

MAGNESIUM AND OXYGEN ISOTOPIC COMPOSITIONS OF CALCIUM-ALUMINUM-RICH INCLUSIONS FROM CR CARBONACEOUS CHONDRITES. K. Makide^{1*}, K. Nagashima¹, A. N. Krot¹, G. R. Huss¹, I. D. Hutcheon² and A. Bischoff³. ¹Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Manoa, Honolulu, HI 96822, USA. *makide@higp.hawaii.edu. ²Lawrence Livermore National Laboratory, Livermore, CA 94551, USA. ³Institut für Planetologie, Muenster, Germany.

Introduction: Calcium, aluminum-rich inclusions (CAIs) are the oldest solids formed in the solar nebula [1]. The timing of formation and thermal processing of CAIs, which can be inferred from their Al-Mg isotope systematics, plays an important role in models of early Solar System evolution [2,3]. However, the Al-Mg isotope systematics of CAIs from many chondrite groups were disturbed during thermal metamorphism on their parent asteroids [2]. CR carbonaceous chondrites are among the least metamorphosed meteorites [4]. Most CR CAIs are mineralogically pristine objects that largely escaped secondary alteration processes and thus preserved solar nebula records virtually unchanged [5]. To constrain the duration of CAI formation and subsequent thermal processing, and evolution of O-isotopic composition in the early Solar System, we have measured O- and Mg-isotopic compositions of CR CAIs.

Samples and Analytical Techniques: The mineralogy and petrography of 19 CAIs from 9 polished sections of CR chondrites (EET 92042-22, EET 96286-6, Temple Bar, Asuka 881828-61-4, El Djouf 001-PL91172, GRA 95229-18, Acfer 097, Acfer 209 and Gao Guinee) were studied using a Cameca SX-50 electron microprobe and a JEOL JSM-5900LV scanning electron microscope equipped with Thermo Electron energy dispersive spectrometer.

Isotopic data were collected *in situ* with the UH Cameca ims 1280 ion microprobe. For Mg isotopes, a 150–300 pA O⁺ primary ion beam was focused to ~5–7 μm. The secondary ion mass spectrometer was operated at +10 keV with a 50 eV energy window. The mass resolving power (MRP) was set to ~3800, sufficient to separate interfering hydrides and doubly charged ⁴⁸Ca⁺. Mg isotopes and ²⁷Al were measured in peak-jumping mode with monocollector EM and FC, respectively. ²⁶Mg* was calculated assuming an exponential mass-fractionation law with a fractionation factor of 0.514 [14]. Instrumental mass fractionation (IMF) and Al-Mg sensitivity factors were determined from Burma spinel, Madagascar hibonite, Miyakejima anorthite, and synthetic melilite glass standards. Oxygen isotopic compositions were collected in multicollector mode with ¹⁶O and ¹⁸O measured on multicollector FCs and ¹⁷O (~1.5×10⁵ cps) measured on the monocollector EM. The mass spectrometer was operated at –10 keV with a 50 eV energy window. A 1.8 nA focused Cs⁺ primary ion beam was rastered over a 25×25 μm² area for 250 seconds. Then the raster was reduced to 10×10 μm² for data collection. The MRP for ¹⁶O and ¹⁸O were ~2000, and that for ¹⁷O was ~5500 (m/Δm), sufficient to separate interfering ¹⁶OH. The normal incidence electron flood gun was used for charge compensation. Data were corrected for IMF using San Carlos olivine, Eagle Station olivine, Miyakejima anorthite and Burma spinel. The reproducibility of 0.5–1‰ (2σ) was obtained for both ¹⁸O/¹⁶O and ¹⁷O/¹⁶O ratios, consistent with statistical errors.

Results: The inferred initial ²⁶Al/²⁷Al ratios [(²⁶Al/²⁷Al)₀] for 11 CAIs from CR chondrites are shown in Table 1. Except for one grossite-hibonite inclusion that has no evidence of ²⁶Al, the (²⁶Al/²⁷Al)₀ range from 4.2×10⁻⁵ to 5.4×10⁻⁵. Where sufficient spread in Al/Mg is available, the inclusions exhibit tight isochrons, as indicated by the uncertainties in Table 1. The experimental uncertainties are consistent with all objects with evidence for ²⁶Al having the same initial ratio. Note that for

two inclusions in Table 1, melilite and grossite are listed as giving different initial ratios in the same inclusion. This is almost certainly due to our not having an appropriate standard for the sensitivity factor for grossite. The data for both minerals in both inclusions show tight isochrons and no evidence of disturbance.

Oxygen isotopic compositions of the majority primary minerals in the CR CAIs are ¹⁶O-rich (–45‰ < δ¹⁸O < –36‰) and homogeneous within an inclusion (Fig. 1). This suggests formation in an ¹⁶O-rich gaseous reservoir without subsequent exchange with an ¹⁶O-poor reservoir; the latter is characteristic for most CAIs from metamorphosed CV and CO chondrites [6–9]. Oxygen isotopic compositions of an igneous melilite-spinel CAI #3 from Gao Guinee (Figs. 1, 2c) define a mass-dependent fractionation line parallel to the terrestrial fractionation line (TFL) at Δ¹⁷O = –22‰. It may be a FUN or F CAI. This will be answered by future Mg, Si, and Ti isotopic measurements.

Two spinel-anorthite igneous Type C CAIs are surrounded by chondrule-like material (Fig. 2a, 2d). Acfer 209 #1 is surrounded by a shell of high and low-Ca pyroxene with minor Fe-Mg-olivine, anorthitic plagioclase and Fe,Ni metal. Data for anorthite plot along the carbonaceous chondrite anhydrous mineral (CCAM) line and are slightly ¹⁶O-depleted (–36‰ < δ¹⁸O < –29‰) compared to typical CAIs (Fig. 1). Rim lath-shaped anorthite is more ¹⁶O-depleted than anorthite in CAI core (Fig. 1), indicating that anorthite experienced melting and incomplete O-isotopic exchange in an ¹⁶O-poor gaseous reservoir. Anorthite in CAI Gao Guinee #4 has an ¹⁶O-poor composition (Δ¹⁷O = –3‰) and plots along CCAM line (Fig. 1). Spinel is slightly ¹⁶O-enriched (Δ¹⁷O = –9‰), but has highly fractionated composition (Fig. 1). We infer that the Gao Guinee #4 anorthite experienced extensive isotopic exchange during chondrule formation, whereas spinel largely retained its highly fractionated composition.

Discussion: All but one of the CAIs studied to date have inferred (²⁶Al/²⁷Al)₀ of (4–5)×10⁻⁵ (Table 1) and O-isotope compositions that cluster near the ¹⁶O-rich end of the CCAM line (Figs. 1). When both isotope systems are measured in the same object, both show these dominant systematics. The Al-Mg and O data sets are consistent with most CR CAIs having a simple single-stage formation history. So far, we do not have Al-Mg data on the rare inclusions that show textural and O-isotope evidence for a more complex thermal history (Acfer 209 #1, Gao Guinee CAI #3). There are literature O-isotope data on CAI El Djouf MK #5, the inclusions with no evidence for ²⁶Al, that give a somewhat less ¹⁶O-rich composition than the majority of CR CAIs [5]. These data are consistent with a second melting event after ²⁶Al had decayed.

The observed differences in O-isotopic compositions of the CR CAIs [5, this study] and chondrules [10 and ref. therein] suggest that formation of CAIs and chondrules occurred in isotopically distinct nebular regions, ¹⁶O-rich and ¹⁶O-poor, respectively. The relative timing of the CR CAI and chondrule formation can be constrained from their Al-Mg isotope systematics. Internal Al-Mg isochrons of the CR chondrules are reported by Nagashima et al. [12]; the inferred (²⁶Al/²⁷Al)₀ range from ~1×10⁻⁶ to ~6×10⁻⁶. The inferred (²⁶Al/²⁷Al)₀ in the

CR CAIs (based on the internal isochrons) with the measured O-isotopic compositions are shown in Fig. 3. The $(^{26}\text{Al}/^{27}\text{Al})_0$ range from 4.1 to 5.4×10^{-5} . No CAIs with clearly supracanonical $(^{26}\text{Al}/^{27}\text{Al})_0$ ($\geq 5.85 \times 10^{-5}$) are identified. We infer that thermal processing of CR CAIs lasted for ~ 0.5 Myr. Several CR CAIs experienced melting during chondrule formation, but their Al-Mg systematics have not been measured yet. Additional measurements of CR CAIs with measured O-isotopic compositions are in progress.

References: [1] Amelin Y. et al. (2002) *Science*, 297, 1678. [2] MacPherson G. J. et al. (1995) *MAPS*, 30, 365-377. [3] Thrane et al. (2006) *ApJL*, 646, L159. [4] Krot A. N. et al. (2002) *MAPS*, 37, 1451. [5] Aléon J. et al. (2002) *MAPS*, 32, 1729. [6] Clayton R. N. et al. (1977) *EPSL*, 34, 209. [7] Clayton R. N. (1993) *Annu. Rev. Earth Planet Sci.* 21, 115. [8] Wasson J. T. et al. (2001) *GCA*, 65, 4539. [9] Itoh S. et al. (2004) *GCA*, 68, 2905. [10] Krot A. N. et al. (2006) *Chem. Erde*, 66, 249. [11] Nagashima K. et al. (2007) this vol. [12] Makide K. et al. (2007) *Workshop on the Chronology of Meteorites and the Early Solar System*, 108-109. [13] Davis et al. (2006) *LPS XXXVIII*, Abstract #2334.

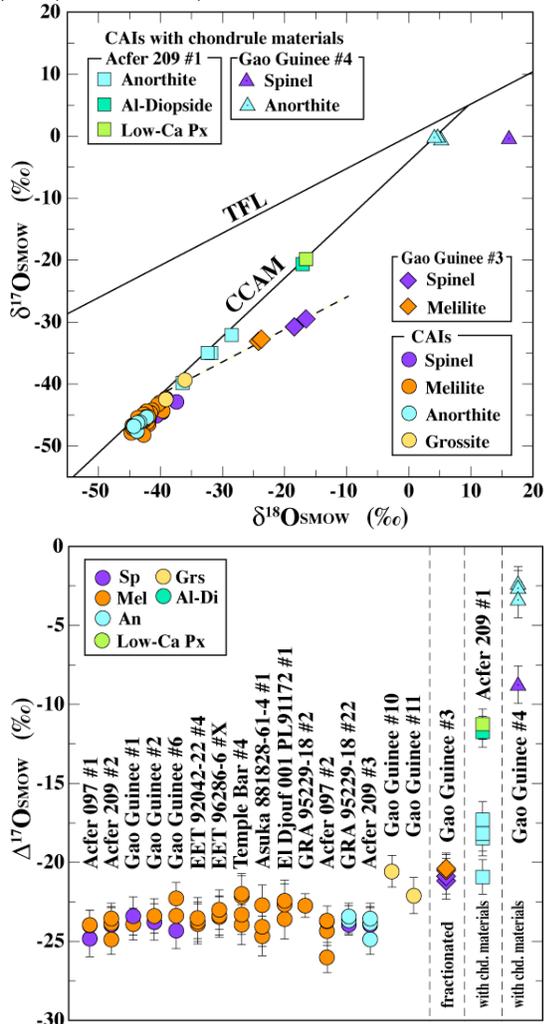


Fig. 1. top - Oxygen isotopic compositions of CAIs from CR chondrites. 2σ error bars for $\delta^{17}\text{O}$ and $\delta^{18}\text{O}$ are $\sim 1\%$. bottom - The same data are plotted in the form of deviation from the TFL, $\Delta^{17}\text{O} = \delta^{17}\text{O} - 0.52 \times \delta^{18}\text{O}$. Each column represents data for a single CAI.

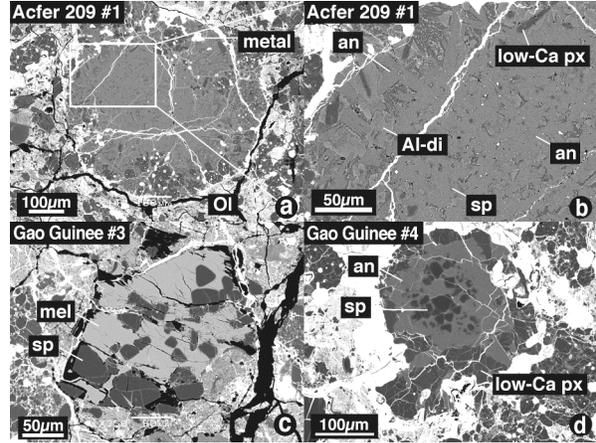


Fig. 2. BSE images of CAIs Acfer 209 #1 (a, b), Gao Guinee #3 (c) & #4 (d). Region outlined in (a) is shown in detail in (b).

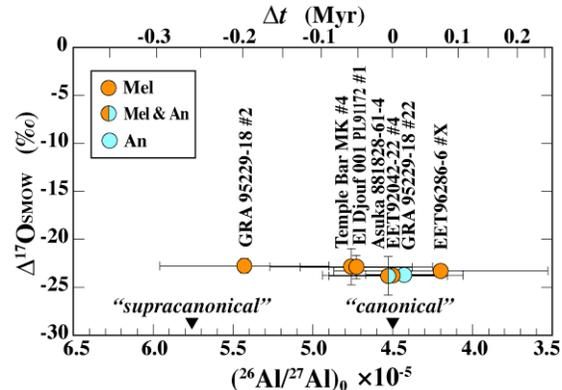


Fig. 3. The inferred $(^{26}\text{Al}/^{27}\text{Al})_0$ in CR CAIs with measured O-isotopic compositions. The $(^{26}\text{Al}/^{27}\text{Al})_0$ ratio were recalculated using exponential law and experimental defined fractionation factor (0.514 [14]). Filled symbols correspond to CAIs for which internal Al-Mg isochrons were obtained. Error bars for $\Delta^{17}\text{O}$ are 2σ for measured spots and that for $(^{26}\text{Al}/^{27}\text{Al})_0$ are 2σ for individual isochrons. The canonical ratio of 4.5×10^{-5} [2] and supracanonical ratio of $(5.85 \pm 0.05) \times 10^{-5}$ [3] in whole-rock CV CAIs measured by MC-ICP-MS are shown for reference.

Table 1. Inferred initial ratios for CR CAIs [13, this study].

Inclusion	$(^{26}\text{Al}/^{27}\text{Al})_0 \times 10^{-5}$
EET 92042-22 #4	4.50 ± 0.44
EET 96286-6 #X	4.20 ± 0.67
Temple Bar #4	4.76 ± 0.51
Asuka 881828-61-4 #1	4.53 ± 0.37
EL Djouf 001 PL91172 #1	4.73 ± 0.35
GRA 95229-18 #2	5.43 ± 0.53
GRA 95229-18 #22	4.43 ± 0.24
GRA 95229-31 #3	4.28 ± 0.11
GRA 95229-17 #7 melilite	5.00 ± 0.23
GRA 95229-17 #7 grossite	4.15 ± 0.11
GRA 95229-18 #8 melilite	5.22 ± 0.62
GRA 95229-18 #8 grossite	4.24 ± 0.15
EL Djouf 001 MK #5	-0.055 ± 0.048