RARE EARTH ELEMENTS AND OXYGEN ISOTOPES IN ALLENDE CHONDRULES AS EVIDENCE FOR CAI MIXING IN CHONDRULE PRECURSORS.

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Introduction: The relationship between calcium-alumnium-rich inclusions (CAIs) and chondrules remains poorly constrained. CAIs appear to be older than chondrules, as inferred from a higher initial $^{26}Al/^{27}Al$ in the former; a chronological interpretation of this difference leads to an age gap of *ca*.1-2Myr between the formation of CAIs and that of chondrules. However this chronological interpretation has been challenged by the suggestion that ^{26}Al may have been produced by irradiation near the active proto-Sun; thus variations in $^{26}Al/^{27}Al$ may be a reflection of distance from the Sun or the degree of mixing of irradiated and unirradiated material.

As well as high initial ^{26}Al abundances other characteristics of CAIs which distinguish them from other chondritic components, are their high abundance of refractory elements and, in the case of Type B (igneous) CAIs, the presence of fractionated Mg isotopes – both results of their high temperature condensation/evaporation formation. Condensation/evaporation effects are also reflected in elevated rare earth element (REE) abundances and fractionation patterns in some CAIs (Group II and ultrarefractory patterns [1, 2, 3], however other patterns are quite unremarkable. Finally CAIs from all meteorite types appear to have a primary composition enriched in ^{16}O by 4%.

These characteristics of CAIs, are produced by fundamentally difference processes; although the effects may be occurring contemporaneously. The observed elemental and isotopic fractionation resulted from high temperature evaporation/condensation, the oxygen isotopes by formation from a reservoir isotopically distinct from the rest of the sampled rocky Solar System material (the origin of these reservoirs are open to question but their presence is not), and the ^{26}Al by irradiation or by nucleosynthesis.

These features help us distinguish between CAIs and other chondritic materials. However there are some chondrules which exhibit ^{16}O enrichments, including Al-rich chondrules and chondrules containing highly forsteritic (Fo>99) olivines. The relationship between these chondrules, CAIs and chondrules with more “chondritic” characteristics (bulk chemistry and oxygen isotopes like their host matrix) remains poorly understood. It has been suggested that the differences observed between these material are the result of chronological, spatial or thermal dichotomies between their formation. Understanding the relationship between these components is of great importance for models of early Solar System evolution. Of particular interest is the origin of Al-rich chondrules as these are most easily dated by Al-Mg methods, hence much reliance for chondrule chronology has rested upon this rare sub-set of chondrules of unknown provenance.

Aims: In order to try to further clarify the relationship between chondrules and CAIs we have undertaken a correlated study of oxygen isotopes and rare earth abundances in order to distinguish between mixing of components and the degree of processing resulting from temporal, spatial or thermal variations.

Techniques: Rare earth element abundances were determined by laser ablation ICP-MS at the University of Maryland. 213nm light was provided by a quintupled Nd-YAG laser, ablated material was transported *via* a He stream into a Finnigan Element 2 magnetic sector ICP-MS. Spot sizes for the ablation ranged from 16µm to 60µm, depending upon the REE concentration of the analysed phases. Between five and ten analyses were made on each chondrule in an attempt to sample each of the mineral species present. Results were normalized using the abundances in [4]

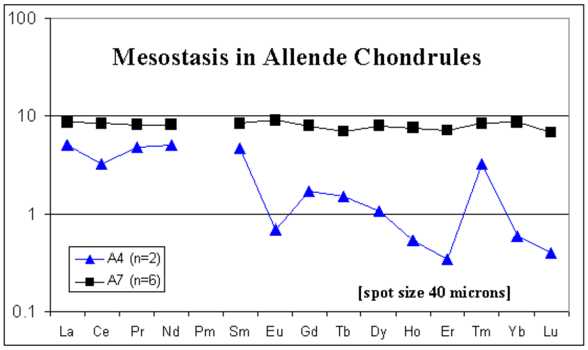
Oxygen isotopes were determined by UV laser ablation, with 248nm light provided by a KrF excimer laser, and isotope ratios measured by a Finnigan Matt 252 stable isotope mass spectrometer at the Geophysical Laboratory. A broad spot-size (*ca*. 800µm, provided a bulk oxygen isotope determination).

Samples were petrographically characterised and mineral chemistry measurements made by electron microprobe.

Samples: Twenty chondrules were separated from the Allende CV3 carbonaceous chondrite. These are representative of the range in textures and chemistries found in Allende. One chondrule, an Al-rich chondrule consisting of anorthitic and diopsidic laths with an abundant scattering of micron to 10’s micron sized spinel chadacrysts throughout the chondrule, was in cluded in the sample suite.

Results: *Oxygen isotopes.* The bulk oxygen isotope abundances span the range found previously for Allende [5]. Iron-rich chondrules with textures suggesting complete melting have oxygen isotope ratios near the meteorite matrix whereas those with textures indicating incomplete melting tend to have more ^{16}O-rich signatures; as has been discussed previously [6, 7]. The oxygen isotope signature of the Al-rich chondrule has the most negative $\Delta^{17}O$ of all the chondrules analysed (-6.1 per mil).

Rare Earth Elements. The majority of the Allende chondrules have flat chondritic normalized REE patterns, with Eu variations following mineralogical controls. Figure 1 shows the pattern for the mean of six analyses of the mesostasis of A7, a coarse grained barred olivine chondrule.



The abundances for most chondrules vary around chondritic, but are controlled by the phase analysed. It is difficult to calculate bulk abundances from the mineral data, but the range for most chondrules is between half and twice chondritic, with the mesostasis generally holding the majority of the REE.

The Al-rich chondrule deviates strongly from chondritic abundances, exhibiting a well defined Group II CAI REE signature, although the magnitude of the REE enrichments are less dramatic than those observed in the Group II pattern CAIs [3]. In the Al-rich chondrule the bulk La abundance is approximately 5x chondritic, whereas for the Group II patterns in CAIs they range from 30-70x chondritic.

Discussion:

Ferromagnesian chondrules: Despite showing a range in oxygen isotopes the majority of chondrules show little deviation from chondritic REE patterns, implying either homogenisation of the REE during chondrule formation or a lack of fractionation in the chondrule precursor material. The forsteritic olivines which are characteristic of many of the ^{16}O-rich chondrules contain low concentrations of REE, hence may not be expected to inherit a characteristic signature. Furthermore Group I, III, V and VI CAI REE patterns are not easily distinguished from chondritic, hence if these are characteristic of inherited precursors they could not be easily recognised.

Aluminium-rich chondrule: The mineralogy, oxygen isotopes and REE patterns for the Al-rich chondrule are consistent with this having the most significant input of CAI material into the chondrule precursor, however the attenuation of the signal, compared with that observed in Group II CAIs indicates dilution by a chondritic REE. A petrographically similar Al-rich chondrule was described previously [8] and this too showed a REE pattern reminiscent of a Group II CAI. Hence it may be that Al-rich chondrules are characterised by REE patterns inherited from a distinct sub-group of CAIs.

Implications for chronology of Al-rich chondrules. The oxygen isotopes and the REE distribution patterns for the aluminium-rich chondrule, and the Mg stable isotope data for other Al-rich chondrules [9] all point toward an input of CAI material into the Al-rich chondrule precursors. If the material with which the CAI material was mixed was more akin to "chondritic" chondrules (*i.e.* those with chondritic REE, oxygen and magnesium isotopes) then is seems likely that this material had little or no live ^{26}Al contribution to the whole as evinced by the lack of any $^{26}Mg^*$ in the high precision Mg isotope analysis of these chondrules and matrix material [9]. If this is so then the apparent age differences between CAIs and Al-rich chondrule may be due to dilution of the initial $^{26}Al/^{27}Al$ by dilution with "inanimate" material *i.e.*chondritic material which never had live ^{26}Al above cosmic background. If so then the apparent range in ages between chondrules and CAIs has no chronological meaning.

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