

²⁶Al-²⁶Mg DATING CALCIUM-ALUMINIUM-RICH INCLUSIONS

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Introduction: Refractory inclusions in meteorites include calcium-aluminium-rich inclusions (CAIs) and amoeboid olivine aggregates (AOAs). These solids are of particular interest because both long- and short-lived chronometers have shown that they are the oldest material that formed in the Solar System [1,2]. Thus, high-precision dating, petrographic, chemical and isotopic studies of refractory inclusions can offer insights into the chemical and astrophysical environment present in the solar nebula and/or proto-planetary disc during formation of our Solar System.

A particularly important aspect of refractory inclusions is the clearly demonstrated evidence of the former presence of the short-lived isotope ²⁶Al (mean age = 1.05 Myr) in most normal CAIs [1] with an initial abundance $> 5 \times 10^{-5}$. For more than 30 years it has been possible to measure this initial abundance of ²⁶Al in CAIs with a relative precision of $< \text{ca. } 10\%$. This makes it possible to determine ²⁶Al-²⁶Mg ages of other meteoritic material relative to CAIs with little significant uncertainty (ca. < 0.4 My) introduced from the initial ²⁶Al abundance measurement of CAIs.

Recent application of multiple-collector inductively coupled plasma mass spectrometry (MC-ICPMS) techniques to Mg isotope analysis of bulk CAIs [3,4] has produced two important results. Firstly, both solution-based and *in situ* studies have suggested that the initial ²⁶Al abundance of CAIs (²⁶Al/²⁷Al₀) is higher than the “canonical” value of ca. 5×10^{-5} i.e., 5.9×10^{-5} . Secondly, the precision of this measurement has been improved by almost an order of magnitude meaning that it is possible to determine ages of other meteoritic material relative to CAIs with uncertainties as low as 0.1 Myr. Given the variety of nebula (condensation/evaporation) and planetary processes (partial melting, crystallization) that were able to fractionate Al/Mg ratios in the young Solar System this should make the ²⁶Al-²⁶Mg system the method of choice for high-resolution dating a wide range of meteorite material.

However, recent reinvestigation of the ²⁶Al-²⁶Mg systematics of six CAIs from Allende [5] has questioned the revision of the initial abundance of ²⁶Al in CAIs to the “super-canonical” abundance of 5.9×10^{-5} . Here we report on a petrographic, chemical and isotopic study of a number (n = 9) of refractory inclusions from CV and CK chondrites, as well as a interlaboratory comparison of the six CAIs analysed in [5].

Analytical Techniques: Refractory inclusions were removed from meteorite slices using a diamond saw. After removal of most matrix material each refractory inclusion was either broken or sawn into two parts. One part was mounted in epoxy and polished for electron microprobe and laser ablation ICPMS analysis of major and trace elements, and any future *in situ* analytical study. The remaining fragment was used to obtain samples for ²⁶Al-²⁶Mg dating.

Petrographic and major and trace element analysis. Each polished sample was imaged and the major mineral phases analysed for major element compositions using a JEOL Superprobe 733 electron microprobe at Victoria University of Wellington. After major element analysis, minerals in each inclusion were analysed for >30 trace elements with a 193 nm laser ablation system coupled to an Agilent 7500 ICPMS at Victoria University of Wellington. BCR-2G was used as a standard to correct for trace element fractionation during the analysis and ⁴³Ca from the electron microprobe analysis was used as an internal standard.

Al/Mg ratio and Mg isotope analysis. Bulk pieces of refractory inclusions or handpicked mineral separates (pyroxene or mellilite/anorthite mixtures) were taken fully into solution using standard HF-HNO₃ digestion techniques. A small aliquot of this solution was used for Al/Mg determination by solution ICPMS. The remaining aliquot was then processed through several steps of ion exchange separation involving anion, Eichrom DGA and cation exchange resins to produce a Mg separate of $> 99\%$ purity. Ultra-pure Seastar acids were used for sample digestion and chemistry. Al/Mg ratios were determined on an Agilent 7500 ICPMS using gravimetrically prepared Al/Mg standards and BCR2 as an internal standard. Replicate analyses of BCR2 reproduce to better than 1% (2 sd) and are within 0.3% of the recommended value of this standard. Mg isotope ratios were determined using a Nu Plasma MC-ICPMS at Victoria University of Wellington and methods described more fully in [6]. The ²⁶Mg excess ($\delta^{26}\text{Mg}^*$) of each CAI is measured to a precision of $< \pm 0.015\%$. We use a kinetic law to calculate $\delta^{26}\text{Mg}^*$ as high-precision Mg isotope studies of CAIs have shown that this approach produces tightly defined isochrons that would not exist if $\delta^{26}\text{Mg}^*$ was calculated using an equilibrium law.

Samples: Refractory inclusions were extracted from the following meteorites:

- NWA2364 (CV3 chondrite) = CAI0, CAI1, CAI2, CAI3 and CAI4
- NWA 1559 (CK3-anomalous chondrite) = CAI8, AOA1 and AOA2
- NWA 760 (CV3 chondrite) = CAI5

In addition we carried out Al/Mg and Mg isotope measurements on aliquots of six CAIs from the CV3 chondrite Allende (A33, A39, A43, A44A, A60 and AJEF) generously provided to us by Dr Qing-zhu Yin and Benjamin Jacobsen from UC Davis by way of a interlaboratory comparison.

In all, a total of 15 refractory inclusions will be ^{26}Al - ^{26}Mg dated. CAI0, CAI1, CAI2, CAI8, A39, A43, A44A and AJEF are coarse-grained type B CAIs. A33 and CAI3 are compact type A CAIs and CAI4 is a fluffy type A CAI.

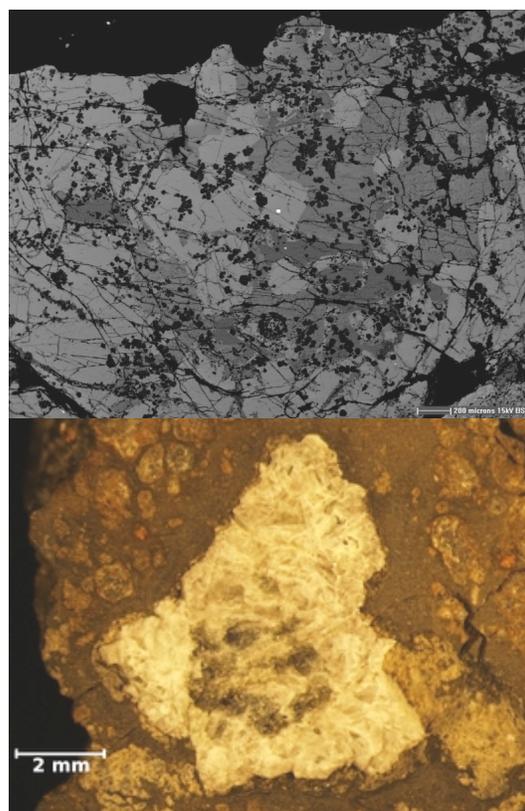
Results: To-date we have reanalyzed the Al/Mg ratios for the six Allende CAIs studied by [5] as well as the Mg isotope composition of an aliquot of A44A processed through our Mg chemical separation procedures. While we obtain some minor differences in Al/Mg ratios measured in New Zealand as compared to UC Davis these are not large enough to account for the discrepancy in initial ^{26}Al abundance of Allende CAIs reported by [3,4,5]. Our Al/Mg and Mg isotope measurement of Allende CAI A44A produces a model initial $^{26}\text{Al}/^{27}\text{Al}_0 = (4.98 \pm 0.14) \times 10^{-5}$, which is essentially within error of the value reported by [5].

We have also analysed a bulk fragment of a coarse-grained Type B CAI from NWA2364 (CAI0) illustrated in Figure 1. This fragment of CAI0 defines a very precise model initial $^{26}\text{Al}/^{27}\text{Al}_0 = (5.04 \pm 0.07) \times 10^{-5}$.

Discussion: The preliminary results of this study confirm that the “canonical” initial $^{26}\text{Al}/^{27}\text{Al}_0$ values reported by [5] for six Allende CAIs are unlikely to be the result of analytical artifacts. Moreover, the one CAI we have analysed from NWA2364 also has a “canonical” initial $^{26}\text{Al}/^{27}\text{Al}_0$ value that is significantly lower than the “super-canonical” $^{26}\text{Al}/^{27}\text{Al}_0$ values reported for CAIs in [3,4]. A critical evaluation of the reason for this discrepancy will be more appropriate when the remaining CAIs in this study have been analysed. In particular, a series of mineral separates and bulk fragments from a large Type B CAI (CAI1) have been prepared in order to precisely determine if CAIs with $^{26}\text{Al}/^{27}\text{Al}_0$ values of 5×10^{-5} have elevated initial ^{26}Mg abundances that are consistent with them recording a later thermal event ca. 300,000 years after primary CAI formation as represented by an initial

$^{26}\text{Al}/^{27}\text{Al}_0 = 5.9 \times 10^{-5}$. One possible explanation to account for the discrepancy between the different initial $^{26}\text{Al}/^{27}\text{Al}_0$ values being measured in the studies of [3,4,5] and also here relates to the scale of the sampling. The study of [3] involved sampling of nearly entire CAIs (i.e. true analyses of bulk CAIs), whereas the study of [5] and herein (thus far) involves sampling of rather small parts of bulk CAIs, which may result in the obtained $^{26}\text{Al}/^{27}\text{Al}_0$ values representing younger thermal events associated with internal redistribution of ^{26}Mg some time after primary CAI formation.

Figure 1 Plain-light and back-scattered electron image of CAI0 from NWA2364. This coarse grained CAI is composed of mellilite, fassaitic pyroxene, anorthite and spinel.



- References:** [1] Lee T. et al. (1976) *GRL*, 3, 41-44
 [2] Amelin Y. et al. (2002) *Science*, 297, 1678-1683
 [3] Thrane K. et al. (2006) *ApJ*, 646, L159-L162
 [4] Young E. D. et al. (2005) *Science*, 308, 223-227.
 [5] Jacobson B. et al. (2007) *LPS XXXVIII*, Abstract #1491 [6] Schiller M. et al. (2007) *this conference*.