

Pristine nature and formation environments of chondrules from Asuka 12236 CM2.9 chondrite: Evidence from mineral chemistry and oxygen isotope systematics

Kohei Fukuda¹, Makoto Kimura² and Noriko T. Kita¹

¹WiscSIMS, Department of Geoscience, University of Wisconsin-Madison, USA

²National Institute of Polar Research (NIPR), Japan

Introduction: Mighei-like (CM) chondrites are the most abundant group among carbonaceous chondrites. They often show evidence of various degrees of aqueous alterations [e.g., 1] so that they are important clues to decipher aqueous alteration processes in the early Solar System. In contrast, their components -refractory inclusions, chondrules, and matrices- have lost their primitive features because of the alteration and/or secondary heating on the asteroid parent body [e.g., 2]. Specifically, chondrule mesostasis phases that can be used for Al-Mg dating have been extensively altered during the aqueous alteration [e.g., 3], which do not allow for determination of formation time of chondrules from CM chondrites. Asuka 12236 (hereafter A 12236) is one of the least altered CM chondrites [CM2.9; 4], which provides us great opportunity to investigate Al-Mg isotope systematics of chondrules from the CM chondrite group. In order to further evaluate their usefulness for Al-Mg dating and decipher their formation environments, we conducted *in situ* chemical and O-isotope analyses of constituent minerals of chondrules from A 12236.

Sample and Methods: Nineteen chondrules in A 12236 [14 for type I (Mg# >90; where Mg# = Mg/[Mg + Fe] molar%), 5 for type II (Mg# <90)] were investigated. Fourteen out of the nineteen chondrules contain plagioclase, which were arbitrarily selected for future Al-Mg isotope analyses. Major and minor element abundances of chondrule minerals (olivine, pyroxene, plagioclase) were obtained with a Cameca SXFive FE EPMA at UW-Madison. Oxygen three-isotope analyses of olivine, pyroxene, and plagioclase were performed with the WiscSIMS Cameca IMS 1280 at UW-Madison. The analytical conditions are similar to those described in [5] for olivine and pyroxene analyses and [6] for plagioclase analyses. Olivine and pyroxene were analyzed by using 2 nA Cs⁺ primary ion beam (10 × 12 μm), while plagioclase were analyzed by smaller beam (2 × 3 μm) with the lower intensity (20 pA). For olivine and pyroxene analyses, the external reproducibility (2SD) of the bracketing standard analyses were typically 0.17‰, 0.24‰, and 0.25‰ for δ¹⁸O, δ¹⁷O, and Δ¹⁷O, respectively (Δ¹⁷O = δ¹⁷O – 0.52 × δ¹⁸O). Those for plagioclase analyses were typically 0.42‰, 0.94‰, and 1.02‰ for δ¹⁸O, δ¹⁷O, and Δ¹⁷O, respectively.

Results: Mg#s of coexisting olivine and pyroxene within individual type I chondrules are similar to each other. Thus we determined mean chondrule Mg#s that were calculated by averaging Mg#s of olivine and pyroxene grains within individual chondrules. The mean Mg#s of type I chondrules studied are all FeO-poor (Mg# ≥98.8). Type II chondrules studied are composed mostly of olivine so that their mean Mg#s (50.5-72.1) were calculated by averaging Mg#s of olivine. For plagioclase, we estimated the abundance of excess silica ([Si₄O₈]) that could be used as a metric for the extent of plagioclase secondary alteration [7]. The excess silica in plagioclase from type I chondrules comprises up to 10% of endmember composition. Anorthite contents (An = [Ca]/[Ca + Na + K] in molar %) and MgO concentrations of plagioclase in type I chondrules range from 86.5 to 99.2 and 0.7 to 1.3 wt%, respectively.

Among 19 chondrules studied, two type I chondrules (A123 and A75) exhibit variations in O-isotope ratios of olivine and pyroxene within individual chondrules (Figs. 1a-b). Other 17 chondrules show internally homogeneous O-isotope ratios so that mean O-isotope ratios of individual 17 chondrules were calculated based on multiple olivine and pyroxene analyses, closely following a data reduction scheme previously described by [8]. On the oxygen three-isotope diagram, the mean O-isotope ratios of type I and type II chondrules are bimodally distributed and plot between the Primitive Chondrule Mineral (PCM [6]) and Carbonaceous Chondrite Anhydrous Minerals (CCAM [9]) lines (Fig. 1c), which are consistent with O-isotopic systematics of chondrules from Murchison (CM2 [10]). The averaged Δ¹⁷O value of type I chondrules is -5.1 ± 0.8‰ (2SD, N = 12), which is more ¹⁶O-rich than that for type II chondrules (-2.4 ± 0.4‰; 2SD, N = 5). Plagioclase in five type I chondrules we analyzed have similar in O-isotope ratios to their olivine and pyroxene, except for chondrule A75 (Fig. 1b).

Discussion: Olivine, pyroxene, and plagioclase in chondrules from A 12236 show chemical and isotopic characteristics similar to those from chondrites with low petrologic type (≤3.1). For example, Mg#s of coexisting olivine and pyroxene within individual type I chondrules are similar to each other, suggesting no Fe-Mg diffusion after their formation. For plagioclase, the observed range of excess silica as well as An contents and MgO concentrations are similar to those from the least metamorphosed carbonaceous chondrites such as Acfer 094 (ungrouped C3.00) and CR2-3 chondrites [7]. Aside from chondrule A75, O-isotope ratios of plagioclase are consistent with those of coexisting olivine and pyroxene, which is also a

characteristic of chondrules from the least metamorphosed carbonaceous chondrites [11 and references therein]. These observations indicate that chondrules from A 12236 have experienced minimal parent body alteration, and thus they are useful for investigating Al-Mg isotope systematics of chondrules from the CM chondrite group.

The observed systematic difference in O-isotope ratios between type I and type II chondrules (Fig. 1c) may reflect differences in their formation conditions such as redox states [e.g., 12]. According to an oxygen mass balance model proposed by [13] and assuming O-isotope ratios of precursor materials estimated by [8], the majority of type I chondrules from A 12236 would have formed under highly reducing environments, that is, a moderately high dust enriched region at relatively dry conditions in the protoplanetary disk ($\sim 50\text{-}100 \times$ dust enrichment compared to Solar abundance gas and $<0.6 \times$ ice enhancement relative to CI chondritic dust), while type II chondrules would have formed under more oxidizing environments ($>1000 \times$ dust enrichment and $>0.8 \times$ ice enhancement).

Chondrules A123 and A75 exhibit distinct O-isotope systematics compared with other chondrules investigated (Figs. 1a-b). Olivine grains in chondrule A123 show ^{16}O -rich signatures down to $\Delta^{17}\text{O} = \sim -25\%$ relative to coexisting pyroxene, suggesting its precursor dust having ^{16}O -rich composition. In contrast, O-isotope ratios of minerals in chondrule A75 are ^{16}O -depleted compared with the other chondrules investigated, which exhibit systematic variations among coexisting minerals with decreasing $\delta^{18}\text{O}$ and $\delta^{17}\text{O}$ in the order of olivine, pyroxene, and plagioclase (Fig. 1b). The ^{16}O -depleted composition of olivine grains are similar to O-isotope ratios of chondrules from ordinary chondrites [5], indicating that at least its precursor dust formed at ordinary chondrite-forming regions [14-16]. The early formation of Jupiter between ordinary and carbonaceous chondrite-forming regions would have prevented significant material mixing between these two reservoirs [e.g., 17]. The presence of ordinary chondrite-like chondrule in A 12236 imply either that the formation of Jupiter did not create a barrier totally impermeable to outward transport [16, 18] or Jupiter was located beyond the region where carbonaceous chondrites accreted.

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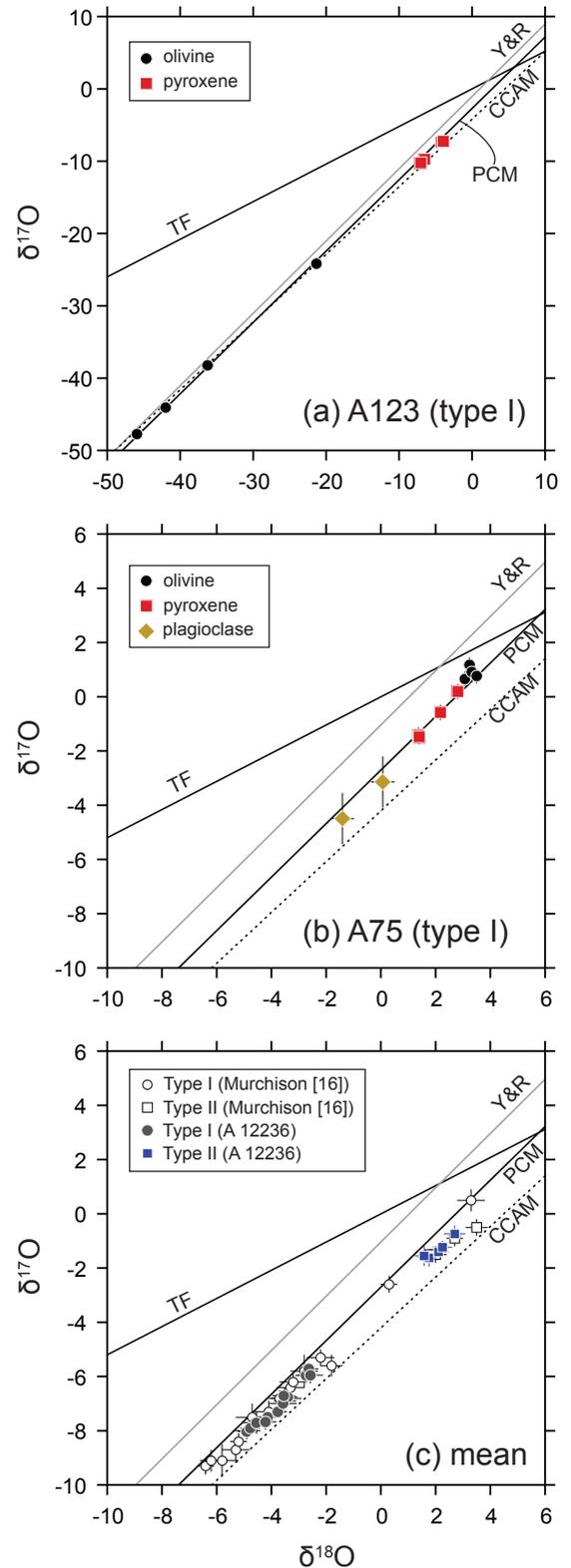


Fig. 1. Oxygen three-isotope diagrams for (a) chondrule A123, (b) chondrule A75, and (c) mean chondrule O-isotope ratios of 17 chondrules. For comparison, mean O-isotope ratios of chondrules from Murchison [10] are shown in (c). TF, Y&R, CCAM, and PCM lines are shown as reference. Errors are 2σ .