

Crystal growth and disequilibrium distribution of oxygen isotopes of minerals in an igneous Ca-Al-rich inclusion from the Allende carbonaceous chondrite

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Coarse-grained Ca-Al-rich inclusions (CAIs) in meteorites, the oldest objects in the Solar System (Connolly et al., 2012), exhibit unequilibrated O isotope distributions among/within minerals (e.g., Clayton et al., 1977; Clayton, 1993; Yurimoto et al., 2008 and references therein); however, the origin of the disequilibrium distribution of O isotopes remains controversial. We have observed in-situ oxygen isotope distribution and ^{26}Al – ^{26}Mg systematics in a Type B1 Ca-Al-rich inclusion (CAI), TS34, from the Allende carbonaceous chondrite by using secondary ion mass spectrometry (Cameca ims-1280HR at Hokkaido University) according to crystal growth of CAI minerals and their crystal growth sequences. The heterogeneous oxygen isotope distribution among and within minerals was established by change of oxygen isotopic composition of melt during crystallization.

TS34 mainly consists of melilite, Ti-Al-rich clinopyroxene (fassaite), and spinel in addition to minor anorthite, in igneous textures, and oxygen isotopic compositions of the constituent minerals plot along the carbonaceous chondrite anhydrous mineral line. The spinel grains are uniformly ^{16}O -rich ($\Delta^{17}\text{O} = -22.7 \pm 1.7$ ‰, 2SD), while the melilite grains are uniformly ^{16}O -poor ($\Delta^{17}\text{O} = -2.8 \pm 1.8$ ‰) irrespective of their crystal growth. 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 $\Delta^{17}\text{O}$ along the inferred directions of crystal growth, from ^{16}O -poor ($\Delta^{17}\text{O} \sim -3$ ‰) to ^{16}O -rich ($\Delta^{17}\text{O} \sim -23$ ‰), which covers a full range of oxygen isotope variations of the minerals in TS34. The early-crystallized ^{16}O -poor fassaite and the melilite are in oxygen isotope equilibrium and chemical equilibrium. The oxygen isotope variations in the fassaite trace the oxygen isotope evolution of CAI melt during the fassaite crystallization, from ^{16}O -poor to ^{16}O -rich, which plausibly originated from oxygen isotope exchange with surrounding ^{16}O -rich nebular gas. The ^{16}O -poor fassaite crystallized 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. Anorthite exhibits oxygen isotope variations ranging between $\Delta^{17}\text{O} \sim -2$ ‰ and -9 ‰. The oxygen isotope variations of anorthite are essentially covered by those of fassaite, indicating co-crystallization with early to intermediate crystallized fassaite. Therefore, oxygen 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 $(^{26}\text{Al}/^{27}\text{Al})_0 = (5.003 \pm 0.075) \times 10^{-5}$, corresponding to a relative age of 0.05 ± 0.02 Myr from the canonical. These data demonstrate that both ^{16}O -rich and ^{16}O -poor reservoirs existed in the solar nebula at least ~ 0.05 Myr after the birth of the Solar System.