Mineralogical investigation of olivine grains in CI chondrites Ivuna and Orgueil

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Introduction: CI chondrites preserve the primitive chemical composition matching with the solar photosphere and thus provide important information about the evolution and dynamics of the protoplanetary disk in the early solar system. Recently, analysis of asteroid Ryugu samples returned by JAXA's Hayabusa2 spacecraft has revealed that they were nearly identical to CI chondrites in chemistry and mineralogy [e.g., 1-3], further strengthening the importance of these primitive solar system materials. Because all of these materials suffered extensive aqueous alteration in their parent body(s), there remains little anhydrous minerals that escaped such alterations. Olivine is one of such minerals, but its abundances in CI chondrites and Ryugu samples are both much less than 1 vol.%. Also, olivine grains with reasonably large size (>10 μm) suitable for oxygen isotope analysis to constrain their origins are limited because most olivine grains in these samples are usually smaller than 5 μm [e.g., 1-7]. Therefore, the origin of such small olivine grains in Ryugu samples and CI chondrites is uncertain. Since we have been successful to detect numerous small olivine grains in Ryugu samples [3,7], we applied the same technique to perform extensive search for olivine grains in CI chondrites (Ivuna and Orgueil) to compare with olivine mineralogy of Ryugu samples and to discuss their possible common origins.

Samples and Methods: In order to mimic the size of Ryugu samples analyzed [3], we prepared polished sections of 1-3 mm fragments of Ivuna and Orgueil and analyzed them using JEOL JXA-8530F FE-EPMA at Univ. of Tokyo. After olivine grains were found using Mg X-ray mapping, the quantitative analysis was performed at 12 kV accelerating voltage with 30 nA beam current (counting times at peaks: 30 sec). This analytical condition allowed us to obtain accurate mineral compositions even from ~1 μm olivine grain both for major and minor elements [7].

Results: As reported in previous studies [e.g., 8,9], both Ivuna and Orgueil exhibit obvious brecciated textures on mm to μm scale. Mg X-ray maps show heterogeneous distributions of olivine grains whose size is up to 50 μm and overall abundance is <<1 vol.%. Olivine is present only in brecciated clasts that show relatively weak degrees of aqueous alteration as we saw in Ryugu samples [3,10]. Phyllosilicates in such "less altered" clasts are slightly more Fe-rich compared to those in altered clasts. These less altered clasts contain Ca carbonates although they are absent in altered clasts. This observation is identical to Ryugu samples as the modeling calculation of progressive aqueous alteration of chondritic anhydrous minerals predicts that only Ca carbonates form when the water to rock ratio is low, resulting in less aqueous alteration [3,10]. Similarly we found a hydrous Mg,Na phosphate grain in Ivuna only in the less altered clast that is also found in Ryugu samples [3,11]. There are numerous tiny olivine grains more abundantly in Ivuna compared to Orgueil (Fig. 1). Accordingly, the abundance of olivine in Ivuna appears slightly higher than that of Orgueil, which is consistent with the previous study [e.g., 9]. Because CAI is only found in Ivuna among CI chondrites [12], it is also consistent with the presence of more abundant "less altered" clasts in Ivuna compared to Orgueil. The olivine compositions of Orgueil and Ivuna are nearly identical. The most Fe-rich olivine in the polished sections studied is Fo_{67}, but >90% grains are clustered at Fo_{99}. There is rare presence of LIME olivine whose MnO contents reach up to 2.2 wt% (Fig. 2). The CaO content is usually less than 0.1 wt%, while Cr_2O_3 has a wide range of 0-0.6 wt%. The Mn-Cr plot shows that there are two distinct compositional trends as seen in Ryugu samples [7] (Fig. 3). We tried to find a relationship between the morphology of olivine grains and their mineral compositions to consider their origins. However, most olivine grains are present as isolated small single crystals (always rimmed by submicron Fe-rich rims), and we could not find a clear relationship. Nevertheless, there are rare grains showing a characteristic mineralogy. For example, there is an aggregate of small olivine grains that have high Mn contents, suggestive of the LIME origin (Fig. 2). Another example is a composite grain of olivine and low-Ca pyroxene (Fig. 4). Combining the texture and high Cr content of olivine, this grain would be a fragment of chondrule.

Discussion and Conclusion: By applying the same analytical method which we employed for the analysis of Ryugu samples [3,5], we found small (<5 μm) olivine grains in CI chondrites Orgueil and Ivuna that have identical mineralogy to Ryugu olivines. Interestingly, we found two compositional trends in minor element contents, especially in Mn-Cr systematics (Fig. 3). It is hard to discuss their origins only from olivine textures because of very limited number of olivine grains showing characteristic morphology, but their distinct compositions provide some hint. The relatively Mn-rich and Cr-poor trend would be origins from amoeboid olivine aggregates (AOA). In fact LIME olivine grains are plotted along this trend, which is common in AOA olivines [e.g., 13]. In contrast, the other trend is relatively Cr-rich and Mn-poor and we interpret that such compositions are suggestive of the chondrule origin. The composite grain of olivine and low-Ca pyroxene (Fig. 4) is plotted on this trend, and such mineralogy is common in chondrules. Similar observation has been known for Ryugu samples, further supporting their close genetic relationship [e.g., 1-3]. It seems that the abundance of AOA-like olivine is higher compared to chondrule-like olivine (Fig. 3) and the similar distinct population is found in Ryugu olivine [7]. Because the formation of the original Ryugu parent body is considered to have been considerably early (~2 Ma after CAI) [3], it would be natural to contain more AOA-like olivine grains than chondrule grains. However, it is closely related to dynamical transportation events of small components happened in the early solar system, and thus more accurate proportional estimate of AOA/chondrule populations will help better understanding such events.

References: [1] Yokoyama T. et al. (2022) Science 10.1126/science.abn7850. [2] Ito M. et al. (2022) Nature Astronomy, 10.1038/s41550-022-01745-5. [3] Nakamura T. et al. (2022) Science 10.1126/science.abn8671. [4] Liu M.-C. et al. (2022) Nature Astronomy, 10.1038/s41550-022-01762-4. [5] Piralla M. et al. (2020) Geochim. Cosmochim. Acta, 269, 451-464. [6] Morin G. L. F. et al. (2022) Geochim. Cosmochim. Acta, 332, 203-219. [7] Mikouchi T. et al. (2022) 85th Annual Meeting of The Meteoritical Society, #6180. [8] Morlok A. et al. (2006) Geochim. Cosmochim. Acta, 70, 5371-5394. [9] Alfing J. et al. (2019) Geochemistry, 79, 125532. [10] Mikouchi T. et al. (2022) Hayabusa Symposium 2022. [11] Ma C. et al. (2022) 85th Annual Meeting of The Meteoritical Society, #6134. [12] Frank D. et al. (2022) Meteoritics and Planet. Sci. (submitted). [13] Komatsu M. et al. (2015) Meteoritics and Planet. Sci., 50, 1271-1294.

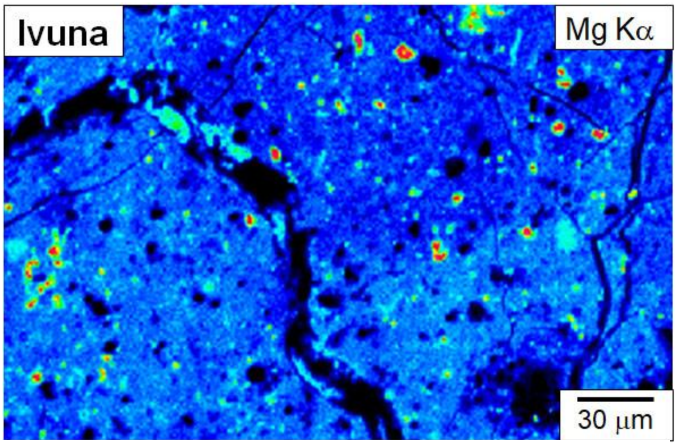

Fig. 1. Mg X-ray map of Ivuna CI chondrite. This clast contains numerous olivine grains smaller than 10 µm (shown in red~bright blue spots in the phyllosilicate (dark blue) matrix).

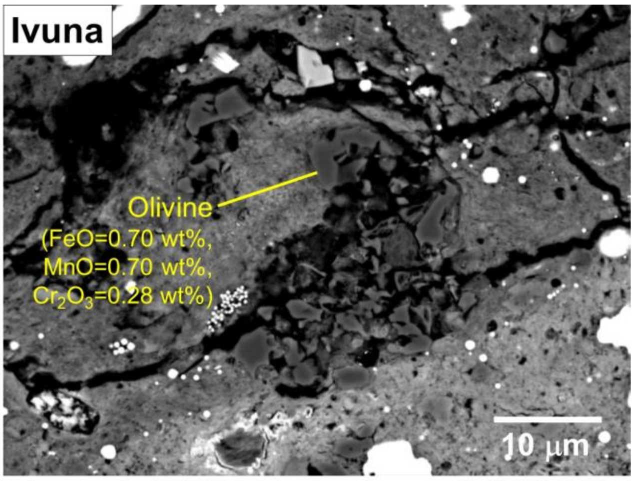

Fig. 2. Back-scattered electron (BSE) image of olivine in Ivuna. There is an aggregate of olivine grains in the center of the image. Most of these olivine grains have high Mn content (~0.7 wt%) similar to LIME olivine.

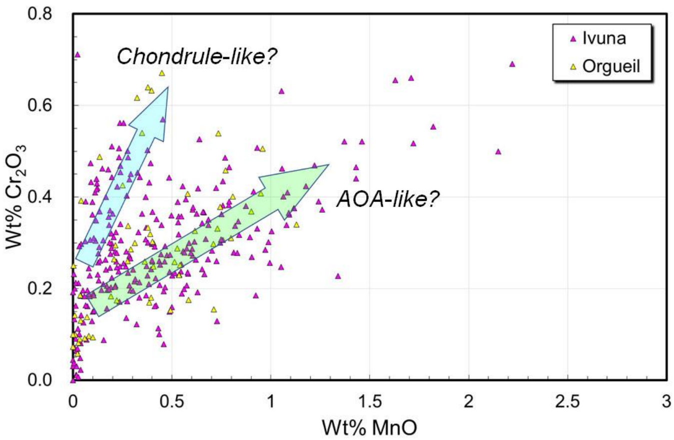

Fig. 3. Mn-Cr systematics of olivine in CI chondrites Ivuna and Orgueil. There are two compositional trends as found in Ryugu olivine [7], suggesting origins of either chondrule or AOA.

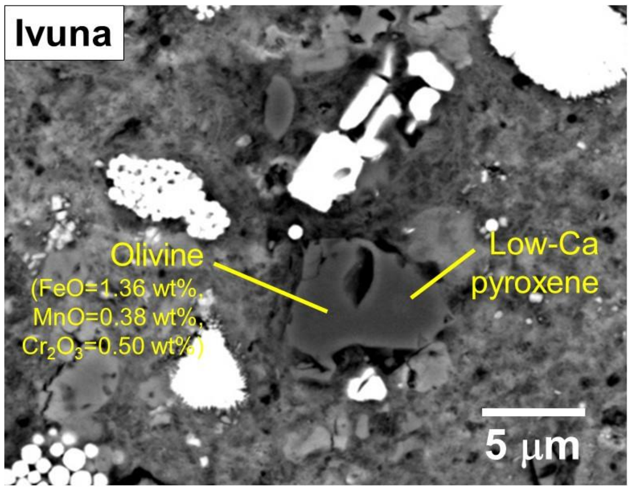

Fig. 4. BSE image of olivine in Ivuna. The olivine grain near the center of the image has a high Cr content. A small low-Ca pyroxene crystal is accompanied.