Chondrule-like objects and CAIs in asteroid Ryugu: Earlier generations of chondrules

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Introduction: The Hayabusa2 spacecraft returned samples from C-type asteroid Ryugu [1]. The "stone" team, one of the six initial analysis teams, received 16 stone samples from the ISAS curation facility and conducted analyses for elucidation of early evolution of asteroid Ryugu [2]. The Ryugu samples mineralogically and chemically resemble CI chondrites [2-5]. It was suggested that the Ryugu original parent body formed beyond the H_2O and CO_2 snow lines (> 3 – 4 au) in the solar nebula at 1.8 – 2.9 Myr after CAI formation [2]. Here we report oxygen isotope analyses (~ 1 µm spots; IMS-1280 at UW-Madison) of chondrule-like objects and CAIs observed in the Ryugu samples [2] and discuss the significance of the presence of chondrule-like objects and CAIs in asteroid Ryugu and their origins.

Results: Small chondrule-like objects and CAIs (< 30 µm; Fig. 1) occur with isolated olivine, pyroxene, and spinel in less-altered clasts in the polished section C0002-P5 and in polished sections of C0040-02 and C0076-10. The three chondrule-like objects have rounded-to-spherical shapes and consist of olivine with Mg# of ~ 99, FeNi metal, sulfide, and Al-Ti-free diopside but free from glass or glass-altered phase. Two of the three chondrule-like objects contain low-iron, manganese-enriched (LIME) olivine [6], and one of them shows sub-µm-sized 120° triple junctions, which is evidence of annealing [7]. The two CAIs consist of spinel and hibonite along with tiny perovskite inclusions. The oxygen isotope ratios show a bimodal distribution at peaks of ~ –43‰ and ~ 0‰ in $\delta^{18}O$ along the CCAM and the PCM lines [8,9] (Fig. 2). Oxygen isotope ratios of the individual objects are indistinguishable within the uncertainty. Two out of the three chondrule-like objects are ^{16}O-rich with $\Delta^{17}O$ of ~ –23‰ (C0002-P5-C2-Chd and C0040-02-Chd), while the other is ^{16}O-poor with $\Delta^{17}O$ of ~ –3‰ (C0002-P5-C1-Chd). The two CAIs are ^{16}O-rich with $\Delta^{17}O$ of ~ –23‰ (C0040-02-CAI and C0076-10-CAI).

Discussion: Mg# of ~ 99 and the $\Delta^{17}O$ value of ~ –3‰ for C0002-P5-C1-Chd are characteristic for type I chondrules in carbonaceous chondrites [10]. The two ^{16}O-rich chondrule-like objects with Mg-rich olivine share characteristics with AOAs [11] and are likely to have been originally AOAs (or fragments) and melted (and annealed) by a heating event in the ^{16}O-rich environment possibly near the Sun. The three chondrule-like objects, which are dominated by Mg-rich olivine and free from glass, resemble what has been proposed as earlier generations of chondrules [12]. If the three objects are earlier generations of chondrules, the two distinct oxygen isotope ratios of ^{16}O-rich and -poor are evidence for the argument that ^{16}O-rich and -poor isotope reservoirs existed in the early stage of the chondrule formation [10].

Spinel-rich CAIs accompanied by altered phases like the two Ryugu CAIs are observed in CM chondrites [e.g., 13]. However, the two Ryugu CAIs are smaller than the CM-CAIs and as small as CAI-like Wild2 particles [14]. Spinel in the CM-CAIs contain Cr_2O_3 mostly less than 0.6 wt% [13], while that in cometary CAIs contains more Cr_2O_3 than 1.7 wt% [15]. The relatively high Cr_2O_3 contents are explained by addition of Cr from Cr-bearing gas or dust during the remelting events at few Myr after CAI formation [15,16]. Spinel in the two Ryugu CAIs contain Cr_2O_3 less than 0.2 wt%. It is possible that the two Ryugu CAIs escaped from remelting events that supplied Cr. If this is the case, the two Ryugu CAIs are possibly as old as the CM-CAIs.

The Ryugu original parent body formed at > 3 – 4 au from the Sun [2], while CAIs formed near the Sun [11]. Radial transport of the CAIs and the two ^{16}O-rich chondrule-like objects to the region where the Ryugu original parent body formed is required. Likewise, it has been suggested from the observations of chondrule-like and CAI-like Wild2 particles that chondrules and CAIs were transported from the inner regions to the Kuiper belt in the solar nebula [14,17]. Given the smaller sizes of the cometary chondrules and CAIs than those in chondrites, radial transport favoring smaller objects to farther locations may have occurred in the solar nebula; e.g., a combination of advection and turbulent diffusion [18]. If this is the case, the occurrence of chondrule-like objects, CAIs, isolated anhydrous grains that are likely to be fragments of chondrules and CAIs, and AOA-like porous olivine

[2,19,20], which are as small as the Wild2 particles, suggests that the Ryugu parent body formed at farther location than any other chondrite parent bodies and acquired these anhydrous objects transported from the inner regions of the solar nebula.

Chondrules in different chondrite groups have distinct chemical, isotopic, and physical properties, suggesting chondrule formation in local disk regions and subsequent accretion to their respective parent bodies without significant inward/outward migration [10]. The rarity of chondrules (and chondrule-like objects) in the Ryugu samples suggests the Ryugu parent body formation in a region scarce in chondrules. Instead, small chondrules and fragments may have been transported with CAIs from the inner regions of the solar nebula. Since the formation age of the Ryugu parent body is as early as those of major types of carbonaceous chondrite chondrules [2,21], chondrules typically observed in chondrites (~ 1 mm) should have presented in the inner regions of the solar nebula when forming the Ryugu parent body. Considering radial outward transport favoring smaller objects, small fragments of relatively large chondrules may have also been provided and observed as isolated anhydrous grains in the Ryugu samples. CAIs in the Ryugu samples are much less abundant (~ 20 ppm) than those in the Wild2 particles (~ 0.5%; [15]), suggesting destruction of the CAIs and chondrules in the Ryugu parent body during the extensive aqueous alteration. The observed chondrule-like objects and CAIs may have survived along with isolated anhydrous grains in less-altered regions in the Ryugu parent body.

References: [1] Yada T. et al. (2021) *Nat. Astron.* 6:214. [2] Nakamura T. et al. (2022) *Science* 10.1126/science.abn8671. [3] Ito M. et al. (2022) *Nat. Astron.* 10.1038/s41550-022-01745-5. [4] Nakamura E. et al. (2022) *Proc. Jpn. Acad. Ser. B* 98:227. [5] Yokoyama T. et al. (2022) *Science* 10.1126/science.abn7850. [6] Klöck W. et al. (1989) *Nature* 339:126. [7] Han J. & Brearley A.J. (2015) *M&PS* 50:904. [8] Clayton R.N. et al. (1977) *EPSL* 34:209. [9] Ushikubo T. et al. (2012) *GCA* 90:242. [10] Tenner T.J. et al. (2018) *in Chondrules: Records of Protoplanetary Disk Processes* 196. [11] Krot A.N. (2019) *M&PS* 54:1647. [12] Libourel G. & Krot A.N. (2007) *EPSL* 254:1. [13] Rubin A.E. (2007) *M&PS* 42:1711. [14] Zolensky M.E. et al. (2006) *Science* 314:1735. [15] Joswiak D.J. et al. (2017) *M&PS* 52:1612. [16] Matzel J.E.P. et al. (2010) *Science* 332:1528. [17] Nakamura T. et al. (2008) *Science* 321:1664. [18] Hughes A.L.H. & Armitage P.J. (2010) *ApJ* 719:1633. [19] Liu M.-C. et al. (2022) *Nat. Astron.* 10.1038/s41550-022-01762-4. [20] Kawasaki N. et al. (2022) *Sci. Adv.* Submitted. [21] Fukuda K. et al. (2022) *GCA* 322:194.

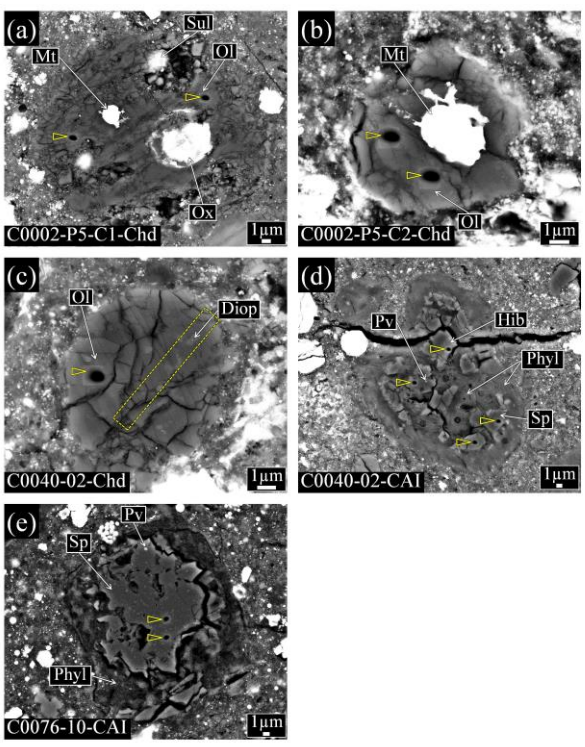

Fig. 1: BSE images of three chondrule-like objects and two CAIs in the Ryugu samples analyzed for oxygen isotopes. SIMS analysis spots are shown by the vertex of an open triangle. The rectangle area drown by the dashed line in panel c corresponds to the region extracted by the FIB sectioning. Abbreviations: Ol, olivine; Mt, Fe-Ni metal; Sul, Fe-sulfide; Ox, oxide; Diop, diopside; Sp, spinel; Hib, hibonite; Pv, perovskite; Phyl, phyllosilicates.

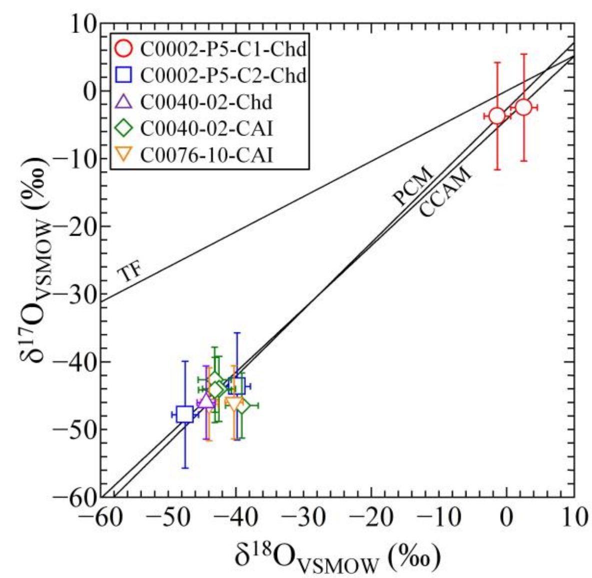

Fig. 2: Oxygen three-isotope ratios of three chondrule-like objects and two CAIs in the Ryugu samples. TF, PCM, and CCAM represent the Terrestrial Fractionation line, the Primitive Chondrule Mineral line, and the Carbonaceous Chondrite Anhydrous Mineral line.