Crystal growth and disequilibrium distribution of O isotopes in an igneous CAI from Allende

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Coarse-grained Ca-Al-rich inclusions (CAIs) in meteorites, the oldest objects in the Solar System [1], exhibit unequilibrated O isotope distributions among/within minerals [e.g., 2]; however, the origin of the disequilibrium distribution of O isotopes remains controversial. We propose O isotope disequilibrium among minerals in an Allende Type B1 CAI TS34 was formed by change of O isotopic composition of melt during crystallization, based on petrography and in-situ O isotope measurements. TS34 mainly consists of melilite, Ti-Al-rich clinopyroxene (fassaite), and spinel in addition to minor anorthite, in igneous textures, and O isotopic compositions of the constituent minerals plot along the carbonaceous chondrite anhydrous mineral line. The spinel is uniformly ^{16}O-rich (Δ^{17}O = −22.7 ± 1.7‰), while the melilite is uniformly ^{16}O-poor (Δ^{17}O = −2.8 ± 1.8‰). The fassaite crystals exhibit growth zoning overprinting poorly-developed sector zoning: they generally grow from Ti-rich to Ti-poor compositions. The fassaite crystals show continuous variations in Δ^{17}O along the inferred directions of crystal growth, from ^{16}O-poor (Δ^{17}O ~ −3‰) to ^{16}O-rich (Δ^{17}O ~ −23‰), which covers a full range of O isotope variations of the minerals in TS34. The early crystallized ^{16}O-poor fassaite and the melilite are in O isotope equilibrium. The O isotope variations in the fassaite likely correlate with the O isotope evolution of CAI melt during the fassaite crystallization, from ^{16}O-poor to ^{16}O-rich, which plausibly originated from O isotope exchange with surrounding ^{16}O-rich nebular gas. The ^{16}O-poor fassaite could have crystalized after ^{16}O-poor melilite, while the ^{16}O-rich spinel was a relict at the melilite crystallization from ^{16}O-poor melt. These crystallization sequences are consistent with phase diagram of CAI melt crystallization. Therefore, O isotope variations of intra- and inter-minerals recorded in the CAI trace crystallization sequences of the CAI melt. The melilite and fassaite show an ^{26}Al–^{26}Mg mineral isochron proving an initial value of $(^{26}Al/^{27}Al)_0$ = (5.003 ± 0.075) × 10^{-5}, corresponding to a relative age of 0.05 ± 0.02 Myr from the canonical [3]. These data demonstrate that both ^{16}O-rich and ^{16}O-poor reservoirs had been existed in the solar nebula at least ~0.05 Myr after the birth of the Solar System.

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Rapid Formation of ^{16}O-poor Rim on a ^{16}O-rich CAI in the Nebular Setting

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Oxygen Isotopes of Ca-Al-rich Inclusions (CAIs): Since the work reported in 1973 by Clayton and co-workers [1], ^{16}O-rich compositions ($\delta^{17,18}$O ~ −40 to −50‰) have proven to be characteristic of many primary minerals in both CAIs and amoeboid olivine aggregates (AOAs) (reviewed by [2]). However, ^{16}O-poor compositions have been reported for some CAI minerals and have been attributed in some cases to isotopic exchange during fluid-enhanced parent body metamorphism [3,4] and in other cases to re-setting in the solar nebula [5,6]. Distinguishing parent body vs. nebular effects is essential for interpreting crystallization histories of CAIs, particularly for evaluating flows of materials between ^{16}O-rich and ^{16}O-poor settings in the solar nebula [7].

In this project, we describe a CAI with a ^{16}O-poor diopside-rich rim from the primitive carbonaceous chondrite Acfer 094 [8–10]. The rim formed on the ^{16}O-rich core of the CAI in the nebular setting, suggesting material transfer between isotopically distinct regions of the solar nebula. Furthermore, the sharp isotopic boundary between rim and core indicates rapid cooling after rim formation.

Acfer 094 and CAI with Diopside-rich Rim: Like many CAIs from Acfer 094 [9,10], CAI RO-64 has a concentric texture: grossite-rich core with spinel and hibonite mantled by an anorthite±melilite layer and an outer rim of diopside with tiny grains of Fe,Ni-rich metal. SIMS spot analyses and isotope imaging (SCAPS, see [11]) indicate that the anorthite-rich layer and core are fairly ^{16}O-rich ($\delta^{17,18}$O ~ −30‰), whereas the diopside-rich outer rim is ^{16}O-poor ($\delta^{17,18}$O ~ −2‰). The isotopic boundary between the outer rim and CAI interior appears to be a discontinuity. Our models of O-diffusion across this boundary suggest that the duration of time at elevated temperature during and after rim formation was less than one year at 1400K or less than six months at 1450K, necessitating a rapidly cooling environment in the solar nebula.

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