# $^{26}$Al IN CHONDRULES FROM THE CR3.0 CHONDRITE QUEEN ALEXANDRA RANGE 99177: A LINK WITH O ISOTOPES.

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**Introduction:** Measurements of the ages of chondrules in primitive chondrites by $^{26}$Al-$^{26}$Mg systematics ($\tau_{1/2}$ of $^{26}$Al: 0.705 Myr; [1]) indicate that the majority formed ~1 to 3 Ma [2-6] after CAI's (($^{26}$Al/$^{27}$Al)$_{0,CAI}$ = 5.2×10$^{-5}$; [7,8]), assuming homogeneous distribution of $^{26}$Al in the inner Solar System [6]. However, many chondrules in primitive CR2 chondrites exhibit no excess in $\delta^{26}$Mg [9-12], which is enigmatic because thus far all primitive carbonacous and ordinary chondrite chondrules have similar ($^{26}$Al/$^{27}$Al)$_0$ values (0.3 to 1.0×10$^{-5}$; [2-6]). It is not known why some CR chondrules have excess $^{26}$Mg and some do not. As a result, we use the O isotopic signatures of chondrules from the highly pristine CR3.0 chondrite Queen Alexandra Range (QUE) 99177 as a proxy to investigate their relative ages. Our goal is to assess potential links between relative ages of CR chondrules and the environments from which their precursors originated.

**Samples and Methods:** Six type I chondrules in section QUE 99177, 49 were investigated. Chondrule $\delta^{17,18}$O values [13] lie on the primitive chondrule minerals (PCM) line [14]. $\Delta^{17}$O ($\delta^{17}$O – 0.52 × $\delta^{18}$O) values range from –5.2 to –1.7‰ (2SD: ~0.5 ‰). Chondrule Mg#'s (mol. % MgO/{MgO + FeO} of olivine and/or low-Ca pyroxene) range from 99.0 to 97.4 [13].

Mg and Al isotopes of chondrule plagioclase (An$_{82–99}$) were measured with the WiscSIMS Cameca IMS-1280 ion microprobe. Analytical procedures are similar to those in [3] and [15]. A 30–60 pA O$^{-}$ primary beam was employed, and was tuned for spot analyses 7–15 µm in diameter (Fig 1a). Secondary Mg ions were detected by peak switching with an electron multiplier. During $^{25}$Mg$^{+}$ acquisition, $^{27}$Al$^{+}$ ions were simulatenously detected with a Faraday cup. Running standards were synthetic anorthite glasses with 0.6 and 1% MgO, respectively [15]. $\delta^{26}$Mg uncertainties (2SE) of unknowns are ~±1.2‰.

Initial $^{26}$Al/$^{27}$Al ratios ($^{26}$Al/$^{27}$Al)$_0$ of chondrules were estimated from slopes of isochrons, using Isoplot 3.00 software. Fits were forced through an assumed origin (Fig. 1b), which will be verified by future Mg and Al isotope analysis of corresponding chondrule olivine and pyroxene.

**Results and Discussion:** Three to six SIMS spot analyses were performed on the chondrules, in order to determine their internal isochrons (e.g. Fig. 1b). Plagioclase $^{27}$Al/$^{24}$Al ratios ranged from 26 to 48. Two chondrules preserve excess $^{26}$Mg in plagioclase ($^{*}\delta^{26}$Mg: 1.0 to 2.1‰), with ($^{26}$Al/$^{27}$Al)$_0$ values of

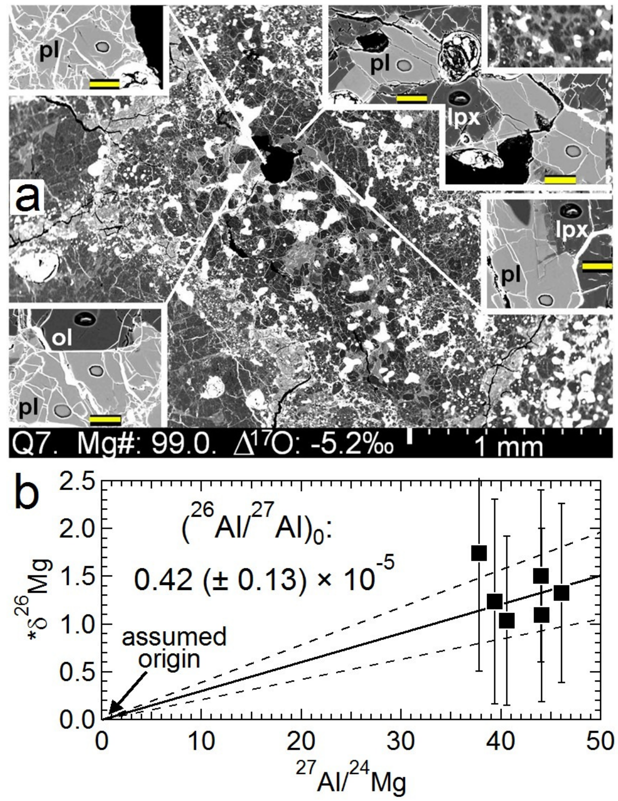


**Fig. 1.** (a) backscattered electron image of chondrule Q7. Chondrule Mg# is the average of olivine and low-Ca pyroxene. Insets with 20 µm scale bars show SIMS Al-Mg analyses of plagioclase, as well as SIMS oxygen-three isotope analyses [13] of ol and lpx. (b) isochron (2SD uncertainties) obtained from Q7 plagioclase SIMS measurements.

0.42(± 0.13)×10$^{-5}$ and 0.57(± 0.13)×10$^{-5}$, respectively (Fig. 2). $\Delta^{17}$O values of these chondrules are –5.2 and –5.0‰, respectively. The remaining chondrules ($\Delta^{17}$O: –2.8 to –1.7‰) have no excess $^{26}$Mg in plagioclase ($^{*}\delta^{26}$Mg: –0.1 to –0.2‰). However, their ($^{26}$Al/$^{27}$Al)$_0$ maxima range from 0.17 to 0.33×10$^{-5}$ (Fig. 2).

*Comparison to other chondrule data:* The ratio of of QUE 99177 chondrules with excess $^{26}$Mg (2 in 6) is similar to other investigations of CR chondrites, as 10 of 31 chondrules from [9-12] have ($^{26}$Al/$^{27}$Al)$_0$ values greater than 0.1 (Fig. 2). In addition, the QUE 99177 chondrules with excess $^{26}$Mg have ($^{26}$Al/$^{27}$Al)$_0$ values that are consistent with CO3.0 [3,4] and Acfer 094 (ungr. C 3.0) [5] chondrules. This is also true of many CR chondrules with excess $^{26}$Mg in the data of [9-12]. Limited data from chondrule fragments in cometary particles have no excess $^{26}$Mg [16] .

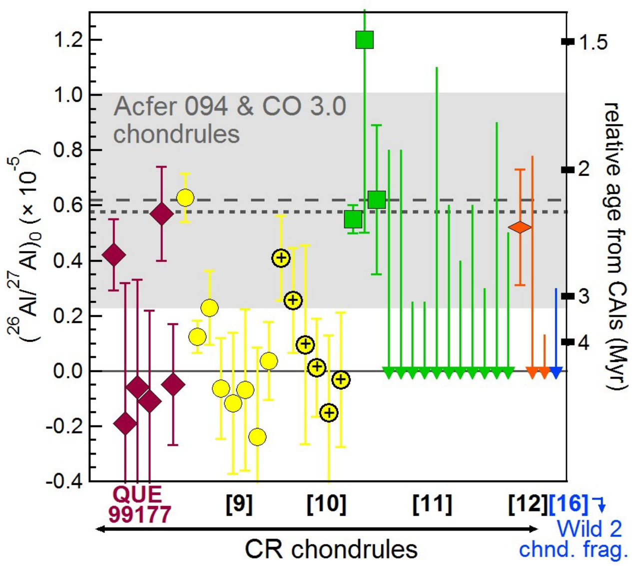


**Fig. 2.** $(^{26}Al/^{27}Al)_0$ comparison of CR, CO [3,4], Acfer 094 (C ungr.; [5]) chondrules, and a Wild 2 chondrule fragment. Dotted and dashed lines are the average of Acfer 094, and CO3.0 chondrules, respectively. The shaded area includes the 2SD max. and min. of CO3.0 and Acfer 094 chondrules, respectively. Several measurements from [11,12,16] show no excess, reporting only upper limits (lines with arrows at the origin). Relative ages are calculated with a $^{26}Al$ $\tau_{1/2}$ of 0.705 Myr [1] and a $(^{26}Al/^{27}Al)_{0,\ CAI}$ of $5.2\times10^{-5}$ [7,8].

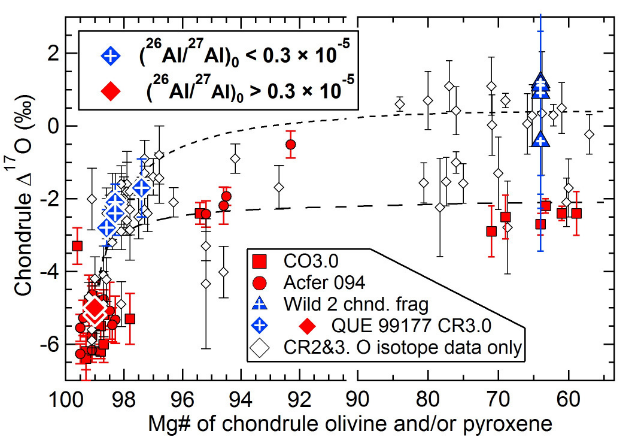


**Fig. 3.** $\Delta^{17}O$ vs. Mg# in CO3.0 [17], Acfer 094 [14], and CR [13,18-20] chondrules, and a Wild 2 chondrule fragment [16] (2SD unc.). All O-isotope data plot on or near the PCM line [14]. All solid symbols have accompanying Mg isotope data [3,5,16, this study]. Dotted and dashed lines show CR chondrule Mg#/$\Delta^{17}O$ relationships discussed in [13].

*The relationship between $^{26}Al$, O-isotopes, and chondrule mineralogy*: Primitive CR chondrules share common characteristics with Acfer 094 and CO3.0 chondrules. In particular Mg# 99 chondrules have $\Delta^{17}O$ values of –5 to –6 ‰, and many Mg# < 95 chondrules have $\Delta^{17}O$ values near –2.5 ‰ [13,14,17-20] (Fig. 3). CR chondrites also have Mg# < 99 chondrules with $\Delta^{17}O$ values near the TF line (0‰) [18-20] (Fig. 3). The wide range of chondrule Mg#'s within a given chondrite is proposed to have been the result of variable chondritic dust enrichment of precursors [13,14,17-20], where increasing dust enrichment yields more oxidized conditions during chondrule formation, leading to chondrule silicates with lower Mg#'s [21]. The increase in chondrule $\Delta^{17}O$ with decreasing Mg# is proposed to have been caused by addition of positive $\Delta^{17}O$ $H_2O$ [22] to precursors [13,14,17-20]. That CR chondrules arguably have two separate $\Delta^{17}O$ vs. Mg# trends [13] (Fig. 3) could suggest their chondrites accreted materials from two distinct chondrule-forming environments, which may have been spatially and/or temporally separated. If true, these two environments appear to be further distinguished by $^{26}Al$ chronology of CR chondrules, as $\Delta^{17}O$ –5 ‰, Mg# 99 chondrules have $(^{26}Al/^{27}Al)_0 > 0.3 \times 10^{-5}$, while Mg# 97.5 to 98.5 chondrules with $\Delta^{17}O$ values of –1.7 to –2.8 ‰ have $(^{26}Al/^{27}Al)_0 < 0.3\times10^{-5}$ (Fig. 3). This result differs from CO3.0 and Acfer 094 chondrules, which have $(^{26}Al/^{27}Al)_0 > 0.3\times10^{-5}$, regardless of $\Delta^{17}O$ and Mg# (Fig. 3). In addition, many low Mg# chondrule-like objects from the comet Wild 2 have $\Delta^{17}O$ values near 0‰ [16,23,24], and limited data suggest $(^{26}Al/^{27}Al)_0 < 0.3\times10^{-5}$ [16] (Fig. 3). Therefore, CR chondrites may have accreted materials in a unique location relative to other carbonaceous chondrites.

**References:** [1] Norris T.L. et al. (1983) *JGR, 88,* B331-B333. [2] Kita N.T. et al. (2000) *GCA 64*, 3913-3922. [3] Kurahashi E. et al. (2008) *GCA 72*, 3865-3882. [4] Kunihiro T. et al. (2004) *GCA 68*, 2947-2957. [5] Ushikubo T. et al. (2010) *LPS XVI*, #1491. [6] Villeneuve J. et al. (2009) *Science 325*, 985-988. [7] Jacobsen B. et al. (2008) *EPSL 272*, 353-364. [8] MacPherson G.J. et al. (2012) *ApJL 711*, L117-L121. [9] Nagashima K. et al. (2007) *MAPS 42*, A115. [10] Nagashima et al. (2008) *LPS XXXIX*, #2224. [11] Hutcheon I.D. et al. (2009) *GCA 73*, 5080-5099. [12] Kurahashi E. et al. (2008) *GCA 72*, A504. [13] Tenner T.J. et al. (2012) *LPS XLIII*, #2127. [14] Ushikubo T. et al. (2012) *GCA 90*, 242-264. [15] Kita N.T. et al. (2012) *GCA 86*, 37-51. [16] Ogliore R.C. et al. (2012) *ApJL 745*, L19. [17] Tenner et al. (2013) *GCA 102*, 226-245. [18] Tenner et al. (2011) *MAPS 46*, A233. [19] Schrader D.L. et al. (2013) *GCA 101*, 302-327. [20] Connolly Jr. H.C. and Huss G.R. (2010) *GCA 74*, 2473-2483. [21] Ebel D.S. and Grossman L. (2000) *GCA*, *64*, 339-366. [22] Sakamoto N. et al. (2007) *Science 317*, 231-233. [23] Nakamura T. et al. (2008) *Science 321*, 1664-1667. [24] Nakashima D. et al. (2012) *EPSL 357-358*, 355-365.