MAGNESIUM ISOTOPIC COMPOSITION OF CALCIUM-ALUMINUM-RICH INCLUSIONS FROM CR CARBONACEOUS CHONDRITES. K. Makide[1], K. Nagashima[1], A. N. Krot[1], G. R. Huss[1], and I. D. Hutcheon[2]. [1]Hawai'i Institute of Geophysics and Planetology, School of Ocean and the Earth Science and Technology, University of Hawai'i at Manoa, Honolulu, HI 96822, USA (E-mail: makide@higp.hawaii.edu). [2]Lawrence Livermore National Laboratory, Livermore, CA 94551, USA.

Introduction: Calcium, aluminum-rich inclusions (CAIs) are the oldest solids formed in the solar nebula by condensation, evaporation and melting processes. High precision absolute, ^{207}Pb-^{206}Pb ages of CAIs (4567.2±0.7 Ma) have been reported only for coarse-grained, igneous CAIs from the CV carbonaceous chondrites [1]. The duration of CAI formation and thermal processing is largely based on Al-Mg isotope measurements and remains controversial[e.g., 2-11]. Most CAIs define the initial ^{26}Al/^{27}Al ratio [(^{26}Al/^{27}Al)$_0$] of 4.5×10^{-5}, referred to as the "canonical" value [2]. Based on the high precision Mg isotope measurements of CV CAIs using multicollector inductively-coupled mass-spectrometry (MC-ICP-MS) and secondary ionization mass-spectrometry (SIMS), the canonical ^{26}Al/^{27}Al ratio has been recently revised upwards to a "supra-canonical" value of $(5.5\text{-}7)\times10^{-5}$ [3-9]. In contrast, high-precision Mg isotope measurements of bulk igneous Allende CAIs and their mineral separates using MC-ICP-MS define (^{26}Al/^{27}Al)$_0$ of $(5.12\pm0.18)\times10^{-5}$ [10], which is inconsistent with $(5.85\pm0.05)\times10^{-5}$ value reported by [5] using the same analytical technique. Although this apparent discrepancy still needs to be resolved, both data sets suggest a very short (<20-30 Kyr) time difference between the formation of precursors of the igneous CV CAIs and their crystallization ages. The very short duration of the CV CAI formation is in conflict with the prolonged duration of the CV CAI thermal processing inferred from internal Al-Mg isochrons obtained by SIMS: e.g., the (^{26}Al/^{27}Al)$_0$ of $(6.44\pm0.27)\times10^{-5}$ and $(4.96\pm0.02)\times10^{-5}$ are inferred for ^{16}O-rich and ^{16}O-poor minerals, respectively, within a single coarse-grained igneous CAI from Allende [11]. We note, however, that internal isochrons of many CAIs from CV chondrites were disturbed during thermal metamorphism on their parent asteroid [2]. To constrain the duration of CAI formation and thermal processing, high precision measurements of internal Al-Mg isochrons in CAIs from primitive carbonaceous chondrites (e.g., CR2, CO3.0, Acfer 094, Adelaide) are required. Here we report Al-Mg systematics of nine CAIs from CR carbonaceous chondrites. The CR CAIs are mineralogically and isotopically pristine [12, 13] and appear to have preserved primary nebular signatures largely undisturbed. Oxygen isotopic compositions of some of these CAIs have been previously reported by [12] and are illustrated in Fig. 1.

Experimental: Nine CAIs identified by X-ray elemental mapping and studied in backscattered electron images from six CR chondrites (GRA 95229, EET 92042, EET 96286, El Djouf 001, Temple Bay, and Asuka-881828) were selected for *in situ* Al-Mg isotope measurements by the UH Cameca ims-1280. A 150–300 pA O^- primary ion beam was focused to ~5-7 μm. The secondary ion mass spectrometer was operated at +13 keV with a 50 eV energy window. ^{24}Mg, ^{25}Mg, and ^{26}Mg, and ^{27}Al were measured in 120 cycles on a monocollector electron multiplier and Faraday cup in a peak jumping mode (4, 10, 10, and 2 sec, respectively). The mass resolving power was set to ~3800, sufficient to separate interfering hydrides. Excess of radiogenic ^{26}Mg (^{26}Mg*) was calculated by normalizing to the terrestrial magnesium isotopic ratios (^{25}Mg/^{24}Mg = 0.12663; ^{26}Mg/^{24}Mg = 0.13932 [14]) according to a linear law. The sensitivity factors for melilite, anorthite, hibonite and spinel were calculated based on the measured ^{27}Al$^+$/^{24}Mg$^+$ (SIMS) and Al/Mg (electron microprobe analysis) ratios in terrestrial standards. The sensitivity factor for grossite was assumed to be the same as for hibonite. ^{27}Al/^{24}Mg ratios in the samples were obtained by dividing the measured ^{27}Al$^+$/^{24}Mg$^+$ ratios with the relative sensitivity factors for grossite, hibonite, and melilite.

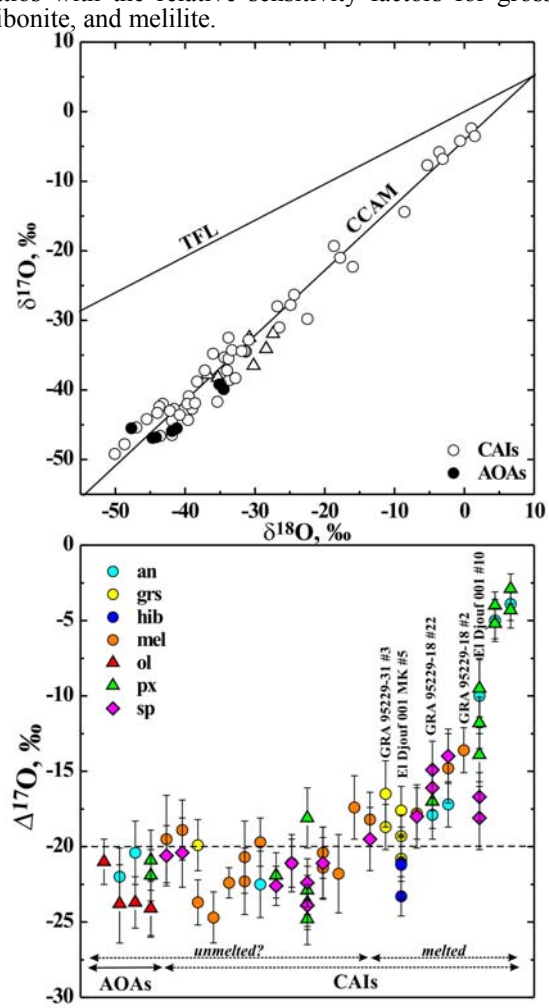

Fig. 1. Oxygen isotopic compositions of CAIs and amoeboid olivine aggregates (AOAs) from CR carbonaceous chondrites (data from [12]). CAI numbers with measured Mg isotopic compositions are indicated. an = anorthite; grs = grossite; hib = hibonite; mel = melilite; ol = olivine; px = Al,Ti-diopside; sp = spinel.

Results and Discussion: Eight out of nine CR CAIs analyzed show ^{26}Mg* corresponding to the $(^{26}Al/^{27}Al)_0$ of $(4.27\pm0.11)\times10^{-5}$ to $(5.63\pm0.46)\times10^{-5}$ (Fig. 2). The grossite-hibonite-rich CAI El Djouf 001 MK #5 shows no ^{26}Mg*: $(^{26}Al/^{27}Al)_0 = (-0.059\pm0.039)\times10^{-5}$. All CAIs analyzed are igneous and ^{16}O-enriched ($\Delta^{17}O = -15‰$ to $-20‰$), although to a lesser degree than AOAs and apparently unmelted CAIs in CR chondrites (Fig. 1). One of these CAIs, GRA 95229-18 #2, contains secondary sodalite replacing melilite; the CAI shows the largest depletion in ^{16}O ($\Delta^{17}O = -15‰$). Sodalite contains ^{26}Mg* that is comparable to the ^{26}Mg* in the melilite, suggesting that ^{26}Mg* in sodalite may have been inherited from melilite. Type C CAI El Djouf UH 154 #10 surrounded by an igneous diopside-forsterite rim is ^{16}O-depleted ($\Delta^{17}O$ up to $-10‰$) and has a small ^{26}Mg* corresponding to the $(^{26}Al/^{27}Al)_0$ of $(1.43\pm0.87)\times10^{-6}$ [15]. The CAI probably experienced late-stage melting in an ^{16}O-depleted nebular gas during chondrule formation [16]. Because El Djouf 001 MK #5 is ^{16}O-rich and surrounded by a multilayered Wark-Lovering rim sequence, the lack of ^{26}Mg* in it cannot be explained by late-stage remelting and must reflect the absence of ^{26}Al in its precursor. We note that ^{16}O-rich, ^{26}Al-poor grossite-rich CAIs are commonly observed in the CH carbonaceous chondrites [17-19]. It has been suggested that these CAIs formed prior to injection and homogenization of ^{26}Al in the solar nebula [18, 19].

Based on these observations, we infer that thermal processing of CR CAIs in an ^{16}O-rich nebular reservoir lasted for ~0.3 Myr after formation of CAIs with $(^{26}Al/^{27}Al)_0$ of $(5.85\pm0.05)\times10^{-5}$) (Fig. 3). Some CAIs were remelted 3-4 Myr later, during chondrule formation [15]. There is no clear evidence for CAIs with supracanonical $(^{26}Al/^{27}Al)_0$ ratio in CR chondrites yet.

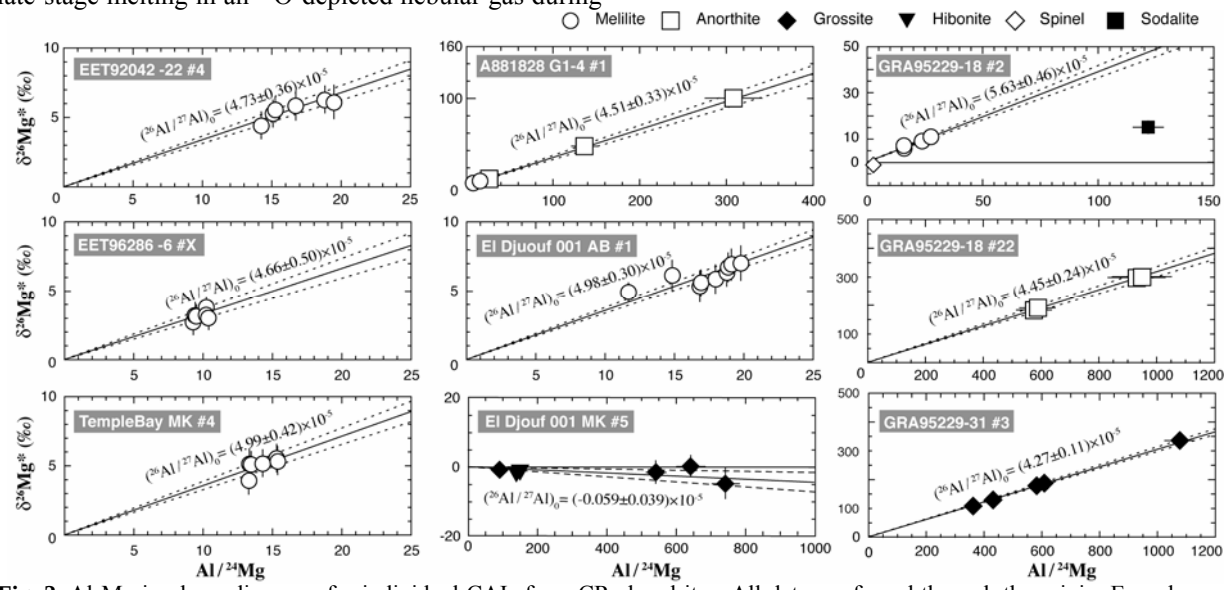

Fig. 2. Al-Mg isochron diagrams for individual CAIs from CR chondrites. All data are forced through the origin. Error bars are 2σ. Sodalite in GRA95229-18 #2 is a secondary phase and was not used for calculation of isochron.

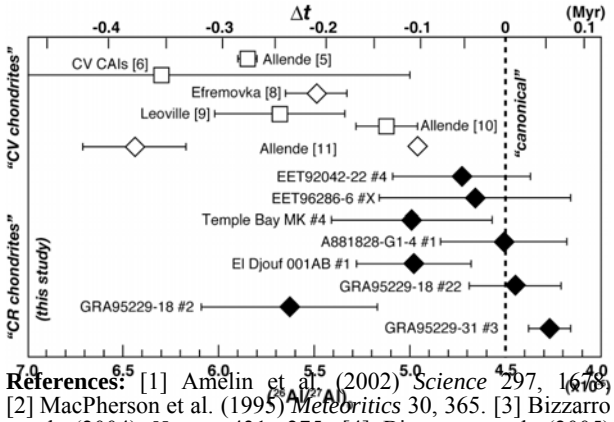

Fig. 3. ← The inferred $(^{26}Al/^{27}Al)_0$ in CR CAIs (this study). The canonical ratio of 4.5×10^{-5} (dashed line, [2]), "supracanonical" ratios of $(5.85\pm0.05)\times10^{-5}$ [5] and $(6.3\pm1.3)\times10^{-5}$ [6] in whole-rock CV CAIs measured by MC-ICP-MS, and several well-defined internal isochrons measured by SIMS [7-9, 11] and by MC-ICP-MS [10] are plotted for comparison. The $(^{26}Al/^{27}Al)_0$ ratios were calculated using linear (diamonds) and exponential (squares) law using kinetic (0.511 [5, 6, 19]) and experimentally defined (0.514 [9]) fractionation factor [20].

References: [1] Amelin et al. (2002) *Science* 297, 1678. [2] MacPherson et al. (1995) *Meteoritics* 30, 365. [3] Bizzarro et al. (2004) *Nature* 431, 275. [4] Bizzarro et al. (2005) *Nature* 435, 1280. [5] Thrane et al. (2006) *ApJL* 646, L159. [6] Young et al. (2005) *Science* 308, 223. [7] Taylor et al. (2005) *LPS* XXXVI, Abstract #2121. [8] Srinivasan et al. (2007) *LPS* XXXVIII, #1781. [9] Richter et al. (2007) *LPS* XXXVIII, #2303. [10] Jacobsen et al. (2007) this volume. [11] Itoh et al. (2007) *MAPS* 42, A75. [12] Aléon et al. (2002) *MAPS* 37, 1729. [13] Weber and Bischoff (1997) *Chem. Erde* 57, 1. [14] Catanzaro et al. (1966) *J. Res. Nat. Bur. Standrads* 71a, 453. [15] Nagashima et al. (2007) *MAPS* 42, A115. [16] Krot et al. (2005) *ApJ* 622, 1333. [17] Kimura et al. (1993) *GCA* 57, 2329. [18] Weber et al. (1995) *GCA* 59, 803. [19] Krot et al. (2007) *ApJ*, in press. [20] Davis et al. (2006) *LPS* XXXVIII, Abstract #2334.