

IN-SITU OXYGEN ISOTOPE STUDY OF ANHYDROUS MINERALS IN A RYUGU PARTICLE: IMPLICATIONS FOR THE PRECURSORS TO CI-CHONDRITE PARENT BODIES. M.-C. Liu¹, K. A. McCain¹, N. Matsuda¹, A. Yamaguchi², M. Kimura², N. Tomioka³, M. Ito³, M. Uesugi⁴, N. Imae², N. Shirai⁵, T. Ohigashi⁶, R. C. Greenwood⁷, K. Uesugi⁴, A. Nakato⁸, K. Yogata⁸, H. Yuzawa⁶, Y. Kodama[†], A. Tsuchiyama⁹, M. Yasutake³, K. Hirahara¹⁰, A. Takeuchi³, S. Sekimoto¹¹, I. Sakurai¹², I. Okada¹², Y. Karouji¹³, T. Yada⁸, M. Abe⁸, T. Usui⁸, S. Watanabe¹², and Y. Tsuda^{8, 14}. ¹UCLA, ²NIPR, ³KOCHI JAMSTEC, ⁴JSRI/SPring-8, ⁵TMU, ⁶UVSOR IMS, ⁷Open Univ., ⁸ISAS JAXA, ⁹Ritsumeikan Univ., ¹⁰Osaka Univ., ¹¹Kyoto Univ., ¹²Nagoya Univ., ¹³JAXA, ¹⁴SOKENDAI, [†]Now at Toyo Corp.

Introduction: Initial characterization of the fragments collected by the JAXA Hayabusa2 mission from the surface and subsurface of asteroid Ryugu revealed that these samples are composed of materials that resemble those of CI-chondrite meteorites [1]. The mineralogy of Ryugu particles was found to be mostly dominated by secondary phases, such as carbonates, magnetite, phyllosilicates, and sulfides, which were produced by extensive aqueous alteration on the parent body [e.g., 2]. Interestingly, in marked contrast to other Ryugu samples that have been examined, the particle C0009, which was collected from the second landing site, is characterized by relatively high abundances (~0.5 vol%) of anhydrous silicate minerals (mostly olivine and minor pyroxene; Fig. 1), reflecting a lesser degree of water-rock interaction experienced by this fragment. Therefore, C0009 provides an opportunity to better understand the origins and isotopic evolution of source materials that constituted the protolith of the Ryugu parent body. Here we report the oxygen isotopic compositions of select anhydrous silicates measured with secondary ion mass spectrometry (SIMS) and discuss their implications for the evolution of Ryugu and CI-chondrite-like parent bodies. This study is part of the Phase2 characterization work of the Ryugu particles allocated to the Phase2 curation Kochi team. Preliminary results from studies carried out by other team members are shown elsewhere [2–6].

Experimental: In-situ oxygen isotope analyses of Ryugu olivine and pyroxene were performed on the CAMECA ims-1290 ion microprobe at UCLA. A polished and Au-coated section of C0009 was sputtered with a 20 keV, ~60 pA Cs⁺ primary beam ($\phi \sim 2 \mu\text{m}$), generating ¹⁶O⁻ signals of order $\sim 4 \times 10^7$ counts/sec. Secondary oxygen ions were collected simultaneously with 1 Faraday cup (for ¹⁶O⁻) and 2 electron multipliers (for ¹⁷O⁻ and ¹⁸O⁻). Since the olivine and pyroxene measured in this session are highly Mg-rich (Mg# > 97, [2]), San Carlos olivine and pyroxene were used as standards to correct for the instrumental mass fractionation [7]. To ensure the accuracy of $\Delta^{17}\text{O}$ determination, contributions of the OH⁻ tail to ¹⁷O⁻ were also evaluated and corrected for. Post-SIMS pits were imaged with the UCLA Tescan Vega scanning electron microscope; data from spots

overlapping surrounding phyllosilicates are excluded from further discussions.

Results and Discussion: The oxygen isotopic compositions of anhydrous silicates in C0009 are found to fall into two groups in $\Delta^{17}\text{O}$ (Fig. 2), which also correlate with the olivine/pyroxene morphology. Of eleven samples measured, eight are isolated, morphologically better-preserved olivine or pyroxene grains in the matrix (Fig 1a-b; collectively referred to as isolated Mg-rich silicates hereafter) and are characterized by $\Delta^{17}\text{O}$ between -5% and -8% , similar to the values found in a handful of mechanically separated olivine grains from the CI chondrite Orgueil [8–9]. The oxygen isotopic compositions of these grains appear to form an array with a slope of ~ 0.4 from the Y&R line [10] to the right of the CCAM line [11] on a three-isotope plot (Fig. 2a). Two olivine crystals having abundant phyllosilicate-filled pores (Fig. 1c; referred to as porous olivine hereafter) are more ¹⁶O-rich and plot on or near the CCAM (or Y&R) line, corresponding to $\Delta^{17}\text{O} = -20$ to -25% . Two olivine grains enclosed in an oval-shaped, phyllosilicate-rich object (Fig. 1d, and green triangles in Fig. 2) show different oxygen isotopic compositions, with the upper and lower grains having $\Delta^{17}\text{O} = -4.5\%$ and -24.5% , respectively. This work represents the first discovery of olivine as ¹⁶O-rich as refractory inclusions (e.g., CAIs, hibonite; [12]) in an asteroid of CI-chondrite characteristics.

The oxygen isotope data have implications for the materials incorporated into the protolith of Ryugu as they reveal a potential relationship between anhydrous silicates in C0009 and other known high temperature components found in non-CI carbonaceous chondrites (CCs). The isolated Mg-rich silicates appear to be related to olivine and pyroxene phenocrysts of chondrules based on the very similar $\Delta^{17}\text{O}$ [13], whereas the porous olivine crystals are isotopically comparable to amoeboid olivine aggregates (AOAs), which are considered primary condensates from an ¹⁶O-rich gas the solar nebula [14]. Definitively relating the olivine grains in the oval-shaped object to any known refractory component in chondrites is more challenging. However, if one assumes that the two grains were part of the precursor to the oval-shaped objects and are survivors of

aqueous processing, their oxygen isotopic compositions would suggest that this precursor could have been a chondrule. This is because $\Delta^{17}\text{O} = -4.5\text{‰}$ and -24.5‰ are consistent with what have been found for olivine and some relict grains, respectively, inside some CC-chondrules [e.g., 13]. Therefore, our results provide strong support for chondrules and AOAs having been part of the materials that accreted into the protolith of Ryugu. The fine-grained nature of AOAs makes them more prone to destruction during aqueous alteration. This explains why refractory mineralogy (AOAs, CAIs) has not been found previously in other Ryugu particles and CI chondrites.

The presence of possible AOA remnants in Ryugu also has important implications for the oxygen isotopic evolution in the Ryugu parent body. Previous attempts at constraining how oxygen isotopes evolved among CI-chondrite materials have assumed the average oxygen isotopic composition of initial anhydrous silicates (prior to aqueous alteration) to be the same as the average value of olivine/pyroxene separated from either CM2 Murchison ($(\delta^{17}\text{O}, \delta^{18}\text{O}) = (-7.4\text{‰}, -4.2\text{‰})$; [15]), or Orgueil ($(\delta^{17}\text{O}, \delta^{18}\text{O}) = (+1.8\text{‰}, +4.8\text{‰})$; [8]). Our data suggest that the starting silicate materials in at least part of Ryugu could have been more ^{16}O -rich than previously considered for the CI-chondrite parent body. Since the bulk Ryugu particles are similar to CI chondrites in terms of $\Delta^{17}\text{O}$ [5], the initial fluid in the Ryugu protolith must have been more $^{17,18}\text{O}$ -rich than that inferred for CI chondrites.

There are two possible explanations for the oxygen isotopic compositions of isolated Mg-rich silicates. One is that based on the array with the slope of ~ 0.4 they form on a three-oxygen isotope diagram, this distribution could result from mass dependent isotope fractionation associated with fluid-silicate interaction. Alternatively, the range of $\delta^{17}\text{O}$ and $\delta^{18}\text{O}$ of Ryugu's isolated Mg-rich silicates is quite comparable to that defined by chondrule olivine/pyroxene crystals from non-CI CCs, and thus could reflect the original isotopic compositions. Given the highly Mg-rich nature of these silicates analyzed here, the second scenario would be more plausible.

References: [1] Yada et al. (2021) *Nat. Astro.* doi.org/10.1038/s41550-021-01550-6. [2] Yamaguchi et al. (2022), *LPSC LIII*, this meeting. [3] Ito et al. (2022), *LPSC LIII*, this meeting. [4] Tomioka et al. (2022), *LPSC LIII*, this meeting. [5] Greenwood et al. (2022), *LPSC LIII*, this meeting. [6] McCain/Matsuda et al. (2022), *LPSC LIII*, this meeting. [7] Isa et al. (2017), *Chem. Geol.* **458**, 14. [8] Leshin et al. (1997), *GCA*, **61**, 835. [9] Piralla et al. (2020), *GCA*, **269**, 451. [10] Young and Russell (1998) *Science*, **282**, 452 [11] Clayton et al. (1977) *EPSL*, **34**, 209 [12] Liu et al.

(2009) *GCA*, **73**, 5051. [13] Tenner et al. (2018) *Chondrules*, 196 [14] Yurimoto et al. (2008) *Rev Min. Geochem.* **68**, 141 [15] Rowe et al. (1994), *GCA*, **58**, 5341.

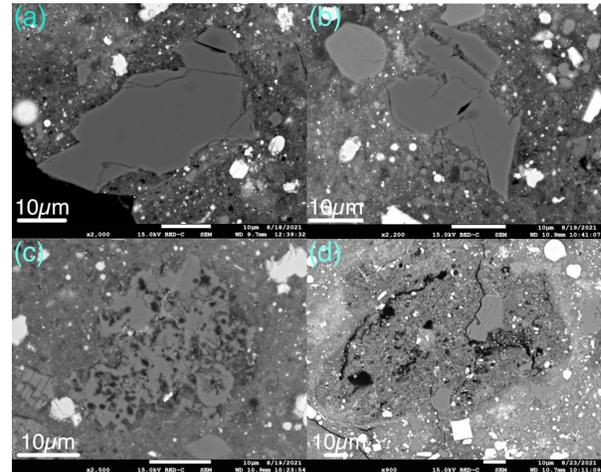


Fig. 1. Representative backscattered SEM images of (a) isolated olivine, (b) isolated pyroxene, (c) porous olivine, and (d) two olivine grains enclosed in an oval-shaped object.

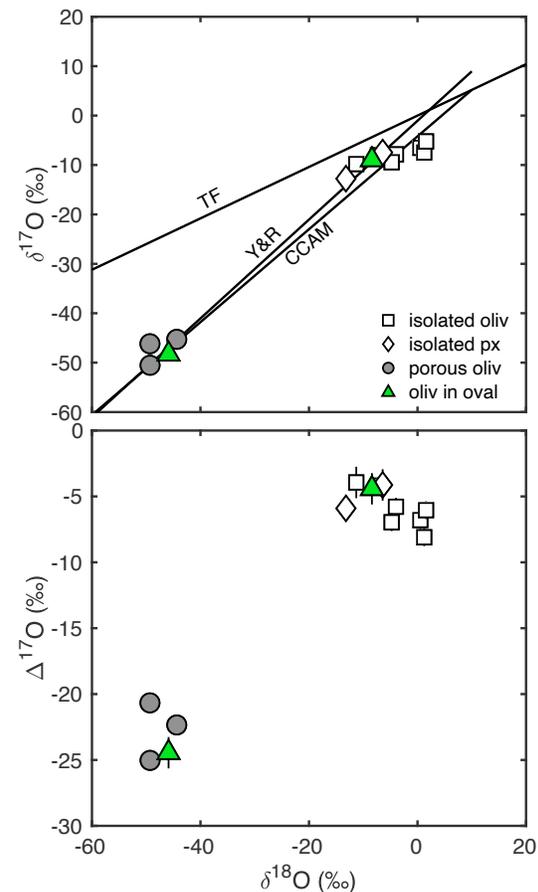


Fig. 2. Oxygen isotopic compositions of Mg-rich anhydrous silicates found in the Ryugu particle C0009.