Extremely heterogeneous oxygen isotopes in an Al-rich chondrule from Yamato 81020 (CO3.05)

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Introduction: Aluminum-rich chondrules (ARCs) are a minor type of chondrules that are defined by bulk Al_2O_3 content (>10 wt.%). In carbonaceous chondrites, ARC shows a range of textures and mineralogy with variable amounts of olivine, pyroxene, plagioclase, and/or Al-rich spinel. Oxygen isotope ratios of majority of ARC are similar to those of ferromagnesian chondrules (e.g., Krot et al. 2006; Tenner et al. 2017), excluding relict spinel and olivine with ^{16}O-rich compositions. The inferred initial (^{26}Al/^{27}Al)$_0$ of ARCs are within a range of ferromagnesian chondrules (Kurahashi et al. 2008; Ushikubo et al. 2012; 2013; Nagashima et al. 2014). It has been suggested that ARCs formed in the common environments with ferromagnesian chondrules by the melting of mixtures of diverse precursors including various types of Ca, Al-rich inclusions (CAIs) and amoeboid olivine aggregates (AOAs) (e.g. Zhang et al. 2020).

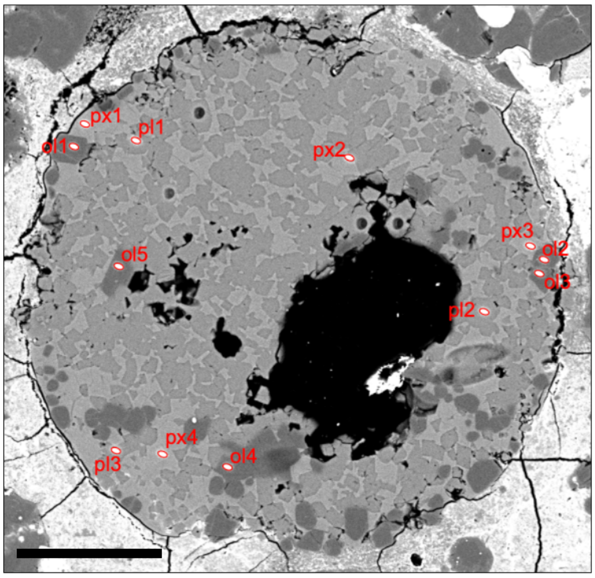
Here we report oxygen isotope ratios of an ARC "Y23" from Y-81020 (CO3.05) that was previously studied for Al-Mg chronology by Kurahashi et al. (2008). Y23 is rounded chondrule consists mainly of fine-grained anorthite and high-Ca pyroxene with high Al_2O_3 contents of ~9%, which resembles to the texture of type C CAIs. While the chemical and textural characteristics of Y23 indicate remelting of refractory precursors, there are no previous oxygen three-isotope analyses on the chondrule because the mineral phases are too small (≤10 μm) for our normal high precision oxygen isotope analyses (e.g. Tenner et al. 2013).

Sample and methods: Chondrule Y23 consists of fine (~10 μm) euhedral anorthite (An_{99-100}, 51 area%) and anhedral high-Ca pyroxene (Wo_{49-66} En_{30-60}, 36 area%) with minor amount of olivine (Fo_{97-99}, 13 area%) mostly in the periphery of the chondrule (Kurahashi et al. 2008). Oxygen three-isotope analyses were conducted using a secondary ion mass spectrometer (SIMS) IMS1280 at the WiscSIMS laboratory. The primary Cs^+ ion beam was focused to 3 μm × 2 μm in size and the intensity of ~20 pA. The oxygen-three-isotopes were detected in multi-collection system (^{16}O on Faraday cup, ^{17}O and ^{18}O on electron multipliers) with the analysis condition similar to that of Ushikubo et al. (2012; 2017). Typical analytical uncertainties are 0.5-1.0‰ for δ^{18}O and δ^{17}O, and 0.8-1.0‰ for Δ^{17}O (= δ^{17}O – 0.52 × δ^{18}O). The SIMS pits were inspected using a scanning electron microscope (SEM). Additional petrographic observations were conducted by using FE-SEM JSM-7100F at NIPR.

Results: FE-SEM observation shows zoning of Al in Ca-pyroxene. There are tiny (≤ 1μm) opaque phases with high BSE brightness, which contain Ir, Os, Pt, Ru, and Fe. The image of the chondrules and location of SIMS analyses are shown in Figure 1. Results of oxygen three-isotope analyses are shown in Figure 2 that shows a large range of δ^{18}O and δ^{17}O from ~ –30‰ to ~0‰, and corresponding Δ^{17}O of –20‰ to 0‰. Olivine analyses show the largest range, in contrast to a small variation of pyroxene analyses with mean of δ^{18}O = –10‰, δ^{17}O = –14‰, and Δ^{17}O = –9‰. Two out of three plagioclase analyses are among lowest δ^{18}O and δ^{17}O. These data generally plot along the Primitive Chondrule Mineral (PCM) line (Ushikubo et al. 2012), similar to most of chondrule data from carbonaceous chondrites, except for one data on the terrestrial fractionation line (TFL).

Discussion: Oxygen isotope ratios of olivine indicate that precursors of Y23 include both CAI-like ^{16}O-rich precursor (Δ^{17}O≤ –20‰) and chondritic ^{16}O-poor precursor (Δ^{17}O ~ 0‰). The spherical shape and igneous texture of plagioclase and pyroxene suggest that the chondrule formed by crystallization of a nearly completely molten Ca-Al-rich melt with olivine crystallized first followed by anorthite and pyroxene. Chondrule melt started with low Δ^{17}O (–20‰), indicating precursors were dominated by refractory solids. Melt might have exchanged oxygen isotope ratios with ambient gas during chondrule formation prior to the crystallization of pyroxene with Δ^{17}O of –9‰. The ^{16}O-poor olivine (ol2) could be a relict grain. If Y23 formed in an environment similar to type I (FeO-poor) chondrules in CO chondrites, the ambient gas might have Δ^{17}O of ~ –5‰ (Tenner et al. 2013), which is higher than all analyses in Y23 except for the relict olivine. It is likely that oxygen isotope exchange between chondrule melt and surrounding gas was not efficient.

The inferred (^{26}Al/^{27}Al)$_0$ of Y23 was determined to be (3.7±0.5)×10^{-6} (Kurahashi et al. 2008; Kita et al. 2019), which is at the low end of the range observed among chondrules in Y-81020 (Kunihiro et al. 2004; Kurahashi et al. 2008; Kita et al. 2019; 2020). It has been suggested that initial abundance of ^{26}Al in the Solar system was significantly heterogeneous in the disk scale, having high (^{26}Al/^{27}Al)$_0$ ~5×10^{-5} in the CAI forming regions and reduced abundance in the chondrule forming regions (e.g. Bollard et al. 2019). Under this scenario, inferred (^{26}Al/^{27}Al)$_0$ ratios of ARCs would likely be variable and systematically higher than those of ferromagnesian chondrules by incorporating CAI-like refractory precursors with a significantly higher ^{26}Al abundance. It is not the case for actual reported $(^{26}Al/^{27}Al)_0$ for ARCs (e.g. Kurahashi et al 2008; Ushikubo et al. 2013; Nagashima et al. 2014). In particular, Y23 with a significantly Ca, and Al-rich chemistry and ^{16}O-rich oxygen isotope signature would argue against the heterogeneous distribution of ^{26}Al between CAI and chondrule forming regions.



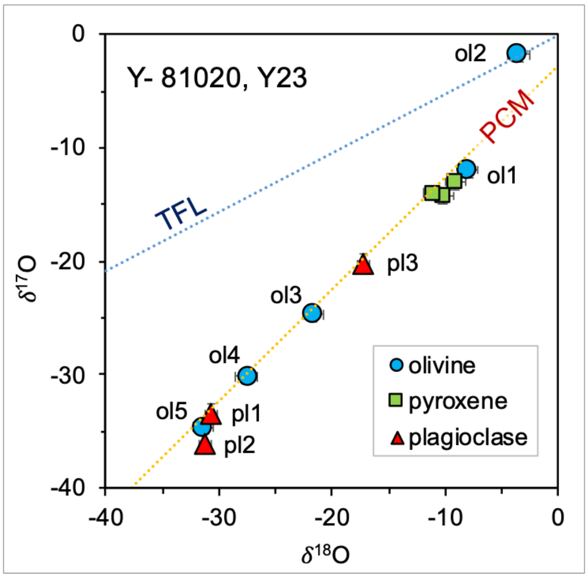


Figure 1 (left). Back scattered electron images of Al-rich chondrule Y23 from Y-81020 (CO3.05). The locations of SIMS analyses are shown using red open oval shapes. Olivine; ol, pyroxene; px, plagioclase; pl. Scale bar, 50 µm. Figure 2 (right) Oxygen-three isotope ratios of Y23. TFL and PCM line are shown as reference. Data from px2 was rejected due to beam overlap with adjacent plagioclase.

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