaro et al. (1966) *J. Res. Natl. Bur. Stand.*, 70A, p. 453. [14] Birck and Allègre (1985) *GRL*, 12, p. 745. [15] Schoenberg et al. (2008) *Chem. Geol.*, 249, p. 294. [16] Shields et al. (1966) *J. Res. Nat. Bur. Stand.*, 70A, p. 193. [17] Williams et al. (2016) *Chem. Geol.*, 436, 1-10. [18] Trinquier et al. (2008) *GCA*, 72, p. 5146. [19] MacPherson et al. (1995) *Meteoritics*, 30, 365-386. [20] Jacobsen et al. (2008) *EPSL*, 272, 353-364.