Oxygen isotope systematics of crystalline silicates in comet Wild 2: Comparison to anhydrous minerals in Ryugu and CI chondrites

Noriko T. Kita[1], Mingming Zhang[1], Donald E. Brownlee[2] and David J. Joswiak[2]
[1] *WiscSIMS, Department of Geoscience, University of Wisconsin-Madison*
[2] *Department of Astronomy, University of Washington*

Initial analyses of Ryugu returned samples indicated that they are similar to CI (Ivuna-type) carbonaceous chondrites, which mainly consist of minerals that formed by parent body aqueous alteration [e.g., 1-5]. Discovery of CO_2 bearing fluid inclusions in Ryugu pyrrhotite suggests that the Ryugu parent body accreted in the outer solar system beyond the CO_2 and H_2O snowlines (>3-4 au [2]). Kawasaki et al. [6] conducted oxygen isotope analyses of anhydrous minerals, such as olivine and pyroxene that are extremely rare in Ryugu and CI chondrite Ivuna. They examined the distribution of mass-independent fractionation factors of oxygen 3-isotopes, expressed by $\Delta^{17}O$ (= $\delta^{17}O - 0.52 \times \delta^{18}O$), in olivine grains from Ryugu and CI chondrites, and found them to be similar to those of comet Wild 2 from the NASA Stardust mission [7-12]. They suggested that the formation region of the Ryugu asteroid could have been farther into the outer solar system than most carbonaceous chondrites and closer to the accretion region of comets.

Here, we summarize oxygen isotope data of olivine and pyroxene from comet Wild 2. To date, ~90 relatively coarse-grained particles (>2 µm to upto 60 µm) have been analyzed for oxygen isotopes, including ~20 from the literature [7, 9-13] and ~70 from recent studies [14-16]. These latter studies include more than 50 particles extracted from the longest type B Stardust track (~17 mm) T227, which contains numerous relatively coarse (>2 µm up to 20 µm) particles in the bulb region in addition to at least four terminal particles (TP). The largest TP measures 60 µm in diameter and has a porphyritic chondrule-like texture [16]. The majority of Wild 2 particle analyses were conducted at the WiscSIMS IMS 1280 using a 2 µm-sized primary beam [7, 9, 12-16]. Oxygen isotope data of individual olivine and pyroxene particles are shown in the plot of $\Delta^{17}O$ versus Mg# (molar [Mg]/[Mg+Fe] in Figure 1. This diagram has been used for the studies of meteoritic chondrules to understand the isotope signatures of precursors and redox states during their formation [e.g., 17]. We also summarize published oxygen isotope analyses of olivine and pyroxene from Ryugu [6, 18] and other CI chondrites [6, 19-20] for comparison (Figure 2).

Wild 2 olivine and pyroxene show a wide range of Mg# ranging from 100 to 50 and are evenly distributed (Figure 1). The $\Delta^{17}O$ values are bimodal where most particles are ^{16}O-poor with $\Delta^{17}O$ values ranging from –7‰ to +7‰ and others with $\Delta^{17}O$ of ~ –22‰, values similar to CAIs in carbonaceous chondrites. The latter ^{16}O-rich particles are either LIME (low iron and Mn-enriched) olivine, nearly pure forsterite, or enstatite, all which are with highest Mg#≥98. They are likely early solar nebula condensates similar to those in AOAs [9,12]. In addition, rare occurrences of ^{16}O-rich relict olivine have been identified, such as in the chondrule-like object Gozen-sama, studied by [7]. The ^{16}O-poor particles show a general tendency of a slight increase in $\Delta^{17}O$ values with decreasing Mg# (Figure. 1). The majority of Wild 2 particles (60-70%) are FeO-rich (Mg#<90) and many of them show zero to slightly positive $\Delta^{17}O$ values. Similar results have been obtained from Giant Cluster IDP U2-20GCA [21], which is considered to be of cometary origin [22]. They overlap with data from CR chondrite chondrules [16, 23-25], suggesting a genetic relationship between CR chondrites and cometary particles [e.g., 9], though FeO-rich chondrules are uncommon in CR chondrites and do not show $\Delta^{17}O$ values higher than 1‰ [12, 16, 21].

Olivine and pyroxene data from Ryugu and CI chondrites are summarized in Figure 2. Most grains have high Mg# (≥98) with bimodal $\Delta^{17}O$ values of ~–5‰ and –22‰ and minor FeO-rich grains show $\Delta^{17}O$ values of ≤0‰. Similar to Wild 2 particles, ^{16}O-rich olivine grains are often Mn-rich [6, 18, 20] and may be related to AOAs (e.g., [26]). However, the majority of ^{16}O-poor olivine and pyroxene in Ryugu and CI chondrites cluster at the $\Delta^{17}O$ values of –5‰, which are uncommon among Wild 2 particles. Ryugu and CI data are more similar to chondrule data in major carbonaceous chondrites, such as CMs and CVs (e.g., [27-28]). Rare chondrule-like objects were identified in Ryugu [29], though they are substantially smaller than typical chondrules in carbonaceous chondrites.

Several Wild 2 particles are chondrule-like objects containing plagioclase and glass [7, 9-11, 16, 30]. Two of them were studied for ^{26}Al-^{26}Mg chronology, but do not show any resolvable excess ^{26}Mg [9, 31], suggesting that they formed later than 3-4 Ma after CAI formation (by assuming homogeneity of ^{26}Al in the solar system). In contrast, the Ryugu and CI chondrite parent bodies might have accreted much earlier ~2 Ma after CAIs and experienced aqueous alteration by the heat generated from ^{26}Al decay [2]. Thus, a major difference between anhydrous minerals in comets and CI chondrites could be related to the timing of accretion in the outer solar system. Comet Wild 2 contains late-forming (>3 Ma) chondrule-like materials, which may have formed in the outer solar system [16]. They were not present in the Ryugu and CI chondrite-forming regions at the time of the CI chondrite parent body accretion.

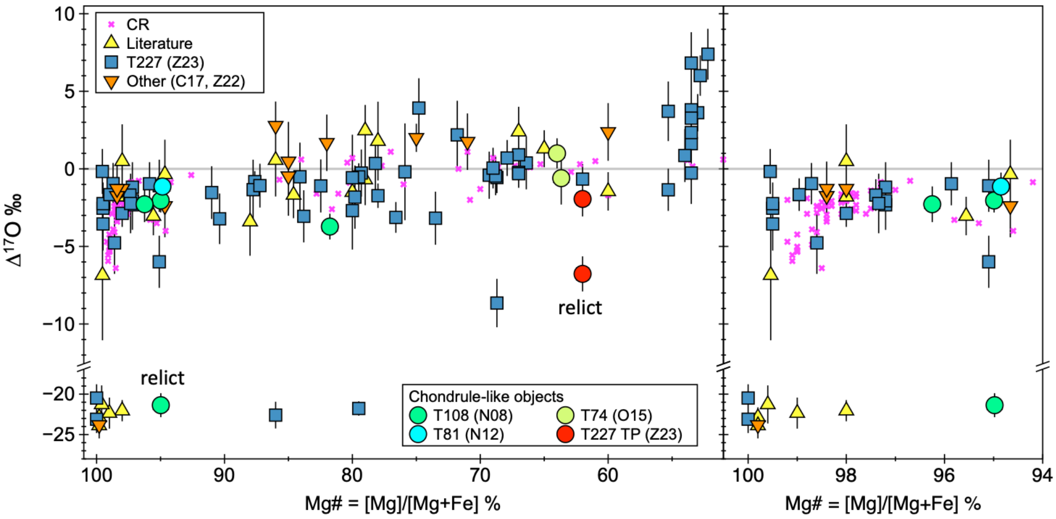

Figure 1. Mg# vs. $\Delta^{17}O$ relationship among olivine and pyroxene particles in comet Wild 2 (after Zhang et al. [16]). Data sources: Literature [7, 9-13], T227 [16] and others [14-15]. Data from CR chondrules [17, 23-25] are plotted for comparison (error bars are ignored). Chondrule-like objects are shown as circles [7, 9, 11, 16] including ^{16}O-rich relict olivine data [7, 16].

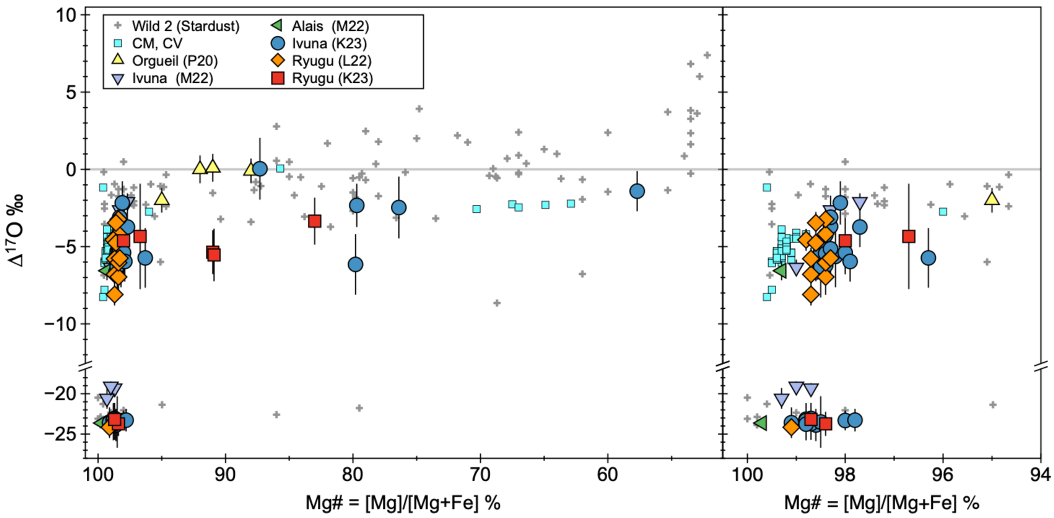

Figure 2. Mg# vs. $\Delta^{17}O$ relationship among olivine and pyroxene grains in Ryugu (K23 [6]; L22 [18]) and CI chondrites Orgueil (P20 [19]), Ivuna (K23, M22 [20]), and Alais (M22). The Wild 2 comet data (Figure 1) and CM and CV chondrite chondrule data [27-28] are shown for comparison (error bars are ignored). Majority of ^{16}O-poor Ryugu and CI chondrite data show systematically lower $\Delta^{17}O$ and higher Mg# than those of Wild 2.

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