(^{26}Al/^{27}Al)$_0$ HOMOGENEITY REINSTATED, AND AN EARLY ONSET OF SILICATE FORMATION IN THE NASCENT SOLAR SYSTEM. T. Gregory[1,2], T.-H. Luu[1], C. D. Coath[1], S. S. Russell[2], and T. Elliott[1], [1]Bristol Isotope Group, School of Earth Sciences, University of Bristol, Bristol, BS8 1RJ, UK, timothy.gregory@bristol.ac.uk, [2]Department of Earth Sciences, Natural History Museum, London, SW7 5BD, UK.

Introduction: Chondrules, a major component of chondritic meteorites, are mm- to µm-sized quench droplets composed primarily of ferromagnesian silicates and feldspathic mesostasis [1]. Several models exist to explain their formation mechanism(s), but experimental and cosmochemical constraints on these models remain loose. A powerful constraint on chondrule formation mechanisms is their age distribution.

Two of the most useful tools at our disposal to understand chondrule chronology are the Al-Mg and the Pb-Pb isotope chronometers. The extinct Al-Mg chronometer relies on the decay of ^{26}Al→^{26}Mg ($t_{½}$ ~ 0.7 Myr), and the extant Pb-Pb chronometer relies on the simultaneous decay of ^{238}U→^{206}Pb ($t_{½}$ ~ 4.5 Gyr) and ^{235}U→^{207}Pb ($t_{½}$ ~ 0.7 Gyr). Both systems agree that CAIs (calcium-aluminium-rich inclusions: ultra-refractory condensates) were the first solids to form in the Solar System and their time of formation was brief [2,3,4]. However, they disagree on the timing of chondrule formation: internal Al-Mg isochrons records a ~2 Myr gap between CAI and chondrule formation [5] while the Pb-Pb chronometer does not [3]. Critically, the Al-Mg system relies on the assumption of initial ^{26}Al/^{27}Al ((^{26}Al/^{27}Al)$_0$) homogeneity.

The current picture of the early Solar System is that CAIs record the so-called "canonical" (^{26}Al/^{27}Al)$_0$ of ~5.2×10^{-5} [6,7], yielded by plotting an Al-Mg isochron of bulk-CAIs and CAI mineral separates. The CAI isochron derived by [8] yields an initial mass-independent Mg-isotope composition (Δ'^{26}Mg$_0$) −40±30 ppm. This is a model that is consistent with a homogeneous (^{26}Al/^{27}Al)$_0$: to evolve to the modern bulk-Solar System of Δ'^{26}Mg = 4.5±1.0 ppm (represented by bulk-CI chondrites) [7] with a (^{26}Al/^{27}Al)$_0$ of 5.24×10^{-5}, a Δ'^{26}Mg$_0$ of -33.3 ppm is required, well within the bounds of error of the [6] isochron intercept.

More recently, [8] constructed an isochron consisting of bulk-CAIs, CAI separates, and AOAs (amoeboid olivine aggregates: irregularly-shaped aggregates of forsterite that have a similar O isotopic composition to CAIs [9]). This array yielded the canonical (^{26}Al/^{27}Al)$_0$ but a Δ'^{26}Mg$_0$ of −15.9±1.4 ppm. To evolve from this Δ'^{26}Mg$_0$ to the modern bulk-Solar System (inferred from bulk-CI chondrites [8]) requires a (^{26}Al/^{27}Al) of ~2.8×10^{-5}. This led [8] to hypothesise a heterogeneity in (^{26}Al/^{27}Al)$_0$ of a factor of ~2 between the CAI-AOA-forming region(s) and the bulk-chondrite forming region(s). This can also explain the apparent gap between CAI and chondrule ages as an artefact of the ^{26}Al→^{26}Mg chronometer. This [9] model predicts that no Solar System object will have a Δ'^{26}Mg of less than −15.9 ppm. We tested this hypothesis using refractory forsterites.

Refractory forsterite: Refractory forsterite grains (RFs) are ubiquitous in unequilibrated chondrites [10]. They are characterised by their extreme Mg enrichment ($Fo_{>98}$), high refractory lithophile (RLE; Ca, Al, Ti) contents, low Ni and Mn contents [11], and their mass-independent enrichment in ^{16}O (expressed as a low Δ'^{17}O) [12]. They possibly originate in RLE-rich condensed melts [11]. They occur in type-I chondrules, and as fragmented isolated matrix grains. Their presence as "relicts" in some chondrules [13] suggests that they pre-date some chondrules, making them potential targets for constraining (i) Δ'^{26}Mg$_0$ of the Solar System and (ii) chondrule chronology.

Techniques: We petrographically and isotopically characterised RFs in sections of Northwest Africa (NWA) 8276 (L3.0), NWA 4502 (CV3), and Felix (CO3.3) using *in-situ* techniques (scanning electron microscopy, electron probe microanalysis, and secondary ionisation mass spectrometry). A sub-set were extracted using high-precision micro-excavation and micro-milling, ensuring that RFs were precisely sampled (Fig. 1): their Mg isotopic composition were measured *ex-situ* using multi-collector inductively coupled plasma mass spectrometry.

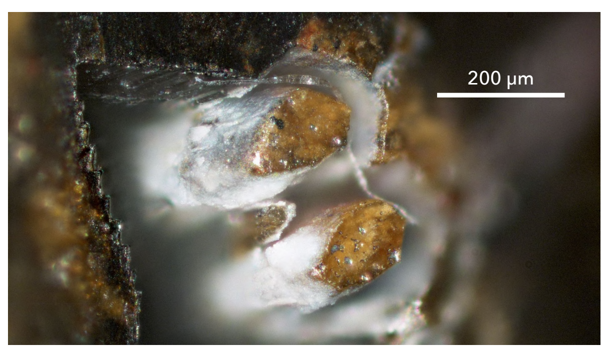

Fig. 1. High-spatial precision micro-excavation of two RFs from a RLE-rich type-I chondrule (side-on).

Fragments of chondrules: Our suite of RFs (Fig. 2) are similar in composition to bulk-chondrules from CV chondrites, with their Δ'^{17}O falling between −4 and −6‰ [14]. They have a range of RLE concentrations, and there is no systematic relationship between their chemical and O isotopic composition, or their petrographic setting. We therefore interpret them to have a common origin in RLE-rich type-I chondrules. Isolated RFs represent phenocrysts from fragmented chondrules, and the relict RFs in type-II chondrules represent unmolten type-II chondrule precursors, in-line with arguments from other authors [11].

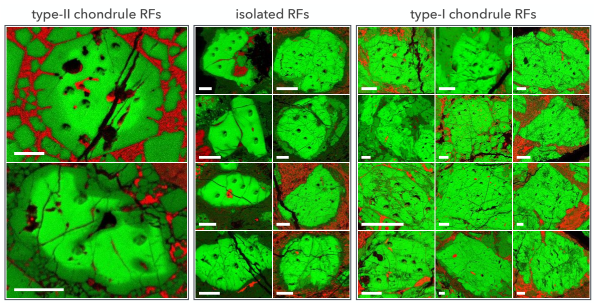

Fig. 2. X-ray maps of the suit of RFs that we petrologically characterised and measured *in-situ* oxygen isotope compositions for. A sub-set were micro-sampled for Mg isotopic measurements. Scale bars = 50 µm; green = Mg, red = Al.

Model ages: The $^{27}Al/^{24}Mg$ for the RFs was ×~10 higher when measured *ex-situ* compared to *in-situ*: we interpret this to reflect contamination by Al-rich veins cross-cutting some RFs during micro-excavation and micro-milling. It is therefore not appropriate to use their *ex-situ* $^{27}Al/^{24}Mg$ in calculating model ages. Correcting model ages using their *in-situ* $^{27}Al/^{24}Mg$ makes negligible difference to their ages. Therefore we do not use $^{27}Al/^{24}Mg$ when calculating model ages: they are based purely on the Solar System $\Delta'^{26}Mg$ growth curve and therefore represent a maximum age.

Early silicate formation: Model RF ages span from CAI formation to >4 Myr post-CAIs (Fig. 3): this places the onset of RF formation, and therefore RLE-rich chondrule formation, alongside CAI formation. Two RFs had a $\Delta'^{26}Mg$ indistinguishable from CI-chondrites, such that most ^{26}Al had decayed and a model age could not be calculated. This removes the apparent gap between CAI and chondrule formation recorded in Al-Mg model ages, and suggests that the onset of major silicate phases (likely RLE-rich chondrules) was concurrent with CAI formation.

(^{26}Al/^{27}Al)$_0$ homogeneity: The $\Delta'^{26}Mg_{DSM\text{-}3}$ of the RFs range over ~44 ppm. They span lower than the $\Delta'^{26}Mg_0$ calculated by [8], suggesting that constructing an isochron from CAIs and AOAs is erroneous and it does not yield the $\Delta'^{26}Mg_0$ of the Solar System. Therefore, the $\Delta'^{26}Mg$ evolution curve based on this isochron does not have chronological significance.

The $\Delta'^{26}Mg$ of RFs are consistent with the canonical CAI evolution curve [8] and thus reinstates $(^{26}Al/^{27}Al)_0$ homogeneity in the Solar System and the chronological significance of the $^{26}Al\rightarrow^{26}Mg$ system.

Conclusions: Refractory forsterite grains originate in RLE-rich chondrules that formed in the chondrule-forming region(s). Their low $\Delta'^{26}Mg$ show that isochrons consisting of both CAI and AOA material [8] are not true isochrons and thus cannot be used to constrain $\Delta'^{26}Mg_0$ or $(^{26}Al/^{27}Al)_0$. The $\Delta'^{26}Mg$ of RFs are consistent with canonical CAI isochrons [e.g. 7], therefore reinstating $(^{26}Al/^{27}Al)_0$ homogeneity in the early Solar System, and demonstrating the chronological significance of the $^{26}Al\rightarrow^{26}Mg$ system.

The Al-Mg model ages suggest that RFs, and therefore RLE-rich chondrules, began forming at the same time as CAIs (Fig. 3), thus refuting the gap between CAI formation and the onset of chondrule formation. We suggest that the discrepancy between Pb-Pb ages and internal Al-Mg ages of chondrules is caused by widespread heating events ~2–3 Myr post-CAI that reset the Al-Mg chronometer but left the Pb-Pb chronometer unperturbed.

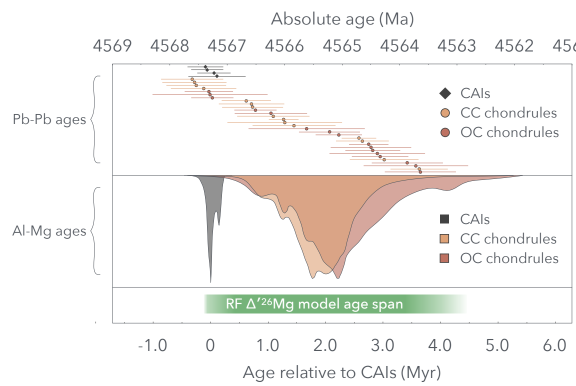

Fig. 3. Pb-Pb (top) and Al-Mg (middle) chondrule ages, and the $\Delta'^{26}Mg$ age range of RFs (bottom).

[1] Russell S. S. et al (2018) *Chondrules: Records of Protoplanetary Disk Processes*, Cambridge Planetary Science. [2] Amelin Y. et al. (2010) *EPSL.*, 300, 343-350. [3] Connelly et al. (2012) *Sci.*, 338, 651-655. [4] MacPherson et al. (1995) *Meteor.* 30, 365-386. [5] Villeneuve et al. (2009) *Sci.*, 325, 985-988. [6] Lee T. et al. (1976) *GRL*. 3, 109-112. [7] Jacobsen et al. (2008) *EPSL*. 272, 353-364. [8] Larsen et al. (2011) *ApJ*. 735, L37. [9] Fagan et al. (2004) *GCA*. 68, 2591-2611. [10] Pack et al. (2004) *GCA*. 68, 1135-1157. [11] Pack et al. (2005) *GCA*. 69, 3159-3182. [12] Weinbruch S. et al. (1993) GCA. 57, 2649-2661. [13] Jones R. H. (1990) *GCA*. 54, 1785-1802. [14] Jones R. H. et al. (2004) *GCA*. 68, 3423-3438.