Abundant refractory materials admixed into the CA chondrule-forming regions

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Introduction: The "CA" is a newly proposed carbonaceous chondrite (CC) grouplet characterized by high chondrule (~80 vol%)/matrix (~15 vol%) ratio and absence of phyllosilicates (Kimura et al., 2014, 2021). So far, this group has three members, i.e., Yamato (Y)-82094, Asuka 9003, and Asuka 09535; all have a petrologic type of 3.2. Chondrules (mean diameter ~0.3 mm), as the dominant component in CA meteorites, are mainly porphyritic and iron-poor (Mg# >90; ~85-96%), with mesostasis typically composed of plagioclase and cristobalite (a SiO_2 polymorph). The Fe-Mn systematics of their olivines are like those of CO and CM chondrites. And their oxygen isotope systematics display two populations, with Mg#=98.8-99.5 ones having the mass-independent oxygen isotope fractionation $\Delta^{17}O$ (= $\delta^{17}O - 0.52 \times \delta^{18}O$) of –6‰ to –4‰, and Mg# <97 one having $\Delta^{17}O$ near –2.5‰, resembling those in CV, CO, CM, and Acfer 094 chondrites (Tenner et al., 2017). Interestingly, plagioclase displays almost identical oxygen isotope ratios to coexisting olivine/pyroxene, suggesting limited fluid-assisted oxygen isotope exchange that possibly due to the low abundance of matrix (ice) of the host chondrite (Tenner et al., 2017). Except for typical ferromagnesium chondrules (FMCs), the CA chondrites, especially Y-82094, apparently have abundant Al-rich chondrules (ARCs). However, the characteristics of these ARCs as compared to those in other CCs remain unknown. Here we report the petrography, major and trace element abundances, and oxygen isotopes of ARCs in the CA chondrite Y-82094.

Methods: Four polished sections (91-1, 91-4, 96-1, and 96-2) of Y-82094, on loan from the NIPR, were surveyed for ARCs under a SEM (Hitachi S3400VP) at UW-Madison. Major and minor element compositions of constituent phases were determined using a field emission-gun (FEG) electron probe micro-analyzer (EPMA, Cameca SXFive). Oxygen isotope ratios of silicates and oxides were determined using the Cameca IMS-1280 at WiscSIMS. Two primary beam settings were used, ~12 µm and ~3 µm, following the analytical protocols described in Zhang et al., (2022) and Ushikubo et al., (2012), respectively. At the end, trace element abundances were measured with a femtosecond laser (Analyte-fs Teledyne-Photon Machines) connected with an ICP-MS (Thermal Agilent 8900 QQQ).

Results: A total of ~32 ARCs were identified out of ~2000 chondrules (abundance ~1.6%). Eighteen were selected for detailed studies, including eight new and ten that have been previously determined for oxygen isotopes by Tenner et al., (2017). Additional petrographic and major element characterization were performed for the ten studied ARCs.

Petrologically, they are dominated by low-Ca pyroxene (up to 14 wt% Al_2O_3, ≤3 wt% TiO_2) and/or olivine (typically Fo_{90-100}, up to 18 wt% FeO) phenocrysts and tabular/lath-shaped plagioclase (An_{70-100}; <1.2 wt% MgO). High-Ca pyroxene ($En_{41-84}Wo_{15-58}$, up to 7 wt% Al_2O_3, <4 wt% TiO_2) appears as overgrowth on low-Ca pyroxene phenocrysts or intergrowth with low-Ca pyroxene between plagioclase laths. Cristobalite (up to 4.5 wt% Al_2O_3) is commonly associated with mesh-like plagioclase laths, likely to be devitrified mesostasis. Spinels (FeO <2 wt%, minor up to 14 wt%) are exclusively round crystals lined up as chains or aggregated as clusters. Three ARCs are nonporphyritic and made of fine-grained intergrowths of high-Ca pyroxene, low-Ca pyroxene, plagioclase, and/or olivine. One ARC is compound consisting of a fine-grained core and a porphyritic olivine-pyroxene mantle. Bulk Al_2O_3 and CaO of these ARCs range from 10 wt% to 40 wt%, and from 6 wt% to 14 wt%, respectively. Bulk FeO and Na_2O abundances are typically <2 wt%.

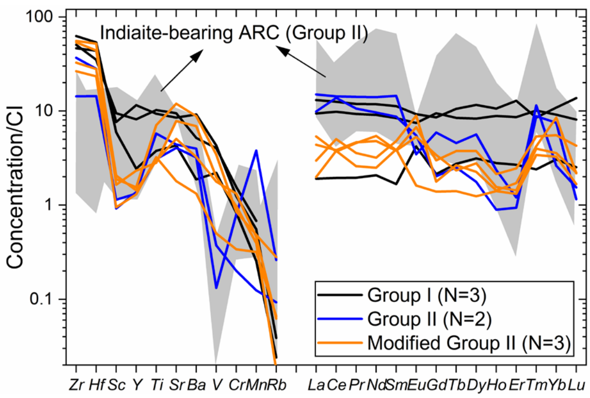

Fig. 1. CI-normalized bulk trace element abundances of nine ARCs studied from Y-82094.

Nine ARCs were measured for trace elements by LA-ICP-MS. Except for general enrichments of Ti, Sr, and Ba (up to 12 ×CI), other non-REE element abundances are monotonically decreasing from Zr and Hf (<50 × CI) to Sc (<10 ×CI), to V, Cr, Mn, and Rb (typically <1 ×CI), with the increasing of their volatilities. Three have flat REE patterns with abundances of ~12 ×CI, ~9 ×CI, and ~2 ×CI, respectively; three have typical highly fractionated group II REE patterns; and three have modified group II-like REE patterns, with positive Ce and Eu anomalies. The indiaite (high-temperature polymorph of cordierite, Mikouchi et al., 2016)-bearing ARC displays the largest compositional range of trace elements, with La content ranging from 20 ×CI to 60 ×CI among its mesostasis and from 7 ×CI to 30 ×CI among its plagioclase (An_{72-100}).

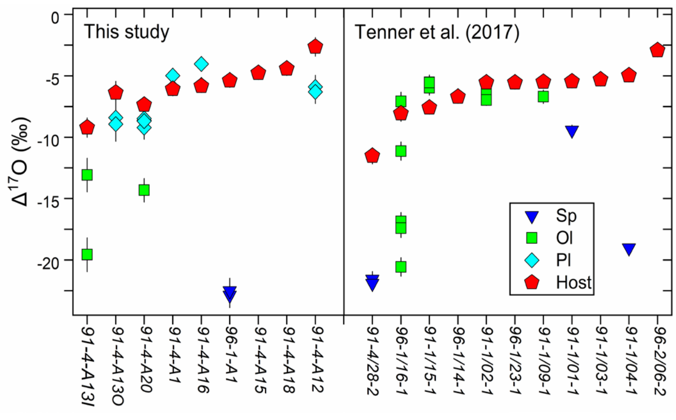

Fig. 2. $\Delta^{17}O$ values of the host and the outliers of ARCs in Y82094 studied here and Tenner et al., (2017). Ol = olivine; Sp = spinel; Pl = plagioclase.

Oxygen isotopes of low-Ca pyroxene, high-Ca pyroxene, most plagioclase, and minor olivine are almost identical and represent the chondrule hosts, with $\Delta^{17}O$ varying from –9‰ to –2.5‰. Relict spinel and olivine with significant ^{16}O-enriched ($\Delta^{17}O$ down to –23‰, like CAIs/AOAs) signatures were found in 7 out of 19 ARCs. Meanwhile, relict olivines in one ARC are less ^{16}O-enriched than coexisting pyroxenes ($\Delta^{17}O$~ –6‰ vs. –7.5‰). Furthermore, compared to the chondrule host, both more ^{16}O-enriched and ^{16}O-depleted plagioclases were identified in this study, which haven't been found in Tenner et al., (2017). The ^{16}O-depleted ones, with $\Delta^{17}O$ less than 1‰ higher than the hosts, are likely resulted from asteroidal metasomatism; the ^{16}O-enriched ones, with $\Delta^{17}O$ 3-4‰ lower than the hosts, are found in three fine-grained ARCs.

Discussions and conclusions: The significant Al-rich bulk composition and pyroxene chemistry, as well as the common fractionated group II (-like) REE patterns and relict spinel/olivine, firmly demonstrated that these ARCs recycled refractory inclusions. Importantly, the identification of ^{16}O-rich plagioclase in fine-grained ARCs suggests that (i) plagioclase could be a common relict mineral in addition to spinel and olivine, limits the refractory inclusion types to anorthite-bearing CAIs/AOAs that formed at late stage of nebular gas condensation (Ebel et al., 2000); and (ii) plagioclase could survive from weak-mild heating events that formed fine-grained ARCs but not from intense melting events that formed well-crystallized porphyritic ARCs. On the other hand, the host oxygen isotope signatures of these ARCs are similar to FMCs of the same meteorite, suggesting that they formed in the same environments. In summary, the characteristics of petrography, mineral chemistry, bulk major and trace elements, and oxygen isotopes of CA ARCs are comparable to those in CV chondrites, suggesting that they formed by similar mechanisms, i.e., melting mixtures of refractory inclusions and FMC materials in the typical chondrule-forming regions (e.g., Sheng et al., 1991; Zhang et al., 2020). Furthermore, their ARCs abundances, ~1.6% in CAs and ~1.3% in CVs (~10/800, Zhang et al., 2020), are also similar, suggesting abundant refractory materials have mixed into the CA chondrule-forming regions.

References

Kimura, M., Barrat, J. A., Weisberg, M. K., Imae, N., Yamaguchi, A., and Kojima, H., Petrology and bulk chemistry of Yamato-82094, a new type of carbonaceous chondrite, Meteoritics & Planetary Science, 49(3), 346-357, 2014.

Kimura, M., Greenwood, R. C., Komatsu, M., Imae, N., Yamaguchi, A., and Sato., R., Petrology and classification of A-9003, A 09535, and Y-82094: A new type of carbonaceous chondrite, Meteoritics & Planetary Science, 57(2), 302-316, 2021.

Tenner, T. J., Kimura, M., and Kita, N. T., Oxygen isotope characteristics of chondrules from the Yamato-82094 ungrouped carbonaceous chondrite: Further evidence for common O-isotope environments sampled among carbonaceous chondrites, Meteoritics & Planetary Science, 52(2), 268-294, 2017.

Zhang, M., Fukuda, K., Spicuzza, M. J., Siron, G., Heimann, A., Hammerstrom, A. J., Kita, N. T., Ushikubo, T., and Valley, J. W, SIMS matrix effects in oxygen isotope analysis of olivine and pyroxene: Application to Acfer 094 chondrite chondrules and reconsideration of the primitive chondrule minerals (PCM) line, Chemical Geology, 608, 121016, 2022.

Ushikubo, T., Kimura, M., Kita, N. T., and Valley, J. W., Primordial oxygen isotope reservoirs of the solar nebula recorded in chondrules in Acfer 094 carbonaceous chondrite, Geochimica et Cosmochimica Acta, 90, 242-264, 2012.

Mikouchi, T., Hagiya, K., Sawa, N., Kimura, M., Ohsumi, K., Komatsu, M., and Zolensky, M., Synchrotron radiation XRD analysis of indialite in Yamato-82094 ungrouped carbonaceous chondrite. 47th Lunar and Planetary Science Conference, #1919, 2016.

Sheng, Y. J., Hutchen, I. D., and Wasserburg, G. J., Origin of plagioclase-olivine inclusions in carbonaceous chondrites, Geochimica et Cosmochimica Acta, 55(2), 581-599, 1991.

Zhang, M., Lin, Y., Tang, G-Q, Liu, Y., and Leya, I., Origin of Al-rich chondrules in CV chondrites: Incorporation of diverse refractory components into the ferromagnesian chondrule-forming region, Geochimica et Cosmochimica Acta, 272, 198-217, 2020.

Ebel, D. S. and L. Grossman, Condensation in dust-enriched systems, Geochimica et Cosmochimica Acta, 64(2), 339-366, 2000.