THE OXYGEN ISOTOPIC COMPOSITION OF HAYABUSA2 PARTICLES: TESTING THE RELATIONSHIP WITH CI AND CY CHONDRITES.

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Introduction: Between June 2018 and November 2019, the JAXA Hayabusa2 spacecraft made detailed observations and measurements of the C-type asteroid 162173 Ryugu. Two samples, from different locations, were collected from the asteroid and returned to Earth on 6th December 2020. One of these was a surface sample, stored in Chamber A of the return capsule and the other was a sub-surface sample collected close to an impactor-formed crater and stored in Chamber C. Near-IR Spectroscopic data collected at Ryugu indicated that it was "similar to thermally and/or shock-metamorphosed carbonaceous chondrite meteorites" [1], the closest match being the CY (Yamato-type) chondrites [2]. In contrast to this interpretation, initial curation studies at the JAXA ISAS facility suggested that the returned samples were "most similar to CI chondrites" [3]. These contradictory classifications of Ryugu, as either CY or CI-like, can only be resolved by detailed characterization studies of the Hayabusa2 particles. Here we present the results of a high precision oxygen isotopic study of 4 Hayabusa2 particles, which provide a firm basis for evaluating these two interpretations.

This work is part of a series of integrated studies, including detailed mineralogy and petrology, combined STXM-NEXAFS – NanoSIMS – TEM analysis of organic components and SIMS analysis of anhydrous minerals and carbonates of the particles allocated to Phase2 curation Kochi [4-9].

Methods: Four sub-samples from the eight particles allocated to Kochi curation were analysed for this investigation [5]; three were from Chamber C (C0014,21; C0068,21; C0087,2) and one from Chamber A (A0098,2). The samples were transported to the Open University in two sealed, nitrogen-filled "FTTC: facility-to-facility transport containers" [4].

Sample loading was undertaken in a continuously purged nitrogen glove box with monitored oxygen levels below 0.1 %. The laser sample chamber configuration was modified so that it could be removed from the fluorination line with the internal volume under vacuum and then opened within the nitrogen-filled glove box. The sample block could then be inserted, clamped and returned to the line without any interaction between the samples and the atmosphere.

All Hayabusa2 samples were run in modified "single shot" mode [10]. For most Hayabusa2 particles the amount of O_2 gas liberated during reaction was less than 140 µg, the approximate limit for using the bellows facility on the MAT 253. In these cases analyses were undertaken using the cryogenic microvolume facility on the MAT 253 mass spectrometer. $\Delta^{17}O$ values have been calculated as $\Delta^{17}O = \delta^{17}O - 0.52\delta^{18}O$.

The NF^+ fragment ion of NF_3^+ can cause interference at mass 33 ($^{16}O^{17}O$). To eliminate this potential problem the majority of samples were treated using a cryogenic separation procedure [11,12].

Material from all four of the Hayabusa2 particles listed above were analysed during this study, so that, including replicates, a total of 7 single shot analyses were performed on the Hayabusa2 material. For comparison, and using the same protocols as set out above, analyses were also undertaken on Orgueil (CI) (n=9) and Y-82162 (CY) (n=7)

Results: The weighted average for the 7 single shot analyses, (weighting based on mass of O_2 gas liberated during fluorination), from all four of the Ryugu particles analysed in this study, is plotted in Fig. 1. This value is close to that for Orgueil (CI) (n=9), but plots well away from the average for the CY chondrite Y-82162 (n=7). This data supports the proposed relationship between asteroid Ryugu and the CI chondrites, and casts doubt on any link with the CYs [5].

Individual Hayabusa2 analyses show a large range in $\delta^{18}O$ values from 10.35‰ for A98 to 18.77‰ for C14-1 (Fig. 2). The largest fragment assigned for oxygen isotope analysis at the Open University (C14) had a total weight of 5.5 mg, which allowed us to undertake multiple measurements (n=4). These analyses had $\delta^{18}O$ values that varied from 14.41‰ to 18.77‰. This relatively large range in values in a single particle may be a reflection of intrinsic isotopic heterogeneity at the sampling scale involved. Note that detailed mineralogical studies [9] reveal a significant level of heterogeneity within individual Hayabusa2 particles. In addition, SIMS analysis reveals that mineral phases in Hayabusa2 particles are isotopically heterogeneous, with magnetite and dolomite differing by more than 30 ‰ [8]. In contrast, analyses for Orgueil and Y-82162 were drawn from powders produced by homogenising relatively large chips (~100 to 150 mg)

The $\Delta^{17}O$ composition of individual Hayabusa2 particles is systematically higher than analyses of Orgueil (Fig. 2). This is reflected in the average $\Delta^{17}O$ values for Hayabusa2 and Orgueil, which are 0.65±0.10‰ (2σ) and 0.55±0.13‰ (2σ) respectively. In contrast, there is no overlap either in terms $\Delta^{17}O$ or $\delta^{18}O$ between the analyses of the Hayabusa2 particles and those for Y-82162 (CY) (average $\Delta^{17}O$ = 0.44±0.11‰ (2σ)). These results cast further doubt on any potential link between Hayabusa2 samples and CY chondrites.

Discussion: It is clear from the oxygen isotope data presented here that there is a much stronger case for a connection between the Hayabusa2 particles and the CIs than with the CYs. This potential relationship is also supported by detailed mineralogical and petrological studies of Hayabusa2 material [3-6,9]. However, our data show systematically higher $\Delta^{17}O$ values for the Hayabusa2 particles compared to Orgueil, with the difference between their average $\Delta^{17}O$ compositions being 0.1‰. This difference may reflect terrestrial contamination of Orgueil since its fall in 1864. It is well document that Orgueil has undergone significant mineralogical modifications due to terrestrial weathering [13]. Weathering in the terrestrial environment would necessarily result in the incorporation of atmospheric oxygen and so pull the bulk analysis closer to the TFL. This conclusion is in keeping with the mineralogical evidence that Ryugu particles do not contain ferrihydrite [6], whereas Orgueil does. While the amount of ferrihydrite present in Orgueil (3.3 vol %) [14] is not enough to account for this $\Delta^{17}O$ difference, other mineralogical changes since its fall have taken place [13] and might be sufficient to account for the $\Delta^{17}O$ mismatch. Further work is being undertaken to evaluate this scenario.

Conclusions: Oxygen isotope analysis of 4 Hayabusa2 particles provides important evidence for a connection between asteroid Ryugu and the CI chondrites. However, a relationship with the CY chondrites appears unlikely. A systematic difference of 0.1‰ in $\Delta^{17}O$ between the average composition of Hayabusa2 particles and Orgueil may reflect terrestrial weathering of the latter. However, this hypothesis requires additional testing.

References: [1] Kitazato et al. (2019) *Science 364*, 272-275. [2] King A. J. et al. (2019) *Geochemistry 79*, 125531. [3] Yada T. et al. (2021) *Nature Astron.* https://doi.org/10.1038/s41550-021-01550-6 [4] Ito M. et al. (2020) *Earth Planets Space, 72*, 133. [5] Ito M. et al. (2022) *LPSC 2022*. [6] Tomioka N. et al. (2022) *LPSC 2022*. [7] Liu M. (2022) *LPSC 2022*. [8] McCain K. A./Matsuda N. et al. (2022) *LPSC 2022*. [9] Yamaguchi A., et al., (2022) *LPSC 2022* [10] Schrader D. L. et al. (2014) *EPSL 407*, 48-60 [11] Findlay R. et al. (2022) *LPSC 2022* [12] Greenwood et al. (2017) *Cheme Der Erde 77*, 1-43. [13]Gounelle M. and Zolensky M. E. (2014) *MAPS 49*, 1769-1794. [14] King A. J. et al. (2015) *GCA* 165, 148-160.

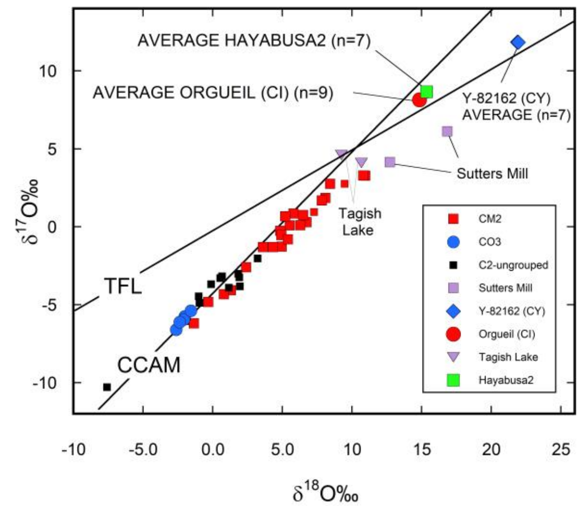

Fig. 1 Oxygen isotopic composition of the weighted average for all four Hayabusa2 particles analysed in this study. See text for discussion.

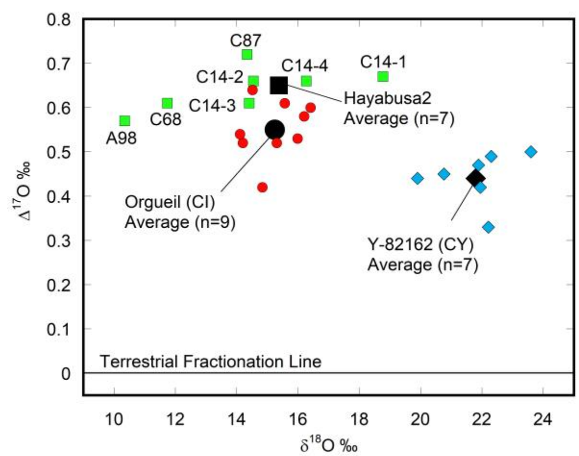

Fig. 2 Oxygen isotopic composition of individual Hayabusa2 analyses shown in relation to data collected for Orgueil (CI) and Y-82162 (CY) under identical analytical conditions. Error bars on the average analysis ±2σ.