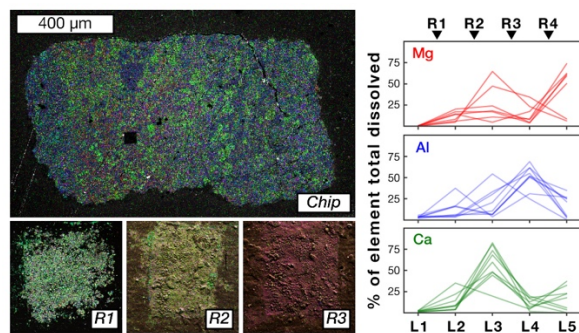


**SEARCH FOR THE CARRIERS OF ANOMALOUS NUCLEOSYNTHETIC SIGNATURES IN EARLY SOLAR SYSTEM CONDENSATES.** R. T. C. Marquez<sup>1</sup>, B. L. A. Charlier<sup>2</sup>, and F. L. H. Tissot<sup>1</sup>. <sup>1</sup>The Isotoparium, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA ([marquez@caltech.edu](mailto:marquez@caltech.edu)). <sup>2</sup>SGEES, Victoria University of Wellington, Kelburn Parade, Wellington 6140, New Zealand

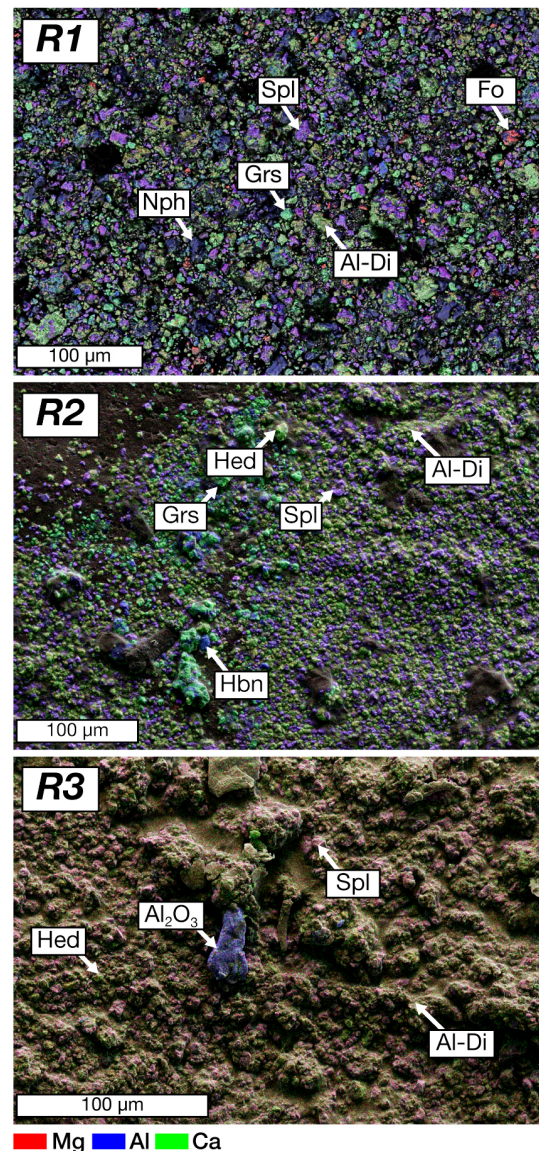
**Introduction:** Calcium-Aluminum-rich inclusions (CAIs) are the oldest dated solids in the Solar System [1-2], making them ideal probes for studying the evolution of the protosolar nebula. These meteoritic components are comprised of refractory minerals formed in high-temperature and reducing environments [3]. A striking feature of CAIs is the presence of relatively large *nucleosynthetic anomalies*, which are mass-independent isotope effects that result from the incomplete homogenization/mixing of presolar material in the reservoirs from which these inclusions formed [4]. Although CAIs display resolvable nucleosynthetic anomalies, the carrier of these anomalies are expected to have been completely destroyed in the CAI forming region (e.g., vaporized, owing to the high-T), or during the melting events that affected coarse-grained CAIs. Presolar carriers are thus not expected to be found inside CAIs - in fact, so far, presolar grains have only been shown to be preserved in the matrix material of carbonaceous chondrites [5].



**Fig. 1.** (Left) SEM/EDS images of a chip of the fine-grained CAI, *Ororo* and its resulting residues after progressively harsher acid leaching steps (R1 to R3; each patch of residue powder is ~1.2 mm wide). (Right) The % of the total Mg, Al, Ca released in each of the leaching steps.

In a recent study of noble gases in fine-grained (spinel-rich) CAIs from Allende, however, Pravdivtseva et al. [6] observed distinct Kr, Ne, and Xe *s*-process signatures released in the 1200-1300°C pyrolysis step, which can most readily be explained by the presence of presolar grains in the sample. They hypothesized that these were presolar SiC (<0.2 µm in size), which were incorporated in fine-grained CAIs during their formation and survived secondary processing. This discovery challenges the long-held views regarding the isotopic homogeneity of CAIs and the preservation of presolar materials in the early stages of Solar System formation.

Using a different set of fine-grained CAIs from Allende, we have conducted a step-leaching experiment



**Fig. 2.** SEM/EDS images of aliquots of the residues taken after the first three leaching steps (R1 to R3).

and measured the Sr isotope composition of the leachates and final residues (see companion abstract, Tissot et al.), which further lends support to the survival of anomalous isotope carriers in refractory inclusions. Through this experiment, we were able to demonstrate that the Sr in the final leaching steps (<1% of total Sr), which represent some of the most refractory phases in these inclusions, have nucleosynthetic signatures that are much more anomalous (up to permil, and sometimes percent, <sup>84</sup>Sr excesses) than the bulk CAI (typically µ<sup>84</sup>Sr~100-200 ppm [7]). These signatures are different from the *s*-

process signature found by Pravdivtseva et al. [6], and instead point towards a rare *p*-process carrier.

Here, we present some recent developments in our search for the carriers of these anomalous signatures. Determining the nature of these carriers will be key to understanding not only the stellar contributions to the nascent solar system, but also establishing how these carriers were incorporated in the earliest solids in the Solar System.

**Methods:** In brief, the leaching procedure consisted of sequentially subjecting the powders from nine Al-lende fine-grained CAIs to progressively harsher acids. Aliquots of the residue material were taken from each sample in between each leaching step, which were then mounted on epoxy and analyzed using the ZEISS 1500 VP field-emission Scanning Electron Microscope at Caltech. Aliquots of the leachates were also taken to measure major and trace element concentrations using a Thermo-Fisher Element 2 sector field ICP-MS.

**Results:** SEM/EDS maps of the unprocessed chip and leaching residues of the fine-grained CAI *Ororo* are shown in **Fig. 1 & 2**. This CAI exhibited the second highest  $^{87}\text{Sr}$  anomaly and is used here as representative of the suite of CAIs studied. The unprocessed chip shows dominantly Ca- and Al-rich phases, which points to the abundance of alteration phases such as grossular, hedenbergite, nepheline, and sodalite. The first leaching step (L1) appears to leave most of the minerals intact: see residue R1 (**Fig. 2**) and the minimal loss of Ca, Al, and Mg (**Fig. 1**). Most of the material in L1 appears to be from Na-bearing phases such as sodalite and nepheline, which is confirmed by variability in the Na/Al ratios falling in between 0.75 and 1.33 (**Fig. 3**).

In the second leaching step (L2), there is a relative increase in % of total Ca, Al, and Mg getting dissolved (**Fig. 1**). This can be seen as the presence of an apparent high-Ca/Al end-member in the L2 leachates (**Fig. 3**), which are likely alteration phases such as grossular/hedenbergite. This step also marks the dissolution of olivine, as can be deduced from the Fe/Mg ratio in L2.

The third leaching step (L3) resulted into the dissolution of a majority of the Ca-bearing phases in these CAIs (~50-75%, **Fig. 1**). Indeed, Ca-bearing phases

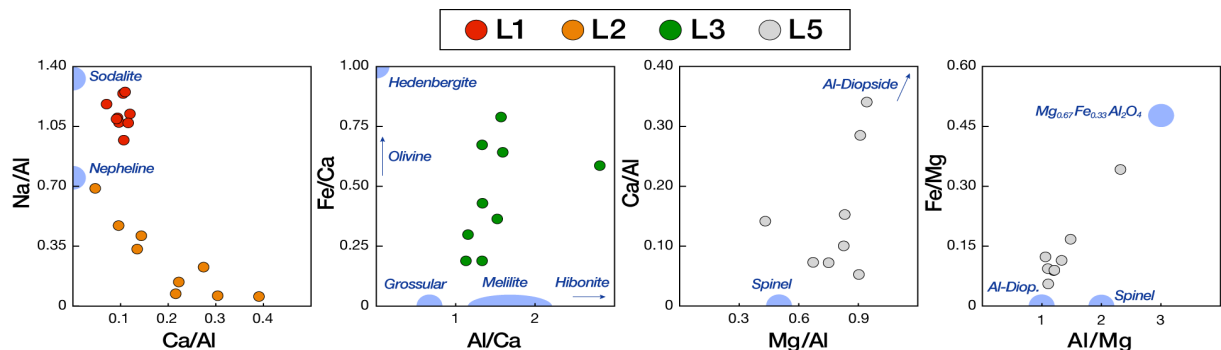
such as melilite and grossular were either very rare or completely dissolved in R3 (**Fig. 2**). There is also a noticeable decrease in hedenbergite abundance, as confirmed by the mixing relationship with a high-Fe/Ca end-member in L3 (**Fig. 3**). The final leaching steps (L4, L5) release most of the Mg and Al in the CAIs (**Fig. 1**), as Al-diopside and spinel get digested by the HF acid attack (**Fig. 3**). The Fe/Mg variability is likely due to the presence of iron in spinel, a product of alteration.

**Discussion:** While the elemental and imaging data allow us to closely follow the sequence of dissolution imparted by the step leaching, no clear correlation was observed between the phase abundances and  $\mu^{84}\text{Sr}$  values. This suggests that none of the phases observed and discussed here can be unequivocally identified as the carrier. There are two main possibilities to explain our data: (1) the carrier of the anomalous Sr signatures are ultra-refractory phases that were not observable by conventional SEM/EDS mapping, either because they are included within the more ubiquitous mineral phases, or simply due to their diminutive sizes; (2) there is a wide range of variability in the nucleosynthetic anomalies within one mineral phase digested late in our step leaching experiment, *i.e.*, some spinel/diopside grains may be presolar in origin and have more anomalous Sr than others. The latter is reminiscent of the role of presolar nanospinel as carriers of the  $^{54}\text{Cr}$  anomalies in bulk carbonaceous chondrites [8].

Further efforts to identify the specific carrier of the *p*-process Sr anomalies are underway and will be reported at the conference.

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**References:** [1] Amelin, Y. et al.. *EPSL* **300**, 343–350 (2010). [2] Kita, N. T. et al.. *MAPS* **48**, 1383–1400 (2013). [3] Grossman, L. et al.. *GCA* **72**, 3001–3021 (2008). [4] Dauphas, N. and Schauble, E.. *Annu. Rev. Earth Planet. Sci.* **44**, 709–83 (2016). [5] Huss, G. R. 721–748 (ASCE, 1997). [6] Pravdivtseva, O., et al.. *Nat. Astron.* (2020). [7] Charlier, B. L. A. et al., *GCA* **265** 413–430 (2019). [8] Dauphas, N. et al. *Astrophys. J.* **720**, 1577 (2010).



**Fig. 3.** Cross-plots of major element atomic ratios in solutions from individual leaching steps. Proposed end-member minerals, denoting the dominant phases getting dissolved in each step, are denoted as blue areas.