Distinct ages and temperatures of aqueous activities recorded in Ryugu samples

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The Ryugu asteroid is a rubble pile body likely composed of materials ejected by impact(s) from a larger parent asteroid [e.g., 1] that may have formed far from the Sun [e.g., 2,3]. The Ryugu samples collected by the Hayabusa2 spacecraft thus may have originated from different parts of the parent asteroid and experienced different thermal histories. We reported that Ryugu's secondary minerals such as dolomite and magnetite formed at 37±10°C, ~5.2 Ma after the formation of the Solar System based on oxygen and Mn-Cr isotope systematics of the sample A0058 collected from the first touch-down site on Ryugu [4]. Here we report oxygen and Mn-Cr isotope systematics of secondary minerals found in a Ryugu sample, C0002, collected from the 2nd touch-down site.

In contrast to A0058-C1001 section, C0002-C1001 section is composed of different lithological units recognizable by differences in BSE contrast and elemental distributions in X-ray maps, including less-altered lithologies [e.g., 3,5]. Most lithologies are dominated by phyllosilicate matrices with sub-micron magnetite and sulfide grains. Larger grains (>10 µm) of magnetite, dolomite, and pyrrhotite are scattered throughout the major lithologies.

Figure 1 shows O-isotope compositions of dolomite, magnetite from the C0002 section, together with those from A0058-C1001. The O-isotope compositions of the dolomites are consistent with those in A0058, and are similar to the bulk Ryugu within uncertainty for their Δ^{17}O values [4,6,7]. In contrast to the majority of magnetites in A0058 having Δ^{17}O of ~ 0‰, all magnetites but one in C0002 have higher Δ^{17}O, ~ 2−3‰ (see also [8]). Some magnetites with high Δ^{17}O are included in overgrown dolomites with Δ^{17}O of ~ 0‰, suggesting earlier formation of these magnetites than the dolomite. These observations suggest that O-isotope composition of aqueous fluid was Δ^{17}O ~ +3‰ before crystallization of dolomite and was Δ^{17}O > +3‰ at the beginning stage of aqueous alteration because olivine and pyroxene in Ryugu have lower Δ^{17}O (–24 to –5 ‰) [3,9,10].

Using O-isotope thermometry [e.g., 11], the dolomite and magnetite pair in A0058 was used to estimate a temperature at which these minerals precipitated; their O-isotope compositions correspond to 37±10°C [4]. In C0002, a pair of dolomite and magnetite in the same lithology has identical Δ^{17}O, ~+0.6‰. Assuming these grains were in O-isotope equilibrium with the same fluid, their difference in δ^{18}O, 25.2±2.0‰, corresponds to 104±22°C.

Figure 2 shows Mn-Cr isotope systematics of dolomites in A0058-C1001, C0002-C1001, and Ivuna CI chondrite. Note we collected Mn-Cr isotope data from dolomites from which the O-isotope data were obtained. All ^{53}Cr excesses are well correlated with Mn-Cr ratios. The inferred initial ^{53}Mn/^{55}Mn ratios are $(2.55\pm0.35)\times10^{-6}$, $(3.78\pm0.34)\times10^{-6}$, and $(3.14\pm0.25)\times10^{-6}$ for A0058-C1001 [4], C0002-C1001 [this study], and Ivuna [4, this study], respectively. The initial ^{53}Mn/^{55}Mn ratio we obtained from C0002 is consistent with that in [10] and that from bulk Mn-Cr data [12] within uncertainty. If we use the initial ^{53}Mn/^{55}Mn ratio of the D'Orbigny angrite and the U-corrected Pb-Pb ages of D'Orbigny and CV CAIs [13−15], the initial ^{53}Mn/^{55}Mn ratios for A0058 and C0002 suggest that dolomite precipitation occurred at 5.2 (+0.8/−0.7) Ma and 3.1 (+0.5/−0.5) Ma after the CV CAI formation, at ~40°C and ~100°C, respectively. These ages could be systematically changed ±million years due to inconsistencies in CAI ages and proposed initial ^{53}Mn/^{55}Mn ratios of the Solar System [4 and references therein]. Other systematic changes may be introduced by inaccurate corrections of Mn/Cr sensitivity for dolomite by SIMS [4, 16−18]. Despite these systematic uncertainties, the relative age between the two isochrons is robust: 2.1±0.9 Ma. Therefore, during the aqueous alteration, one location in the Ryugu parent asteroid was at ~100°C. Then ~2 Ma later, possibly another location in the asteroid experienced ~40°C. These are new conditions to restrict thermal models of the Ryugu parent body. Thermal modeling to satisfy the conditions is in progress using methods in [19].

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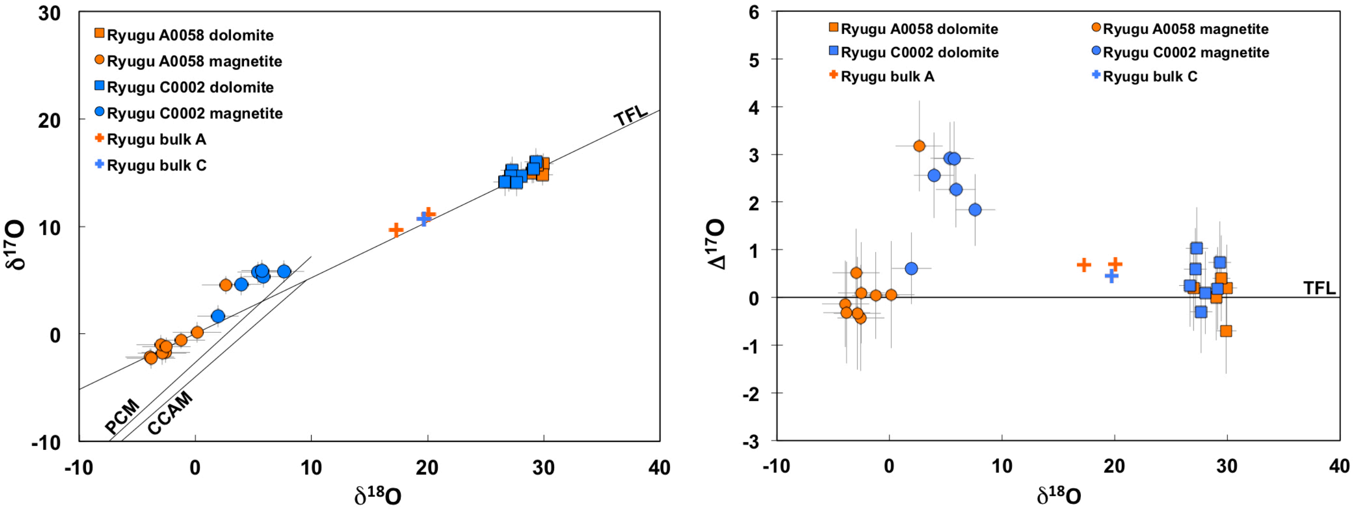

Fig. 1. Oxygen isotope compositions of dolomite and magnetite from Ryugu samples, A0058-C1001 [4] and C0002-C1001 [7, this study]. Also shown are bulk O-isotope data of A and C samples [4,6].

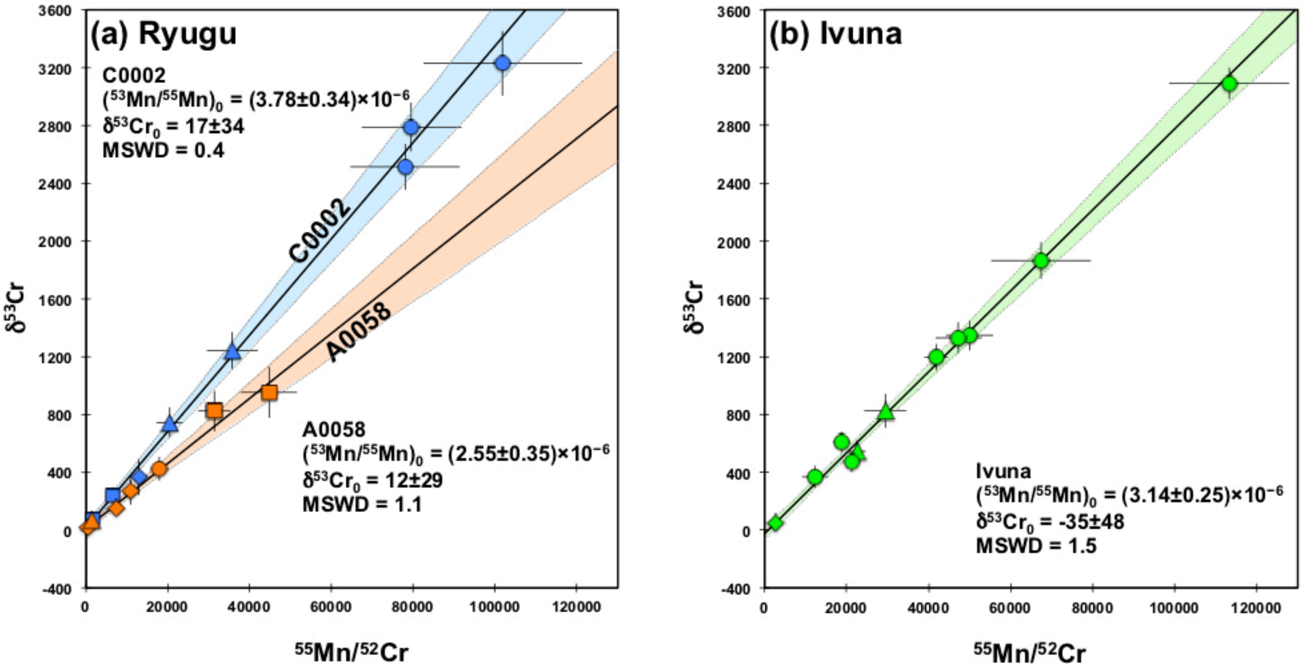

Fig. 2. Mn-Cr isotope systematics of dolomites from (a) Ryugu samples, A0058-C1001 [4] and C0002-C1001 [this study], and (b) Ivuna [4, this study]. Several dolomite grains were analyzed from each sample and they are shown as different symbols. Note data from dolomite grain HK2-#7 in Ivuna, shown as green circles were obtained in the two measurement sessions when we analyzed A0058-C1001 and C0002-C1001 samples and showed no differences in their initial ^{53}Mn/^{55}Mn ratios.