Oxygen isotope systematics of chondrules in the Paris CM2 chondrite: indication for a single large formation region across snow line

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Electronic Annex EA4

Texture, Petrography, and Mineralogy of Individual Chondrules

Type I porphyritic chondrules

Olivine in type I porphyritic chondrules is present as large anhedral phenocrysts and euhedral grains (up to ~300 µm) (Fig. 1, 2). In several chondrules (e.g., C4, C8, C7; Fig. 2a for C7), olivine is located in the cores while the pyroxene is more abundant in the peripherry. In type I POP chondrules, low-Ca pyroxene often displays a poikilitic texture with numerous cracks and pores (e.g., C7; Fig. 2). Low-Ca pyroxene was also observed as large euhedral grains, i.e., up to ~150 µm length in chondrule C7 (Fig. 2a). In type I PP chondrules, low low-Ca pyroxene display less cracks and pores (e.g., C11, C12, C21; Fig. 1c for C21). High-Ca pyroxene is also present in many type I porphyritic chondrules as small grains (from a few µm to ~70 µm length), either in association with Low-Ca pyroxene (e.g., C2, C6, C23) or olivine (e.g., C30; Fig. 1b). Olivine grains in type I porphyritic chondrules are chemically homogeneous, with an average Mg# of 99.0±0.8 (2SD) (97.6–99.8). They contain up to 0.44 wt% Al_2O_3, 0.84 wt% CaO, 0.67 wt% Cr_2O_3, and 0.46 wt% MnO. Low-Ca pyroxene grains have Mg#'s ranging from 92.5 to 99.2 and compositions of $En_{89-98}Fs_{1-7}Wo_{0-4}$. We measured 0.17–2.13 and 0.30–1.07 wt% Al_2O_3 and Cr_2O_3, respectively.

The center part of the type I PO chondrule C30 is mostly composed of olivine either present as large phenocrysts (up to ~300 µm in size) or euhedral grains (<120 µm), with minor interstitial high-Ca pyroxene grains (~<10 µm) (Fig. 1b). A ~50 µm-thick rim of similar composition (olivine + high-Ca pyroxene) surrounds the central part of the chondrule C30. Grains in this rim are generally <5 µm in size, only a few olivine grains having sizes of around 50 µm. Olivine is chemically homogeneous and displays similar compositions in the central part and the rim. The average Mg# is 98.8±0.3 (total range of 98.4–98.9) and we measured 0.27±0.07 wt% CaO, 0.49±0.17 wt% Cr_2O_3, and up to 0.19 wt% MnO.

The type I POP chondrule C7 displays a core composed of rounded olivine grains (from ~10 to ~60 µm) embedded in a mixture of high- and low-Ca pyroxene (corresponding to the alteration product of the former mesostasis) (Fig. 2a). The external parts of the chondrule are mostly composed of large euhedral grains of low-Ca pyroxene (up to ~150 µm) in which olivine grains (<40 µm) are enclosed. The average Mg# of olivine in the core and external part are identical, 98.8±0.2 and 98.9±0.3, respectively. We measured 0.19 wt% CaO, 0.61 wt% Cr_2O_3, and 0.19 wt% MnO in olivine in the core, and 0.21 wt% CaO, 0.47 wt% Cr_2O_3, and 0.13 wt% MnO in olivine from the external part of the chondrule C7. The average Mg# calculated for low-Ca pyroxene grains is 99.1±0.1, with an average composition of $En_{98.2\pm0.2}Fs_{0.9\pm0.1}Wo_{0.9\pm0.1}$. Low-Ca pyroxene also contain significant amount of TiO_2 (0.25–0.31 wt%), Cr_2O_3 (0.36–0.53 wt%), and Al_2O_3 (1.01–1.13 wt%).

The type I PP chondrule C25 is mostly composed of low-Ca pyroxene phenocrysts (up to ~150 μm), located at the borders of the chondrule (Fig. 2d). A few grains of olivine (~<15 μm) are enclosed within these phenocrysts. With the exception of one nodule composed of magnetite armoring a core of Fe-rich sulfide (~150 μm in diameter), the interior part of the chondrule C25 is composed of a mixture of diopside and Mg,Fe pyroxene. We also observed in the interior part of the chondrule C25 a few grains of high-Ca pyroxene with size up to ~40 μm, most of them being in contact with low-Ca pyroxene grains. The Mg#'s of olivine and low-Ca pyroxene are 99.1±0.1 and 98.8±0.2, respectively. The Mg# calculated from one measurement of high-Ca pyroxene is 98.0. We measured in olivine 0.19±0.05 wt% CaO, 0.45±0.12 wt% Cr_2O_3, and up to 0.17 wt% MnO. Low-Ca pyroxene has an average composition of $En_{98}Fs_1Wo_1$ and contains significant amount of Al_2O_3 (0.55±0.05 wt%), Cr_2O_3 (0.51±0.16 wt%), but low in MnO (0.08±0.03 wt). In comparison, the grain of high-Ca pyroxene ($En_{63}Fs_1Wo_{36}$) analyzed shows 1.88 wt% Al_2O_3, 0.67 wt% Cr_2O_3, 0.26 wt% MnO, and 0.60 wt% TiO_2.

The biggest chondrule analyzed is the type I PP compound chondrule C29 (~ 2 mm in diameter; EA2). This chondrule has a rounded core, ~200 μm in diameter composed of olivine. This core is enclosed in a low-Ca pyroxene-bearing area of around 1 mm in diameter that contains a few olivine grains and large metal blebs (~100 μm). This low-Ca pyroxene-bearing area is surrounded by a mantle composed primarily of low-Ca pyroxene and numerous metal grains with sizes <25 μm. We interpret this mantle as an aggregation of numerous former silicate droplets from ~100 μm to 350 μm in diameter, analogous to those reported for chondrules in the Renazzo CR2 chondrite (Zanda et al., 2002). The Mg#'s of olivine and low-Ca pyroxene are 99.2±0.2 and 98.4±2.1 (98.1–99.1), respectively. Excluding one grain of low-Ca pyroxene (Mg# = 96.4) found in an aggregated chondrule from the mantle, the average Mg# and composition of low-Ca pyroxene is 98.8±0.9 and $En_{97.7\pm0.6}Fs_{1.3\pm0.8}Wo_{1.1\pm0.2}$, respectively. Grains of low-Ca pyroxene and olivine display homogeneous minor elements contents across the entire range of Mg#. Olivine contains 0.20±0.04 wt% CaO, 0.52±0.03 wt% Cr_2O_3, and 0.17±0.07 wt% MnO. In low-Ca pyroxene, we measured 0.67±0.13 wt% Cr_2O_3, 0.19±0.08 wt% MnO, and 0.53±0.23 wt% Al_2O_3.

<u>Type I porphyritic chondrules with BO cores</u>

The cores of chondrules C5 (Fig. 2b) and C14 (Fig. 3) are composed of a BO fragment ~200 μm and ~600 μm in size, respectively. The BO core of the chondrule C5 contains both phenocrysts of low-Ca pyroxene (up to 70 μm length) and high-Ca pyroxene grains (<40 μm length) (Fig. 2b). This core is armored by large Fe-Ni metal grains (up to ~200 μm long) and surrounded by a porphyritic rim mostly composed of low-Ca pyroxene with minor olivine and blebs of Fe-Ni metal. Olivine from the BO core and low-Ca pyroxene from the porphyritic rim display indistinguishable Mg#'s, 98.7±0.1 and 98.5±0.3, respectively. Olivine contains 0.13–0.44 wt% Al_2O_3, 0.22–0.41 wt% CaO, and 0.57±0.13 wt% Cr_2O_3. Low-Ca pyroxene has an average composition of $En_{97.4\pm0.5}Fs_{1.5\pm0.3}Wo_{1.1\pm0.8}$ and contains 1.00–1.20 wt% Al_2O_3, 0.50–0.94 wt% CaO, 0.18–0.08 wt% TiO_2, and 0.58±0.21 wt% Cr_2O_3. The BO core of the chondrule C14 also contains highly fractured grains of high-Ca pyroxene between the olivine bars, as well as minor low-Ca pyroxene (Fig. 3). This BO core is rimmed by Fe-Ni metal that also surrounds a porphyritic olivine area with minor low-Ca pyroxene. The outermost part of the chondrule C14 is primarily composed of low-Ca pyroxene phenocrysts with minor olivine and Fe-Ni metal. The largest low-Ca pyroxene phenocrysts (up to ~250 μm length) have euhedral shapes. Olivine and low-Ca pyroxene in both core and outermost part have indistinguishable Mg#'s, 99.1±0.3 and 98.9±0.2, respectively. Minor element compositions of olivine are also similar, within analytical uncertainties, between the core and the outermost part. Olivine contains significant amounts of CaO (0.20±0.02 wt%), Cr_2O_3 (0.49±0.09 wt%), and MnO (0.14±0.08 wt%). One analysis of low-Ca pyroxene in the core ($En_{94.6}Fs_{1.0}Wo_{4.3}$) displays higher contents of Al_2O_3 (3.35 wt%), TiO_2 (0.44 wt%), Cr_2O_3 (0.82 wt%), and MnO (0.25 wt%), in comparison with the measurements of low-Ca pyroxene grains in the external part of the chondrule C14 that contain 0.98±0.26 wt% Al_2O_3, 0.22±0.09 wt% TiO_2, 0.54±0.17 wt% Cr_2O_3, and 0.08±0.06 wt% MnO with an average composition of $En_{98.0\pm0.4}Fs_{1.1\pm0.2}Wo_{0.9\pm0.2}$.

Type I BO chondrules and BO chondrule fragment

The type I BO chondrule C13 is composed of irregular forsteritic bars with lobed protrusions or spiky sidearms. Between olivine bars, we observed porous grains of nearly pure enstatite, high-Ca pyroxene (diopsidic), and iron oxide (possibly magnetite). Olivine in chondrule C13 has an average Mg# of 99.1±0.3 and contains significant amount of CaO (0.13–0.23 wt%), Cr_2O_3 (0.28–0.40 wt%), and MnO (0.10–0.18 wt%).

We also analyzed a fragment of a type I BO chondrule (C16) (Fig. 2c). Between the barred olivine crystals, we observed Mg,Fe pyroxene in association with tabular grains of nearly pure diopside (~5 μm width and up to ~20 μm length). The Mg# of olivine in the chondrule C16 is 99.4±0.3 and we measured 0.11–0.56 wt% CaO, 0.06–0.23 wt% Cr_2O_3, and up to 0.13 wt% MnO.

Type I granular chondrules

We recognized two type I granular chondrules (C1, GOP; C9, GO) that are composed of evenly sized grains. Approximately 90% of the olivine grains in the chondrule C9 display linear trails of micron-sized inclusions of metal (Fig. 2e). In all around the olivine grains armoring the center part of the chondrule, these trails are globally parallel to each other. The center part contains small grains of sulfides and diopsidic pyroxene (<10 μm). The Mg#'s of olivine and low-Ca pyroxene in the two granular type I chondrules range from 98.7 to 99.5 and from 98.3 to 99.3, respectively. We measured 0.22±0.5 wt% CaO, 0.15–0.47 Cr_2O_3 wt%, and up to 0.15 wt% MnO. Low-Ca pyroxene displays compositions ranging from $En_{92.5}Fs_{1.1}Wo_{6.4}$ to $En_{96.2}Fs_{0.7}Wo_{3.1}$. We measured significant amounts of Al_2O_3 (1.24–3.63 wt%), TiO_2 (0.31–0.50 wt%), as well as 0.25–0.78 wt% Cr_2O_3 and 0.04–0.25 wt% MnO.

Type II PO chondrules

The three type II chondrules analyzed display a porphyritic texture and are mainly composed of olivine phenocrysts. Most of the olivine grains in chondrule C15 have euhedral shapes. The chondrules C15 (Fig. 4a) and C17 also contain olivine grains with forsteritic cores (~20–80 μm, $Fo_{99\text{-}91}$). The ranges of olivine Mg#'s excluding forsteritic core in chondrule C15 and C17 are 58.9–77.3 and 69.9–79.7, respectively. In chondrule C22, olivine displays Mg#'s ranging from 60.3–79.0. Olivine grains in these three type II chondrules contain 0.20–0.60 wt% Cr_2O_3 and 0.02–0.40 wt% MnO.

Isolated FeO-rich olivine grains

The isolated grain of FeO-rich olivine G32 has an euhedral shape (Fig. 4b). The borders of the grain are more FeO-rich than the core, with an average Mg# of 72.2±7.6 (66.5–74.5). This olivine grain throughout contains 0.41±0.03 wt% Cr_2O_3, 0.29±0.09 wt% MnO, and 0.20±0.06 wt% CaO. The isolated grain of FeO-rich olivine G33 displays an irregular shape with a rim more FeO-rich than the core (Fig. 4c). The Mg# varies from 29.6 to 48.7 and Cr_2O_3, MnO, and CaO contents are 0.37±0.11, 0.55±0.06, and 0.15±0.08 wt%, respectively.

Isolated Fe-poor olivine grain

We analyzed one FeO-poor olivine-bearing object (G24) isolated within the matrix (Fig. 4d). The interior of the object G24 is composed of olivine that contains numerous parallel or sub parallel linear trails of Fe-metal inclusions, similar to dusty olivine containing µm-sized Fe-rich metal that formed by reduction of FeO in olivine (Nagahara, 1981; Rambaldi, 1981). These inclusions are homogeneous in size within each trail (~2 µm), while a few larger inclusions (up to ~10 µm) of Fe-rich sulfides are also present in the center of this object. The interior part of G24 is rimmed by relatively coarse grains of olivine that contain no inclusions. Olivine is chemically homogeneous (Mg# ~99.4±0.1). We measured significant amount of Al_2O_3 (0.14±0.09 wt%), CaO (0.40±0.11 wt%), and Cr_2O_3 (up to 0.33 wt%), while MnO (<0.08 wt%) and TiO_2 (<0.08 wt%) contents are low.