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Distribution of ^{26}Al in the CR chondrite chondrule-forming region of the protoplanetary disk

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Abstract

We report on the mineralogy, petrography, and *in situ* measured oxygen- and magnesium-isotope compositions of eight porphyritic chondrules (seven FeO-poor and one FeO-rich) from the Renazzo-like carbonaceous (CR) chondrites Graves Nunataks 95229, Grosvenor Mountains 03116, Pecora Escarpment 91082, and Queen Alexandra Range 99177, which experienced minor aqueous alteration and very mild thermal metamorphism. We find no evidence that these processes modified the oxygen- or Al–Mg isotope systematics of chondrules in these meteorites. Olivine, low-Ca pyroxene, and plagioclase within an individual chondrule have similar O-isotope compositions, suggesting crystallization from isotopically uniform melts. The only exceptions are relict grains in two of the chondrules; these grains are ^{16}O-enriched relative to phenocrysts of the host chondrules. Only the FeO-rich chondrule shows a resolvable excesses of ^{26}Mg, corresponding to an inferred initial ^{26}Al/^{27}Al ratio [(^{26}Al/^{27}Al)$_0$] of $(2.5 \pm 1.6) \times 10^{-6}$ (±2SE). Combining these results with the previously reported Al–Mg isotope systematics of CR chondrules (Nagashima et al., 2014, *Geochem. J.* **48**, 561), 7 of 22 chondrules (32%) measured show resolvable excesses of ^{26}Mg; the presence of excess ^{26}Mg does not correlate with the FeO content of chondrule silicates. In contrast, virtually all chondrules in weakly metamorphosed (petrologic type 3.0–3.1) unequilibrated ordinary chondrites (UOCs), Ornans-like carbonaceous (CO) chondrites, and the ungrouped carbonaceous chondrite Acfer 094 show resolvable excesses of ^{26}Mg. The inferred (^{26}Al/^{27}Al)$_0$ in CR chondrules with resolvable excesses of ^{26}Mg range from $(1.0 \pm 0.4) \times 10^{-6}$ to $(6.3 \pm 0.9) \times 10^{-6}$, which is typically lower than (^{26}Al/^{27}Al)$_0$ in the majority of chondrules from UOCs, COs, and Acfer 094. Based on the inferred (^{26}Al/^{27}Al)$_0$, three populations of CR chondrules are recognized; the population characterized by low (^{26}Al/^{27}Al)$_0$ ($<3 \times 10^{-6}$) is dominant. There are no noticeable trends with major and minor element or O-isotope compositions between these populations. The weighted mean (^{26}Al/^{27}Al)$_0$ of 22 CR chondrules measured is $(1.8 \pm 0.3) \times 10^{-6}$. An apparent agreement between the ^{26}Al–^{26}Mg ages (using weighted mean value) and the revised (using ^{238}U/^{235}U ratio for bulk CR chondrites of 137.7789 ± 0.0085) ^{207}Pb–^{206}Pb age of a set of chondrules from CR chondrites (Amelin et al., 2002, *Science* **297**, 1678) is consistent with the initial ^{26}Al/^{27}Al ratio in the CR chondrite chondrule-forming region at the canonical level ($\sim 5.2 \times 10^{-5}$), allowing the use of ^{26}Al–^{26}Mg systematics as a chronometer for CR chondrules. To prove chronological significance of ^{26}Al for CR chondrules, measurements of Al–Mg and U–Pb isotope systematics on individual chondrules are required. The presence of several generations among CR chondrules indicates some chondrules that accreted into the CR chondrite parent asteroid avoided melting by later chondrule-forming events, suggesting chondrule-forming processes may

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have occurred on relatively limited spatial scales. Accretion of the CR chondrite parent body occurred at $>4.0^{+0.5}_{-0.3}$ Ma after the formation of CAIs with the canonical $^{26}Al/^{27}Al$ ratio, although rapid accretion after formation of the major population of CR chondrules is not required by our data.

Keywords: ^{26}Al; Chronology; Oxygen isotopes; CR chondrite; Renazzo; Chondrule; Accretion

1. INTRODUCTION

^{26}Al is a short-lived radionuclide that decays to ^{26}Mg with a half-life of ~0.705 Myr (Norris et al., 1983). Its short half-life and presence in the early Solar System make ^{26}Al potentially one of the most precise chronometers of early Solar System processes, if it can be demonstrated that ^{26}Al was uniformly distributed in the protoplanetary disk (e.g., MacPherson et al., 1995; Jacobsen et al., 2008; Larsen et al., 2011; Krot et al., 2012; Liu et al., 2012; Wasserburg et al., 2012; Kita et al., 2013; Park et al., 2013). It is also possibly an important heat source for early-accreted planetesimals (e.g., Urey, 1955; Ghosh and McSween, 1998; Hevey and Sanders, 2006; Sahijpal et al., 2007; Elkins-Tanton et al., 2011; Schiller et al., 2015). Both local, solar energetic particle irradiation, and external, stellar origins for ^{26}Al have been proposed to explain the presence of ^{26}Al in the early Solar System at a high initial $^{26}Al/^{27}Al$ ratio, $(^{26}Al/^{27}Al)_0$, relative to the Galactic chemical background (e.g., McKeegan et al., 2000; Meyer, 2005; Chaussidon et al., 2006; Arnould et al., 2006; Wasserburg et al., 2006; Duprat and Tatischeff, 2007; Larsen et al., 2011; Gounelle and Meynet, 2011). However, the maximum amount of ^{26}Al produced by irradiation during the life-time of the protoplanetary disk is insufficient to account for the amount of ^{26}Al that was present in the disk assuming its uniform distribution at the canonical level [$(^{26}Al/^{27}Al)_0 \sim 5.2 \times 10^{-5}$ (Jacobsen et al., 2008)], which instead requires a recent stellar input (Duprat and Tatischeff, 2007). The stellar origin of ^{26}Al in the solar protoplanetary disk is generally accepted (e.g., Meyer, 2005; Arnould et al., 2006; Wasserburg et al., 2006; Duprat and Tatischeff, 2007; Gounelle and Meynet, 2011; Krot et al., 2012), but the abundance of ^{26}Al and the degree of its heterogeneity remain controversial (e.g., Larsen et al., 2011; Wasserburg et al., 2012; Kita et al., 2013; Bizzarro et al., 2014; Bizzarro, 2015; Bollard et al., 2015; Schiller et al., 2015).

Utilizing the ^{26}Al–^{26}Mg chronometer depends upon ^{26}Al being homogeneously distributed in the protoplanetary disk during an object's formation (i.e., CAI [calcium–aluminum-rich inclusion], chondrule, or achondrite), and the possible non-radiogenic abundance variations of ^{26}Mg being accounted for. ^{26}Al appears to have been heterogeneously distributed during the epoch of CAI formation, and, therefore, cannot be used as a chronometer for the duration of this epoch (e.g., Krot et al., 2012; Liu et al., 2012; Makide et al., 2013; Park et al., 2013). In addition, some refractory grains and inclusions show large variations (typically deficits) in the initial $^{26}Mg/^{24}Mg$ ratio (e.g., Wasserburg et al., 1977; Liu et al., 2009; Wasserburg et al., 2012; Park et al., 2013). These observations provide clear evidence for Mg-isotope heterogeneity in the CAI-forming region. Despite these variations, the majority of CAIs from the Vigarano-like carbonaceous (CV) chondrites have the canonical $(^{26}Al/^{27}Al)_0$ (e.g., MacPherson et al., 1995; Jacobsen et al., 2008; Larsen et al., 2011). While CV CAIs with the canonical $(^{26}Al/^{27}Al)_0$ are generally considered to have formed over a short timescale (i.e., 0.004–0.02 Ma; Jacobsen et al., 2008; Larsen et al., 2011), uncertainties in the distribution of ^{26}Al make this interpretation ambiguous. Instead, variations in the $(^{26}Al/^{27}Al)_0$ of CAIs may suggest that there are multiple CAI generations.

While the canonical $(^{26}Al/^{27}Al)_0$ was reached in the CV CAI-formation region (e.g., Krot et al., 2012; Kita et al., 2013; Wadhwa et al., 2013), the distribution of ^{26}Al (homogeneous *vs.* heterogeneous) in the protoplanetary disk after the epoch of CAI formation remains controversial (e.g., Villeneuve et al., 2009; Larsen et al., 2011; Kleine et al., 2012; Krot et al., 2012; Kruijer et al., 2014). The U-corrected ^{207}Pb–^{206}Pb and ^{182}Hf–^{182}W ages applied to angrites have been found to be inconsistent with their inferred ^{26}Al–^{26}Mg ages (Larsen et al., 2011; Kleine et al., 2012; Schiller et al., 2015), suggesting either ^{26}Al and/or Mg-isotope heterogeneity in the disk, or resetting of the ^{26}Al–^{26}Mg system in these meteorites. However, homogeneity of ^{182}Hf and ^{26}Al at least in the CV CAI and angrite formation region has been argued due to agreement of ^{182}Hf–^{182}W and inferred ^{26}Al–^{26}Mg ages using a revised initial $^{182}Hf/^{180}Hf$ ratio (Kruijer et al., 2014).

In contrast, evidence for heterogeneity of ^{26}Al in two chondrule-forming regions of the protoplanetary disk comes from correlated ^{26}Al–^{26}Mg and U-corrected Pb–Pb studies of individual chondrules from Allende (CV3) and Northwest Africa (NWA) 5697 (L3.1). These coordinated analyses, where each isotopic system is studied on the same chondrule, show that the ^{26}Al–^{26}Mg ages are younger than the U-corrected Pb–Pb ages by ~1–3 Ma (Bizzarro et al., 2014; Bollard et al., 2015; Bizzarro, 2015). If the Al–Mg and Pb–Pb systems were not disturbed, this age discrepancy argues for heterogeneity of ^{26}Al, at least in the regions of the protoplanetary disk where these chondrules formed.

Assuming a homogeneous distribution of magnesium isotopes in the disk, ingrowth of radiogenic ^{26}Mg in chondrules due to the decay of ^{26}Al is consistent with ^{26}Al homogeneity to ±10% of the canonical level (Villeneuve et al., 2009). We note, however, that due to the relatively low-precision measurements of $^{26}Mg/^{24}Mg$ ratio by SIMS (>±10 ppm) compared to the total ingrowth of ^{26}Mg (~40 ppm) in solids having solar $^{27}Al/^{24}Mg$ ratio of 0.101, this conclusion is rather uncertain.

Using the ^{26}Al–^{26}Mg system as a chronometer requires also that aluminum or magnesium did not migrate to, or