

Origin of nucleosynthetic Sr isotope anomalies in fine grained calcium and aluminum-rich inclusions from Allende. Y. Masuda¹ and T. Yokoyama¹, ¹Department of Earth and Planetary Sciences, Tokyo Institute of Technology (masuda.y.an@m.titech.ac.jp).

Introduction: Recent innovations in mass spectrometric technology revealed that Calcium and Aluminum-rich Inclusions (CAIs) in chondritic meteorites possess stable isotopic compositions distinct from those in terrestrial materials for various elements including Ti, Cr, Sr, Mo, Ba, Nd, and Sm [1,2]. The observed differences, which are recognized as nucleosynthetic isotope anomalies in CAIs, suggest that stable isotopes of these elements were not homogeneously distributed in the early Solar System. Most of previous studies regarding isotope anomalies in CAIs were targeting coarse-grained inclusions (CGs) because CGs are easy to separate from meteorite specimens. However, CGs are considered to have experienced melting via reheating after their condensation, such that the observed isotopic data of CGs do not necessarily represent the original compositions. As opposed to CGs, fine-grained CAIs (FGs), consisting of fine-grained minerals (~ 20 μm), have most likely evaded the melting after their formation, making FGs useful to investigate the primitive chemical and isotopic conditions in the early Solar System.

Previous studies on nucleosynthetic Sr isotope anomalies in CAIs revealed that the $\mu^{84}\text{Sr}$ values in CGs were relatively uniform at ~100–120 ppm, while those in FGs varied from 31 to 287 ppm [3, 6, 7]. Most recently, a stepwise acid leaching experiment on some FGs showed that there were multiple phases within single FGs presenting distinct $\mu^{84}\text{Sr}$ values, the maximum of which reached ~80,000 ppm [8]. Such a high $\mu^{84}\text{Sr}$ value suggests the presence of presolar grains enriched in p-nuclides in FGs [8], although the coexistence of presolar grains and materials condensed from a high temperature gas remains enigmatic.

In this study, we conducted coordinated analyses of elemental abundances and Sr isotopic compositions in FGs from the Allende meteorite. Our goal is to decipher the origin of Sr isotope anomalies in FGs and the processes that FGs have experienced before accretion of the meteorite parent body.

Experimental: Eight FGs (FG1–8) in four Allende slabs were examined in this study. The mineralogical description of the FGs was conducted by elemental mapping (Mg-Al-Ca) with a scanning electron microscope coupled with electron diffraction spectrometry (SEM-EDS; S-3400N, Hitachi). The FG samples dedicated for chemical and isotopic analyses were collected using a micro-milling sampling system. In cases of three relatively large FGs (FG2, 7, and 8), two separate sample aliquots were collected from individual inclusions.

It should be noted that FG8 is doubly layered (Fig. 1); the samples FG8-1 and FG8-2 were collected from the inner and outer part of FG8, respectively.

After acid digestion for the collected FGs, elemental abundances of 22 elements (Rb, Sr, Y, Cs, Ba, REEs, Pb, Th, and U) were analyzed with ICP-QMS (X series 2, Thermo Scientific) using 2–5% fractions of digested sample solutions. The remainder of the aliquot was dedicated for obtaining the $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{84}\text{Sr}/^{86}\text{Sr}$ ratios with TIMS (Triton-plus, Thermo Scientific). The $^{84}\text{Sr}/^{86}\text{Sr}$ ratio was reported as $\mu^{84}\text{Sr}$ notation representing 10^6 times relative deviation from a standard NIST 987 measured in the same analytical campaign.

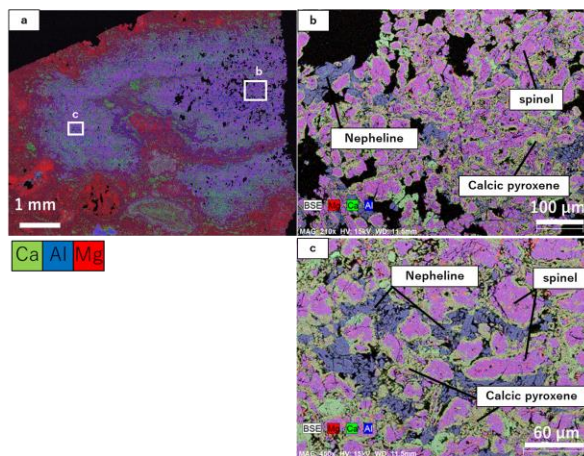


Fig. 1. a) Combined X-ray elemental map of FG8 with Mg (red), Ca (green), and Al (blue). b and c) Combined X-ray elemental map of the regions outlined in (a).

Results: The CI-normalized [10] REE abundances in the FG samples showed group II REE patterns, in which HREEs (e.g., Er, Lu) were depleted compared to LREEs (e.g., La, Nd). The REE patterns for FG8-1 and FG8-2 were consistent with each other, suggesting that FG8 was not an aggregate made up of distinct FGs.

The $\mu^{84}\text{Sr}$ values in FG1 to FG8 varied from 57 to 853 ppm. Our new data cover nearly the entire range of $\mu^{84}\text{Sr}$ values obtained in the previous studies [3, 6, 7]. In particular, FG8-1 ($\mu^{84}\text{Sr} = 83 \pm 50$ ppm) and FG8-2 ($\mu^{84}\text{Sr} = 853 \pm 47$ ppm) presented a large Sr isotopic heterogeneity within a single refractory inclusion. The value in FG8-2 was notably higher than the values that have been reported to date.

Discussion: Because FGs are composed of fine-grained minerals with complex shapes, it is necessary to consider the potential involvement of matrix materials

during micro-drill sampling. Additionally, it is important to evaluate Sr influx from the matrix associated with the aqueous alteration in the parent body. There was a correlation between the $\text{Sr}/\text{Th}_{\text{n(CI)}}$ and $\text{Rb}/\text{Th}_{\text{n(CI)}}$ values in FGs, which was not found in CGs. The observed correlation cannot be created by the mechanical mixing between FGs and matrix, arguing against the incorporation of matrix during the micro-drill sampling. In contrast, a positive correlation between $\text{Sr}/\text{La}_{\text{n(CI)}}$ and $\text{Yb}/\text{La}_{\text{n(CI)}}$ values in the FGs suggests that the Sr abundance in FGs was controlled by the evaporative and condensation process during the formation of FGs in the solar nebula. Therefore, it is unlikely that the $\mu^{84}\text{Sr}$ values in the FGs were influenced by the incorporation of matrix via alterations.

Previous studies argued that the $\mu^{84}\text{Sr}$ value in FGs became more variable with decreasing the size of analyzed FGs (i.e., nugget effect), which suggests the presence of isotopically anomalous materials with elevated $\mu^{84}\text{Sr}$ values in FGs [5, 6]. It follows that the carrier phase, most likely presolar grains enriched in p-nuclides, was distributed heterogeneously in individual FGs. In this study, we found that the sample FG8-2, collected from the outer part of FG8, had a distinctively higher $\mu^{84}\text{Sr}$ value than the inner sample FG8-1. Therefore, it is conceivable that (1) the p-nuclide-enriched presolar grains are concentrated in the outer part of individual FGs, and (2) such materials were incorporated into the FGs after their formation because presolar grains are difficult to survive in a high temperature gaseous environment from which FGs have condensed.

Figure 2 plots the $\mu^{84}\text{Sr}$ values and $\text{Er}/\text{La}_{\text{n(CI)}}$ ratios in FGs obtained in this and previous studies. The $\mu^{84}\text{Sr}$ value was constant at ~ 100 ppm for samples with $\text{Er}/\text{La}_{\text{n(CI)}} > 0.1$, while it became more variable for samples with $\text{Er}/\text{La}_{\text{n(CI)}} < 0.1$. The $\text{Er}/\text{La}_{\text{n(CI)}}$ value reflects the history of elemental fractionation experienced by individual FGs associated with their formation. Hu et al. [12] argued that CAIs with group II patterns might have experienced several cycles of evaporation and condensation prior to the final condensation in refractory inclusions, which was caused by rapid heating induced by explosive events such as FU Orionis in the early Solar System. Therefore, the FGs with distinctive $\text{Er}/\text{La}_{\text{n(CI)}}$ ratios would have formed differently within the protoplanetary disk in terms of the time and space. FU Orionis have caused mass transport of several AU [13], which possibly transported FGs from the inner to outer Solar System. Therefore, the FGs with $\text{Er}/\text{La}_{\text{n(CI)}} < 0.1$ are considered to have undergone large scale transport and intense thermal processing by the FU Orionis outburst, resulting in the incorporation of low-temperature components including presolar grains in the outer Solar System. This mechanism explains the variable $\mu^{84}\text{Sr}$

values in the FGs with lower $\text{Er}/\text{La}_{\text{n(CI)}}$, as well as the distinctively high $\mu^{84}\text{Sr}$ value in FG8-2. On the other hand, the FGs with $\text{Er}/\text{La}_{\text{n(CI)}} > 0.1$ did not experience such intense thermal processing and large scale transport. Therefore, these FGs could not interact with presolar grains after their final condensation, resulting in a relatively uniform $\mu^{84}\text{Sr}$ value that would reflect the mean Sr isotopic composition of the source reservoir from which the FGs have condensed.

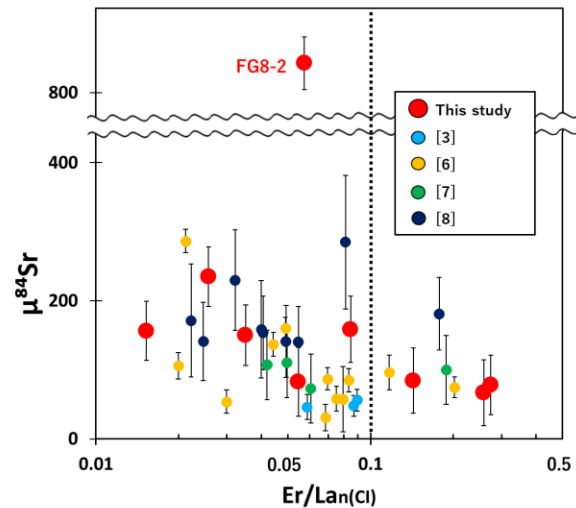


Fig. 2. Diagram for $\text{Er}/\text{La}_{\text{n(CI)}}$ versus $\mu^{84}\text{Sr}$ in FGs obtained in this study and previous studies.

References: [1] Trinquier, A. et al. (2009). *Science*, 324(5925), 374-376. [2] Brennecka, G. A. et al. (2013). *PNAS*, 110(43), 17241-17246. [3] Myojo, K. et al. (2018). *ApJ*, 853(1), 48. [4] Davis, A. M. et al. (2018). *GCA*, 221, 275-295. [5] Torrano, Z. A. et al. (2019). *GCA*, 263, 13-30. [6] Charlier, B. L. A. et al. (2019). *GCA*, 265, 413-430. [7] Brennecka, G. A. et al. (2020). *Science*, 370(6518), 837-840. [8] Charlier, B. L. et al. (2021). *Science Advances*, 7(28), eabf6222. [9] Yokoyama, T. et al. (2015). *EPSL*, 416, 46-55. [10] Lodders, K. (2021). *Space Sci. Rev.*, 217(3), 1-33. [11] Pravdivtseva, O. et al. (2020) *Nat. Astron.*, 4(6), 617-624. [12] Hu, J. Y. et al. (2021). *Science Advances*, 7(2), eabc2962. [13] Wurm, G. and Haack, H. (2009). *MPS*, 44(5), 689-699.