BRIEF FORMATION INTERVAL FOR CALCIUM-ALUMINUM-RICH INCLUSIONS IN THE EARLY SOLAR SYSTEM. K. Thrane[1], M. Bizzarro[1] & J. Baker[2], [1]Geological Institute, University of Copenhagen, Øster Voldgade 10, DK-1350, Denmark, [2]School of Earth Sciences, Victoria University of Wellington, P.O. Box 600, Wellington, New Zealand.

A recent study of the ^{26}Al-^{26}Mg chronometer ($t_{1/2}$ ~ 730,000 yr) in six bulk CAIs from the Allende carbonaceous chondrite indicated that these objects may have formed over a short time interval, possibly within 50,000 yr [1]. However, in situ ^{26}Al-^{26}Mg data for CAIs from a number of carbonaceous chondrites suggest that these may have experienced a series of later transient heating events over ~ 300,000 yr [2]. This is in contrast with chondrules, the most abundant component of chondritic meteorites, which appear to have formed over a time interval of ≥ 3 Myr [1,3]. To elucidate the timing of the CAI-forming event(s), we have extended our ^{26}Al-^{26}Mg study of CAIs to other carbonaceous chondrites such as the Vigarano, SAH98044 and NWA779 meteorites. Rare earth elements (REE) analyses of a subset of these CAIs show they represent a wide range of types including objects with typical group II, III and V REE patterns. We also report high-precision δ^{26}Mg* measurements [the per mil (‰) excess in ^{26}Mg/^{24}Mg due to the presence of radiogenic ^{26}Mg (^{26}Mg*)] for terrestrial, lunar and martian samples, as well as chondrite meteorites, in order to assess the degree of ^{26}Mg isotope heterogeneity in the inner Solar System.

One basalt, two mantle olivines and two Mg standard solutions from Earth yield an average δ^{26}Mg* = −0.0002 ± 0.0022‰ (2 sd), providing an estimate of the reproducibility of δ^{26}Mg* measurements during the course of this study. Samples from the Moon and Mars have mean δ^{26}Mg* of 0.0012 ± 0.0031‰ and −0.0004 ± 0.0033‰ respectively, which are identical to the terrestrial average. Likewise, four chondrite meteorites have a δ^{26}Mg* value of −0.0010 ± 0.0023‰. These results show that the majority of inner Solar System bodies have a homogeneous ^{26}Mg abundance. Eleven new analyses of bulk CAIs combined with our earlier high-precision Mg isotope measurements of Allende CAIs [1] define an isochron corresponding to an initial ^{26}Al/^{27}Al of (5.85 ± 0.05)×10^{-5} and intercept of −0.0317 ± 0.0038‰ (Fig. 1). The CAI regression intercepts the present-day inner Solar System ^{26}Mg abundance at a ^{27}Al/^{24}Mg ratio of 0.0752 ± 0.0082 (Fig. 1, inset) that is significantly lower (25%) than current estimates of the solar ^{27}Al/^{24}Mg ratio (0.101 ± 0.004; [4]).

We infer that the bulk CAI isochron records the original Al/Mg fractionation leading to the CAI-forming event(s), in contrast to internal mineral isochrons of individual CAIs, which in most cases record secondary events such as thermal re-processing and melting [1-2]. As such, the bulk CAI isochron dates the timing of primary formation of CAI material (and/or CAI precursor material) from the early solar nebula, and this may have occurred in a time interval as short as ~ 20,000 yr, as this corresponds to the analytical uncertainty of the isochron. The majority of CAIs appear to have formed within a very restricted time interval, prior to thermal processing and/or transport to the accretion zone(s) of chondrite parent bodies. Thermal processing of CAI material may have

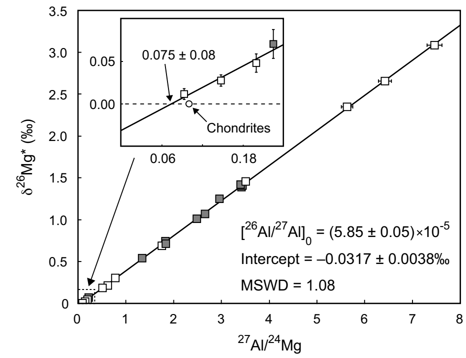

Figure 1: Al-Mg isochron diagram. Error bars are 2se and, in most cases, smaller than symbols. MSWD, mean square of weighted deviations. Open squares are data from this study, while gray squares are from [1]. The extremely good fit of the isochron (MSWD = 1.08) for CAIs with different stable Mg isotope ratios indicates that kinetic mass fractionation processes were responsible for the observed stable isotope variability. In contrast, calculating the δ^{26}Mg* value using an equilibrium (0.521) rather than a kinetic (0.511) mass dependent isotope fractionation relationship between δ^{26}Mg and δ^{25}Mg does not produce an isochron, and yields the following regression parameters: [^{26}Al/^{27}Al]$_0$ = (6.39 ± 0.29) ×10^{-5}, intercept of −0.058 ± 0.067‰ (MSWD = 27).

occurred over periods of a few 100,000 yr [2] or even up to a few million years after the CAI-forming event(s) [3]. Moreover, the presence of CAIs and younger chondrules in individual chondrite parent bodies imply a residence time for CAIs in the protoplanetary disc of > 2 Myr before their ultimate incorporation in these chondrite parent bodies.

CAIs for which precise model ages can be calculated (^{27}Al/^{24}Mg ≥ 0.3), however, display a range of ages of up to 110,000 yr, although these are all identical within uncertainty. We thus use a conservative estimate of 100,000 yr for the maximum duration of the CAI-forming event(s). CAIs from CV chondrite for which high-precision Mg isotope data are available ([1] and this study) record δ^{25}Mg values ranging from −3.1 to 6.8‰. Given the isochronous relationship defined by these objects (Fig. 1), our study also constrains the observed Mg stable isotope fractionations to have been primarily imparted during or shortly after the CAI-forming event(s). This is because some CAIs record heavy Mg isotope compositions which are indicative of 25-20% evaporative loss of Mg [5], and modeling of the data constrains partial evaporation of Mg in these objects to within 200,000 yr of the CAI-forming event(s), otherwise the isochron would be disturbed.

Our revised timescale for the CAI-forming event(s) places constraints on the astrophysical setting of the CAI-forming region. Astronomical observations of young stellar objects (YSO) indicate that the brief CAI formation interval defined by Al-Mg dating is inconsistent with the secular evolution of T-Tauri stars, since this stage typically lasts ~ 1 to 10 Myr [6]. Rather, it corresponds to the time-scale of Class 0 and I YSOs, that is, proto-stars deeply embedded in their nascent molecular clouds and surrounded by infalling envelopes and outflowing jets. In addition, the high mass accretion rates typical of Class 0 and I YSOs ($>10^{-6} M_{\odot}$/yr; [7] yield disc midplane temperature estimates reaching 1500K within 2 AU of the central proto-star [8], in agreement with temperature gradients inferred from the mineralogy and bulk composition of most CAIs. The data presented in this study thus support models favoring CAI formation during the infall stage of the proto-stellar evolution of the Sun, at radial distances less than ~ 2 AU.

The negative intercept of the CAI isochron (Fig. 1, inset) is consistent with a solar $^{27}Al/^{24}Mg > 0$, and thus average Solar System material has elevated $^{26}Mg^*$ as compared to an Al-free reservoir having formed at the same time as CAIs. This observation unequivocally demonstrates that the ^{26}Al nuclide was widespread and homogeneously distributed in the inner protoplanetary disc of the young Solar System, as the Earth, Moon, Mars and chondrite parent bodies have identical and elevated ^{26}Mg compared to the initial $\delta^{26}Mg^*$ of -0.0317 ± 0.0038‰ defined by the CAI isochron. We calculate, however, a range of 0.0084‰ in the $\delta^{26}Mg^*$ from the uncertainty of the weighted averages of these bodies, which allows a variation of ~15% in the initial abundance of ^{26}Al within the accretion region of Earth, Moon, Mars and chondrite parent bodies. None the less, these results cannot be reconciled with models proposing an origin for ^{26}Al by irradiation processes within the Solar System, which would lead to large scale heterogeneous distribution of this nuclide in early Solar System materials [9-10]. Instead, our data support a stellar origin for ^{26}Al, that is, synthesis within an Asymptotic Giant Branch star or supernova, and rapid injection and homogenization prior to or during collapse of the molecular cloud from which our Solar System formed.

The CAI regression intercepts the present-day Solar System ^{26}Mg abundance ($\delta^{26}Mg^* = 0$) at a $^{27}Al/^{24}Mg$ ratio that is lower by ~ 25% as compared to current estimates of the solar $^{27}Al/^{24}Mg$ ratio based on analyses of chondritic meteorites or the composition of the solar photosphere (Fig. 1, inset). This observation can potentially be reconciled in a number of ways: (1) CAIs have an exotic, non-solar, Mg isotope composition, (2) the abundance of the ^{26}Al nuclide was diluted by ~ 15% in the accretion region of the terrestrial planets compared to the CAI-forming region, (3) some (but not most) of the ^{26}Al in the CAI-forming region has been generated by energetic particle irradiation, and this irradiation component is not present in the accretion region of the terrestrial planets, or (4) CAIs formed from a reservoir with lower $^{27}Al/^{24}Mg$ compared to average inner Solar System bodies.

The uniform Mg isotope composition ($\delta^{25}Mg$ and $\delta^{26}Mg^*$) of most inner Solar System planets and planetesimals ([11-12] and this study) is not easily reconciled with either a non-solar Mg isotope composition for CAIs, or a lesser abundance of ^{26}Al in the accretion region of the terrestrial planets compared to the CAI-forming region. Further, the extremely good fit of the isochron support solar ^{24}Mg and ^{25}Mg abundances for CAIs analysed in this study, since a terrestrial $^{25}Mg/^{24}Mg$ ratio is assumed in the calculation of the $\delta^{26}Mg^*$ value. An irradiation-produced component in the $^{26}Mg^*$ of CAIs is difficult to reconcile with the fit of the isochron, since the production of ^{26}Al by particle irradiation is not restricted to reactions involving ^{27}Al. This can also occur through reactions with ^{24}Mg, ^{25}Mg and ^{28}Si [10], in which case the isochron relationship of Figure 1 would not be readily preserved. As such, the non-solar $^{27}Al/^{24}Mg$ inferred from the CAI isochron is most easily understood if it reflects a source feature of the CAI-forming reservoir.

Astronomical observations of protoplanetary discs indicate that dust around YSOs is highly crystalline, mainly in the form of Mg-rich silicates such as forsterite and enstatite, and this crystallization appears to have occurred in the active phase of the disc [13]. Furthermore, these show that the highest levels of crystallinity are observed within the innermost portion of the disc (< 2 AU), with increased abundances of forsterite as compared to enstatite. Similar crystalline silicates are present in the matrices of pristine primitive chondrites, and can form as a result of thermal annealing of amorphous grains or by local vaporization and subsequent gas-phase condensation [14]. Inward drift of mm-sized particles due to gas drag will occur over relatively short time-scales of ~ 10^4 yr [15] as compared to the CAI-forming interval of ~ 10^5 yr. Inward particle drift will lead to local enhancement in the abundances of specific vapor phases when solids are vaporized as they travel through evaporation fronts [16]. As such, inward transport of Mg-rich silicates can result in a rapid increase of the Mg concentration in the ambient nebular gas when solids travel trough the forsterite evaporation front at 1400K. This provides a mechanism by which the Al/Mg ratio of the CAI-forming reservoir can be decreased in a short time span by thermal processing of Mg silicates within the innermost part of the accretion disc. This interpretation suggests that thermal processing of amorphous silicate dust occurred very early in the evolution of protoplanetary discs.

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