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1                   **Deciphering recycling processes during solar system evolution**  
2                   **from Mg-rich relict olivine grains in type II chondrules**

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16  
17                  **Abstract**

18                  Ferromagnesian chondrules present a remarkable dichotomy between reduced (type I)  
19                  and oxidized (type II) varieties. How these formed, and how they may be related remains  
20                  contentious. Many type II chondrules, especially in carbonaceous chondrites, contain  
21                  forsteritic grains in disequilibrium with FeO-rich host olivine grains, which must be relicts of  
22                  precursor material. In this study, we analyzed the oxygen isotopic composition of magnesian  
23                  relict and host olivine grains in type II chondrules in CO and CR chondrites. The analyzed  
24                  relicts are generally more <sup>16</sup>O-rich than host grains and plot in the range (isotopic and mineral  
25                  chemical) of type I chondrules in carbonaceous chondrites. Remarkably, they tend to cluster  
26                  around the dominant  $\Delta^{17}\text{O}$  peaks of the type I chondrules in their host chondrites, viz.  $-6\text{‰}$   
27                  and  $-2\text{‰}$  for CO and CR, respectively. With the occurrence of relatively intact type I  
28                  chondrules within some type II chondrules, this corroborates that local type I chondrules were  
29                  among the precursors of type II chondrules, and that chondrule formation occurred within the  
30                  accretion reservoir of the eventual chondrites. This supports the nebular brand of chondrule-  
31

32 forming scenarios. Since not all previous generations of chondrules (or other precursor  
33 objects) have been recycled, chondrule formation events must also have been extremely  
34 localized.

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37 **Keywords**

38 Carbonaceous chondrites, chondrules, oxygen isotopes, recycling processes, protoplanetary  
39 disk

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## 1- Introduction

74         The evolution of the circumsolar disk led to the formation of solids through a wide  
75 range of processes such as evaporation/condensation (Ebel et al., 2018; Marrocchi et al.,  
76 2019a), fusion/crystallization (Connolly & Jones, 2016) and thermal annealing (Han &  
77 Brearley, 2015). The resulting dust provided the various building blocks of asteroids and  
78 planets, either in the form of refractory inclusions (i.e., CAIs = Calcium Aluminum-rich  
79 Inclusions and AOA = Amoeboid Olivine Aggregates), chondrules and fine-grained matrix.  
80 The mineralogical, petrographic, and isotopic features of these early solids thus represent a  
81 powerful proxy for deciphering the conditions that prevailed in the circumsolar disk and how  
82 they evolved with time.

83         The mm-sized igneous spheroids called chondrules are the most abundant high-  
84 temperature components of both non-carbonaceous (NC) and carbonaceous (C) chondrites,  
85 which most likely represent material from the inner and outer solar system, respectively  
86 (Kruijer et al., 2017; Schneider et al., 2020). This suggests that the whole circumsolar disk  
87 was affected by chondrule production and/or redistribution. The most abundant chondrules  
88 are ferromagnesian porphyritic chondrules that can be classified to first order into type I and  
89 type II chondrules, depending on their oxidation state (Jones, 2012). Type I chondrules are  
90 more reduced than type II chondrules. This translates into high and low Mg# ( $\equiv 100 \times$  molar  
91 ratio  $\text{Mg}/(\text{Mg}+\text{Fe})$ ) for type I and type II chondrules, respectively. While the limit between  
92 type I and type II is arbitrarily defined as  $\text{Mg}\# = 90$ , there is a hiatus between the two types,  
93 with few chondrules between Mg# of 90 and 97 (e.g., Villeneuve et al., 2015). Type II  
94 chondrules are predominantly observed in ordinary chondrites but are consistently present in  
95 all types of carbonaceous chondrites (Jones, 2012).

95           Type I chondrules are complex objects whose mineralogy, textures, and chemical and  
96 isotopic compositions result from multi-step processes involving precursor recycling, melting  
97 event(s) and complex gas-melt interactions (Ebel et al., 2018; Libourel & Portail, 2018;  
98 Marrocchi et al., 2018, 2019b; Schneider et al., 2020; Tenner et al., 2018; Villeneuve et al.,  
99 2020). The mechanism(s) at their origin remain(s) however controversial: they may  
100 correspond to melted aggregates of nebular dust (Hewins et al., 2005; Piralla et al., 2021), e.g.  
101 because of bow shocks induced by eccentric planetary embryos (Morris et al., 2012), or by-  
102 products of planetary collisions (Johnson et al., 2015; Libourel et al., 2022; Libourel & Krot,  
103 2007). In addition, type I chondrule formation took place over a long period of time (i.e., 3–4  
104 Ma; (Bollard et al., 2017; Piralla et al., 2023) and could have been repeated, as supported by  
105 evidence for distinct generations of chondrules in CR chondrites (Marrocchi et al., 2022).  
106 Compared to reduced and volatile-depleted type I chondrules, type II chondrules are  
107 characterized by FeO-rich silicates and more chondritic abundances of moderately volatile  
108 elements (e.g., Jacquet et al., 2015). The more oxidized conditions of type II chondrule  
109 formation could result from either formation in regions with higher dust to gas ratios  
110 (Schrader et al., 2013) or lower carbon content in the precursors (Connolly et al., 1994). It has  
111 been also proposed that type II chondrules derived from their type I counterparts through  
112 nebular oxidation shocks (Villeneuve et al., 2020) or within impact-generated vapor plumes  
113 (Libourel et al., 2023).

114           Oxygen isotopes may provide more constraints into the formation conditions of both  
115 type I and type II chondrules and their potential relationship. First, chondrule isotopic  
116 compositions are widely separated from those of AOAs and CAIs (very  $^{16}\text{O}$ -rich, with  $\Delta^{17}\text{O} =$   
117  $\delta^{17}\text{O} - 0.52 \times \delta^{18}\text{O}$  around -25 ‰; e.g., (Krot et al., 2004). There is also a systematic  
118 difference between type I and type II chondrules, especially in carbonaceous chondrites,  
119 where the former are  $^{16}\text{O}$ -richer than the latter (Libourel et al., 2023; Schrader et al., 2013;

120 Tenner et al., 2018; Ushikubo & Kimura, 2020). Likewise, there are some differences  
121 depending on the reservoir of origin with type I chondrules in (i) CO–CM–CV chondrites  
122 having  $\Delta^{17}\text{O}$  ranging from  $-7$  to  $-4$  ‰ with a maximum observed near  $-6$  ‰ (Tenner et al.,  
123 2018; Ushikubo and Kimura, 2020) and (ii) CR chondrules that are characterized by  $\Delta^{17}\text{O}$   
124 varying from  $-6$  to  $-1$  ‰ and peaking circa  $-2$  ‰ (Marrocchi et al., 2022; Schrader et al.,  
125 2014; Tenner et al., 2015). The recent characterization of the chemical and isotopic  
126 compositions of relict olivine grains in different carbonaceous chondrites suggest that type I  
127 chondrules derived (in part) from AOA-like precursors (Marrocchi et al., 2018, 2019b), in  
128 agreement with (i) trace element signatures ((Jacquet, 2021; Jacquet & Marrocchi, 2017;  
129 Ruzicka et al., 2007) and (ii)  $^{50}\text{Ti}$  and  $^{54}\text{Cr}$  excesses (Schneider et al., 2020).

130  $^{16}\text{O}$ -rich forsteritic olivine grains have been occasionally reported in type II chondrules  
131 ((Jones, 1996, 2012; Kunihiro et al., 2004, 2005; Libourel et al., 2023; Schrader et al., 2015,  
132 2018; Wasson & Rubin, 2003; Yurimoto & Wasson, 2002). The similitude of such grains  
133 with type I chondrules in the same chondrites have long suggested that these were relicts of  
134 type I chondrules, hence highlighting a potential link between type I and type II chondrules.  
135 This was also proposed based on the similar large silicon isotopic variations observed within  
136 type I chondrules and in Mg-rich olivine relict grains in type II chondrules (Villeneuve et al.,  
137 2020). However, no systematic chemical and oxygen isotopic characterization of Mg-rich  
138 relict olivine grains in type II chondrules has been performed. In this study, we report a  
139 comprehensive survey of the oxygen isotopic compositions of relict-bearing type II  
140 chondrules in carbonaceous chondrites, where they are proportionally most abundant,  
141 specifically in CO and CR chondrites. We use our data to quantify the conditions of formation  
142 of type II chondrules and discuss the implications for the reprocessing of primordial dust in  
143 the outer circumsolar disk.

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## 147 **2- Material and Methods**

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149 We surveyed all chondrules within (i) four home-made thick sections of CO3  
150 carbonaceous chondrites (Los Vientos 123 [CO3.05], Catalina 008 [CO3.1], El Medano 463  
151 and 465 [CO3.2]) and (ii) two thick sections of CR2 carbonaceous chondrites (Renazzo and  
152 Dar al Gani 574, sections no. 719sp3 and 3681sp2, respectively; from the Muséum national  
153 d'Histoire naturelle, Paris, France). The petrography and mineralogy of type II chondrules  
154 were determined by optical microscopy, backscattered electron (BSE) imaging, and X-ray  
155 compositional mapping. For the latter two, we used (i) a Zeiss Evo MA10 equipped with an  
156 Oxford X-MAX N 20 SDD energy dispersive spectrometer and operating with a 3 nA  
157 electron beam accelerated at 15 kV (Universidad de Atacama, Copiapó, Chile) and (ii) a  
158 JEOL JSM-6510 scanning electron microscope equipped with a Genesis EDX detector using  
159 a 3 nA electron beam accelerated at 15 kV (CRPG-CNRS, Nancy, France).

160 Thirteen type II chondrules with and without apparent Mg-rich relicts were selected: 8  
161 in COs and 5 in CRs chondrites. Quantitative analyses of Al, Ti, Ca, Cr, Mn, Ni, Mg, Fe, and  
162 Si in all olivine grains large enough to be isotopically characterized by SIMS were performed  
163 using a CAMECA SX-Five electron microprobe at the CAMPARIS service (Sorbonne  
164 University, Paris, France). The microprobe was calibrated using the following natural and  
165 synthetic standards for silicate analyses: diopside (Si, Ca, Mg), orthoclase (Al), MnTiO<sub>3</sub> (Mn,  
166 Ti), Cr<sub>2</sub>O<sub>3</sub> (Cr), and Fe<sub>2</sub>O<sub>3</sub> (Fe). A 20 nA focused beam, accelerated to 15 kV potential  
167 difference, was used for spot analyses of olivine with 20 s analysis times. Detection limits in  
168 silicates were 0.03 wt% for SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, CaO and MgO; 0.04 wt% for MnO and TiO<sub>2</sub>, and

169 0.07 wt% for NiO, Cr<sub>2</sub>O<sub>3</sub> and FeO. The PAP software was used for matrix corrections  
170 (Pouchou and Pichoir, 1984).

171 We measured the oxygen isotopic compositions of olivine grains with varied iron  
172 contents in type II chondrules using Secondary Ion Mass Spectrometry (SIMS). We used the  
173 CAMECA IMS 1270 E7 at the Centre de Recherches Pétrographiques et Géo-chimiques  
174 (CRPG-CNRS, Nancy, France). <sup>16</sup>O<sup>-</sup>, <sup>17</sup>O<sup>-</sup>, and <sup>18</sup>O<sup>-</sup> ions produced by a Cs<sup>+</sup> primary ion  
175 beam (~10 μm, ~2–2.5 nA, rastered over 5 × 5 μm<sup>2</sup>) were measured in multi-collection mode  
176 using three Faraday cups (FCs). To remove the interference of <sup>16</sup>OH<sup>-</sup> on the <sup>17</sup>O<sup>-</sup> peak and to  
177 maximize the flatness atop the <sup>16</sup>O<sup>-</sup> and <sup>18</sup>O<sup>-</sup> peaks, the entrance and exit slits of the central  
178 FC were adjusted to obtain mass resolution power (MRP =  $M/\Delta M$ ) of ~7,000 for <sup>17</sup>O<sup>-</sup>. As an  
179 additional safeguard against <sup>16</sup>OH<sup>-</sup> interference, a liquid N<sub>2</sub> trap was used to reduce the  
180 pressure in the analysis chamber to <1 × 10<sup>-8</sup> mbar. The two off-axis multicollection FCs, L'2  
181 and H1, were respectively used to measure <sup>16</sup>O<sup>-</sup> and <sup>18</sup>O<sup>-</sup> and were set on exit slit 1 (MRP =  
182 2,500). We used 10<sup>10</sup> Ω, 10<sup>12</sup> Ω, and 10<sup>11</sup> Ω resistors for the L'2 (<sup>16</sup>O), central (<sup>17</sup>O), and H1  
183 (<sup>18</sup>O) FCs, respectively (see Bouden et al. 2021 for further details). A normal-incidence  
184 electron gun was used for charge compensation. Total measurement times were 300 s,  
185 comprising 120 s of pre-sputtering and 180 s of analysis. Two terrestrial standards, San Carlos  
186 olivine and JV1 diopside, were used to define the mass-dependent fractionation line. The  
187 instrumental mass fractionation (IMF) and matrix effect of chondrule olivine grains was  
188 corrected using San Carlos olivine and a set of synthetic standard olivines with Mg# ranging  
189 from 36 to 100 (Villeneuve et al., 2019, 2020). To monitor any instrumental drift and to  
190 achieve good precision, the San Carlos olivine was analyzed after every 10–15 sample  
191 analyses. Typical count rates obtained on San Carlos olivine were 1.0 × 10<sup>9</sup> cps, 4.0 × 10<sup>5</sup> cps,  
192 and 2.1 × 10<sup>6</sup> cps for <sup>16</sup>O, <sup>17</sup>O, and <sup>18</sup>O, respectively. All SIMS analytical spots were checked  
193 thoroughly by scanning electron microscopy, and any spot near fractures, in the mesostasis, or



194 not completely within olivine grains was excluded from the dataset. Oxygen isotopic  
195 compositions are expressed in  $\delta$  units as  $\delta^{17,18}\text{O} = [({}^{17,18}\text{O}/{}^{16}\text{O})_{\text{sample}}/({}^{17,18}\text{O}/{}^{16}\text{O})_{\text{V-SMOW}} - 1] \times$   
196 1000 ‰ where V-SMOW refers to the Vienna Standard Mean Ocean Water value. Samples  
197 related by mass-dependent fractionation to the composition of V-SMOW fall on a line with a  
198 slope of 0.52 (defining as the Terrestrial Fractionation Line, TFL; Clayton et al., 1991)  
199 whereas mass-independent variations are described by  $\Delta^{17}\text{O} = \delta^{17}\text{O} - 0.52 \times \delta^{18}\text{O}$   
200 (representing vertical deviations from the TFL in a triple oxygen isotope diagram). Typical  $2\sigma$   
201 measurement errors, accounting for internal errors on each measurement and the external  
202 reproducibility of the standards, were estimated to be  $\sim 0.4$  ‰ for  $\delta^{18}\text{O}$ ,  $\sim 0.7$  ‰ for  $\delta^{17}\text{O}$ , and  
203  $\sim 0.7$  ‰ for  $\Delta^{17}\text{O}$ .

204

### 205 **3- Results**

206

#### 207 **3.1- Petrography and chemistry**

208

209 We examined all type II chondrules in the five thick sections and selected 13  
210 chondrules with minimum evidence of secondary alteration and olivine grains large enough to  
211 perform detailed chemical profiles and isotopic analysis (**Figs. 1–2**). The chondrules are fairly  
212 rounded but not, in general, perfectly circular in cross-section, and some may be actually  
213 compound (e.g., **Fig. 1c,f** & **Fig. 2c,e**; see also Jacquet 2021). They all display porphyritic  
214 texture (except EM463\_Ch05, **Fig. 2f**), with several subhedral to euhedral Fe-rich olivine  
215 grains immersed in well-preserved glassy mesostases (**Figs. 1–2**). The maximum apparent  
216 diameter of chondrules ranges from 250 to 740  $\mu\text{m}$  and 400 to 750  $\mu\text{m}$  in CO and CR  
217 chondrites, respectively. Among the 13 type II chondrules, 11 exhibit Mg-Fe zoning with  
218 sharply defined Mg-rich cores and abrupt FeO and/or CaO variation in the chemical profiles

219 (Figs. 1–2), similar to the relict-bearing chondrules described by Jones et al., (2018). Some  
220 relict-bearing chondrules (e.g., LoV123\_Ch02, Fig. 1a) display several forsteritic grains  
221 showing Mg diffusion and sharper border inside either larger or smaller Fe-rich olivine grains.  
222 The position of relict grains is random, and most of them were found as (i) isolated  
223 phenocrysts with Fe-rich rims or (ii) clusters of 3 or (sometimes much) more phenocrysts,  
224 where each grain is surrounded by a Fe-rich mantle (Figs. 1–2). Sometimes, the Mg-rich  
225 olivine is even part of a more or less intact type I chondrule-like object, with enstatite (stricto  
226 sensu, i.e., Fs < 10 mol%), mesostasis and/or metal grains (Fig. 1d & Fig. 2a,b,c), at variance  
227 with the contention of Libourel et al. (2023) that enstatite virtually never occurs in type II  
228 chondrules. Troilite and chromite are the main opaque and accessory phases in all described  
229 FeO-rich chondrules. They are contained in the mesostasis and display sizes up to 90  $\mu\text{m}$ ,  
230 except for CR, where troilite reaches up to 200  $\mu\text{m}$ .

231 The mean chemical composition of relict and host olivine grains among the 13  
232 chondrules is shown in Table 1. The Mg# of olivine grains varies widely in the selected  
233 chondrules, from 24.6 to 98.3 (Table S1), depending on whether the olivine is a host or relict  
234 grain. Host olivine grains in CO and CR chondrites display mean Mg# ( $\pm$  standard deviation)  
235 of  $48.9 \pm 11.8$  (N= 447) and  $51.8 \pm 6.1$  (N= 22), respectively. Previous values estimated in  
236 host olivine show somewhat higher Mg# for CO and CR chondrites (~66 and 71, respectively;  
237 Berlin et al., 2011), but this may hinge on our relict-centered chondrule selection, biasing  
238 against large uniformly host (i.e., relict-free) phenocrysts (with less ferroan cores), thus  
239 confining host analyses to (more ferroan) overgrowths of large grains or small phenocrysts.  
240 As expected, while showing a large range of Fa values (1.8 to 41.8 mol% in CO), relict  
241 olivine grains tend to be more forsteritic, with mean Mg# of  $85.0 \pm 10.6$  (N= 189) and  $84.3 \pm$   
242  $12.9$  (N= 15) for CO and CR chondrites. 70 % of relicts in CR chondrules and 38 % of relicts  
243 in CO chondrules (Table S2) display Fa values < 10 mol%, that is, in type I compositional

244 territory (**Fig. 2**), but the other obviously exited it only because of diffusion of Fe from the  
245 host chondrule.

246 Commonly, Mg-rich relicts in type II chondrules are MnO-poor, and slightly CaO-rich  
247 compared to their host olivine grains (**Table 1**). Host olivines display higher mean MnO (0.35  
248 and 0.27 wt%, respectively) and Cr<sub>2</sub>O<sub>3</sub> (0.42 vs. 0.25 wt%) in CR than CO chondrites,  
249 consistent with earlier data (e.g., Berlin et al., 2011; Schrader et al., 2015).

250

### 251 **3.2- Oxygen Isotopes**

252

253 We performed a total of 88 O-isotopic measurements of relicts and host grains (**Table**  
254 **2**); 26 and 62 spots were made in CR and CO chondrites, respectively. The olivine O-isotopic  
255 composition in CO and CR chondrites ranges respectively from -13.1 to +15.2 ‰ and -11.3  
256 to 8.1 ‰ for  $\delta^{18}\text{O}$ ; and from -14.2 to 5.8 ‰ and -13.1 to 4.4 ‰, in the case of  $\delta^{17}\text{O}$ .  $\Delta^{17}\text{O}$   
257 ranges from -7.7 to +0.7 ‰. In the three-oxygen diagram (**Fig. 3a**), our data plot along the  
258 PCM line proposed by Ushikubo et al. (2012).

259 Most relict olivine grains are <sup>16</sup>O-rich compared to those in their Fe-rich host  
260 phenocrysts (**Figs. 3–4**). However, 36 % (4 over 11) of relict-bearing chondrules show an  
261 overlap or similar O-isotopes signature. Only one relict grain in the biggest phenocryst of  
262 LoV123\_Ch02 (**Fig. 4a**) shows the opposite relation to its host. The mean  $\Delta^{17}\text{O}$  values of  
263 relict grains in CO and CR chondrites are -4.7 and -2.8 ‰, lower than the mean  $\Delta^{17}\text{O}$  values  
264 in type II olivine hosts: -2.6 and -0.5 ‰ for CO and CR chondrites, respectively (**Fig. 5**).  
265 Analogous difference of the mean  $\Delta^{17}\text{O}$  values have been reported between relict and host  
266 grains in type I chondrules for CR (-5.2 and -3.4 ‰; Marrocchi et al., 2022). The latest  
267 indicate a larger  $\Delta^{17}\text{O}$  difference between relict and host grains from type II chondrules (**Figs.**  
268 **6–8**). Same was observed by Tenner et al. (2013) for type II chondrules in CO3.0 chondrite

269 Yamato 81020. In our data set, the isotopic compositions do not show any correlation with  
270 size or location within chondrules.

271 Host grains tend to be isotopically uniform within each chondrule, but there are three  
272 apparent exceptions, LoV098-Ch02p, Ren\_Ch01 and DaG574\_Ch01 (**Fig. 4**). In the former  
273 two, the exception is restricted to one outlying  $^{16}\text{O}$ -rich grain ( $\Delta^{17}\text{O} = -1.3$  and  $-3.0$  ‰,  
274 respectively). In the latter, three Fe-rich “host” grains show three distinct  $\Delta^{17}\text{O}$  values ( $-4.7$ ,  $-$   
275  $3.0$  and  $0.5$  ‰; **Table S2**). Two of them in the latter, and the former two may be isotopic  
276 relicts in the sense of Ushikubo et al. (2012) but no longer recognizable in Mg# because of Fe  
277 diffusion.

278 Generally, Mg-rich relicts among CO and CR chondrites overlap the oxygen isotopic  
279 composition of relict and host olivine grains in type I chondrules (**Figs 3–4**). In particular, all  
280 relicts in CR chondrites plot around  $-6$  ‰ or  $-2$  ‰, i.e. the  $\Delta^{17}\text{O}$  values characteristic of the  
281 two generations of type I CR chondrules (“type I-CO” and “type I-CR”) described by  
282 Marrocchi et al. (2022). The most  $^{16}\text{O}$ -rich grain found (in chondrule Ren\_Ch03) has a mean  
283  $\Delta^{17}\text{O}$  value of  $-7.5 \pm 0.4$  ‰. Yet most relicts (8/10 = 80 %) are in type I-CR territory (i.e.,  
284  $\Delta^{17}\text{O} > -4$  ‰; Marrocchi et al., 2022), as are most type I chondrules in CR. In contrast, type II  
285 chondrule forsteritic relicts in CO chondrites are mostly in type I-CO territory (i.e.,  $\Delta^{17}\text{O} < -4$   
286 ‰), as are most type I chondrules there (e.g., Tenner et al., 2013; Libourel et al., 2023).

287

## 288 **4- Discussion**

289

### 290 **4.1- The source of Mg-rich relict grains in type II chondrules**

291

292 Although type II chondrules have been less studied than their type I counterparts, their  
293 formation conditions are no less controversial. They have been historically interpreted as

294 resulting from closed-system, fractionally crystallized droplets heated at near-liquidus  
295 temperature and cooled at  $\sim 1\text{--}500$  K/h (see Jones et al., 2018 for a review). The larger size of  
296 type II chondrules and their higher concentrations of volatile and moderately volatile elements  
297 (i.e., Na, K, Mn, Cr, S, and Fe) compared to type I chondrule were used as arguments for  
298 suggesting formation in different nebular (sub)-reservoir than type I chondrules (Hewins &  
299 Zanda, 2012; Jacquet et al., 2015). Comprehensive oxygen isotopic observations also suggest  
300 the formation of type I and type II chondrules in environments characterized by distinct  
301 dust/gas ratios and water ice enhancement, type II being formed in location with dust-  
302 enrichment factors up to  $\sim 4000$  above solar (Chaumard et al., 2018, 2021; Hertwig et al.,  
303 2018; Tenner et al., 2015). This suggested that type I and type II chondrules formed in two  
304 different astrophysical settings, possibly on different sides of the snowline (Tenner et al.,  
305 2018). However, the common presence of Mg-rich relict olivine grains within type II  
306 chondrules (**Figs. 1–2**) as well as their chemical and isotopic features (**Figs. 3–8**) suggest that  
307 type II chondrules derive from type I chondrules through oxidation shocks<sup>1</sup> and protracted  
308 gas-melt interactions (Ruzicka et al., 2008, Schrader et al., 2015, 2018; Ebel et al., 2018;  
309 Villeneuve et al., 2020). A comprehensive experimental approach also showed that these  
310 processes can account for several prominent features of type II chondrules, such as chemical  
311 zoning in olivine grains and the preservation of Mg-rich olivine relict grains (Villeneuve et  
312 al., 2015).

313 Most of our Mg-rich relict olivine grains in type II chondrules are  $^{16}\text{O}$ -rich compared  
314 to their Fe-rich host phenocrysts (**Figs 3–4**). Mg-rich relict grains with  $\Delta^{17}\text{O}$  values  $< -15$  ‰  
315 were also reported in type II chondrules from CO and CV chondrites (Jones et al., 2002;  
316 Libourel et al., 2023; Yurimoto & Wasson, 2002), thus advising a possible genetic link with  
317 refractory inclusions (Krot, 2019). However, all our relict grains in CO chondrites display

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<sup>1</sup> The expression "oxidation shock" should not be construed to imply a shock wave chondrule-forming scenario.

318  $\Delta^{17}\text{O}$  values ranging from  $-7.7$  to  $-0.1$  ‰ ( $n = 8$ ), similar to those reported in the pristine  
319 CO3.05 Yamato 81020 ( $-11.4$  ‰  $< \Delta^{17}\text{O} < 0.2$  ‰,  $n = 11$ ; Kunihiro et al., 2004; Tenner et al.,  
320 2013). Lumping this with previous literature data, this indicates that only  $\sim 11$  % (3 out of 27)  
321 of relicts sample  $^{16}\text{O}$ -rich dust similar to refractory inclusions (this study; Yurimoto and  
322 Wasson, 2002; Kunihiro et al., 2004; Tenner et al., 2013; Libourel et al., 2023).

323 Mg-rich relicts in type II chondrules always plot in the range of O-isotopic  
324 composition of host olivines in type I chondrules (**Figs. 4–6**), and mostly near the dominant  
325 mode for type I chondrules in the same chondrites (i.e., near  $\Delta^{17}\text{O} = -6$  ‰ in CO and  $\Delta^{17}\text{O} =$   
326  $-2$  ‰ in CR; **Figs 4–6**). Some outlying Fe-rich “host” grains also do as well (for the CR  
327 chondrules Ren\_Ch01 and DaG574\_Ch01, **Fig. 4i,l**) and may have been of the same nature,  
328 but their Mg# was likely overprinted by Fe diffusion during chondrule melting. The mineral  
329 chemistry of Mg-rich grains in type II chondrules is also similar to type I chondrule olivine,  
330 not only in terms of Fa content, but also in minor element content, e.g. depletion in MnO and  
331 enrichment in CaO (**Figs 5–8**). We also observe varying degrees of assimilation of type I  
332 chondrules in type II hosts, from relicts corresponding to whole type I chondrules to more or  
333 less identifiable forsterite clusters (**Figs 1–2**). This suggests that Mg-relicts in type II  
334 chondrules originate mainly from Mg-rich type I chondrules, pointing toward a genetic link  
335 between both types of chondrules with type II being derived from type I chondrules *via*  
336 oxidation shocks inducing the dissolution of Fe-Ni metal beads and the subsequent  
337 crystallization of FeO-rich olivine overgrowths (Ruzicka et al., 2008; Schrader et al., 2015,  
338 2018; Villeneuve et al., 2015, 2020; Libourel et al., 2023).

339

#### 340 **4.2 Implications for chondrule formation**

341

342 Establishing a genetic relationship between type I and type II chondrules does not in  
343 itself provide any information on their environments of formation, as both nebular and  
344 planetary conditions may be invoked (e.g., Tenner et al., 2015; Libourel et al., 2023). Libourel  
345 et al., (2023) recently proposed that both types of chondrules formed within an isotopically  
346 heterogeneous impact-generated vapor plume with a type I-CO-like core region (i.e.,  $\Delta^{17}\text{O} < -$   
347  $4 \text{ ‰}$ ) gradually mixing with type I-CR surroundings (i.e.,  $\Delta^{17}\text{O} > -4 \text{ ‰}$ ). In such a  
348 framework (the impact splash scenario; e.g., Sanders & Scott, 2012; or the jetting scenario;  
349 Johnson et al. 2015), type II chondrules derive from first-formed type I chondrules following  
350 the drop in the vapor plume temperature (in its outer regions) under unbuffered redox  
351 conditions (Libourel et al., 2023). However, several observations weaken this interpretation  
352 and, in contrast, favor evolving nebular settings and episodic recycling:

353 1– Type I chondrules in carbonaceous chondrites commonly display relict grains with  
354 chemical (Al-Ti-poor) and isotopic ( $\Delta^{17}\text{O} < -15 \text{ ‰}$ ) similar to olivine grains present within  
355 AOAs (**Fig. 9**; Marrocchi et al., 2018, 2019b; Schneider et al., 2020; Jacquet et al., 2021). In  
356 addition, isolated type I chondrules from carbonaceous chondrites show variable  $^{50}\text{Ti}$  and  $^{54}\text{Cr}$   
357 nucleosynthetic anomalies, most of which differing from the host chondrite compositions  
358 (Schneider et al., 2020). These isotopic variations suggest that type I CC chondrules were  
359 partially formed from precursors isotopically similar to  $^{50}\text{Ti}$ - $^{54}\text{Cr}$ -rich CAIs and AOAs  
360 (Gerber et al., 2017; Schneider et al., 2020; Burkhardt et al., 2023). This thus appears difficult  
361 to reconcile with the impact scenario as it would imply that nearly each melt droplet from the  
362 impact plume ingested unmelted and unvaporized refractory inclusions wandering in the  
363 impact vapor plume.

364 2– The correlation between Mg# and  $\Delta^{17}\text{O}$  reported in the literature (e.g., Tenner et  
365 al., 2018 and references therein; Kita et al., 2022) for type I chondrules supports  
366 systematically different oxygen fugacities in the type I-CO and type I-CR isotopic reservoirs

367 (e.g., Schrader et al., 2013; Tenner et al., 2015), or different cooling rates (Jacquet et al.,  
368 2021) and hence their likely spatial separation. This correlation was however recently denied  
369 (Libourel et al., 2022, 2023) based on data from just two chondrules from CO3.05 chondrite  
370 Yamato 81020 (since type I-CR compositions are rare there). In one of them (Ch#35; Libourel  
371 et al., 2023), the type I-CR oxygen isotopic compositions are found in  $\sim\text{Fo}_{99.5}$  olivine cores  
372 with type I-CO overgrowths that we would rather interpret as relicts from a previous  
373 generation of chondrules. They may derive from possibly originally larger grains which  
374 fossilized higher-temperature, more forsteritic compositions at their (surviving) centers, as  
375 observed in isolated olivine grains (Jacquet et al. 2021). Indeed, isolated olivine grains are not  
376 restricted to type I-CO compositions, as those of Libourel et al. (2023) are (although virtually  
377 all isolated *refractory* forsterites are type I-CO; Jacquet et al. 2021). They need not represent  
378 phenocrysts of lost “megachondrules” with which Libourel et al. (2023) populate the  
379 innermost regions of their impact plumes, but plausibly crystals expelled from “normal”  
380 molten chondrules and which have grown on all sides by recondensation (Jacquet et al. 2021).  
381 Libourel et al. (2022, 2023) do not interpret the isotopically distinct olivine cores as relicts,  
382 but rather as the earliest crystallized olivine in the same chondrule-forming event (with  
383 isotopically evolving ambient gas). It becomes then difficult to understand why the minor  
384 element contents (and in particular the *refractory* minor elements), and thence their  
385 cathodoluminescence properties (Libourel and Portail 2018) abruptly change as the isotopic  
386 composition of the gas evolved and the overgrowths crystallized. Libourel et al. (2022, 2023)  
387 also suggested that the literature  $\text{Mg}\#-\Delta^{17}\text{O}$  correlation is an artifact of excluding putative  
388 relicts. However, the said relicts are rare, and mostly  $^{16}\text{O}$ -richer than their host, so including  
389 them should not really destroy (although it does denature) the correlation. This may be  
390 verified in the Marrocchi et al. (2019) compilation (their **Fig. 10** with both relict and host  
391 data), bearing in mind that some Kaba (CV3.1; Bonal et al., 2006) type I olivine FeO



392 concentrations may have been increased by incipient metamorphism. Consequently, chemistry  
393 and isotopic compositions are not decoupled among type I chondrules in carbonaceous  
394 chondrites.

395         3– The Libourel et al. (2023) contention that type I chondrule relicts within type II  
396 chondrules do not contain enstatite is erroneous (see results), so at least some type I  
397 chondrules must have crystallized their whole mineral assemblage before remelting in a type  
398 II chondrule-forming environment. This argues against a monotonous cooling history with  
399 oxygen fugacity increasing from type I to type II territory. It must be allowed that enstatite is  
400 rare in type II chondrules, when compared to forsterite, which likely marks its easier  
401 remelting (because of lower melting temperature).

402         Taken together, this suggests that type I chondrules are likely nebular products formed  
403 through complex processes implying recycling of early condensates, addition of dust and gas-  
404 melt interactions (Schneider et al., 2020; Marrocchi et al. 2022). If correct, and considering  
405 the genetic link between type I and II chondrules, this would also support a nebular origin for  
406 type II chondrules. Since the bulk chemistry of type II chondrules is less devolatilized than  
407 type I chondrules (e.g., Jacquet et al., 2015), the latter cannot be the sole precursors of the  
408 former. We may envision type I chondrules, whole or fragmented mixed with more chondritic  
409 (matrix-like) dust (see **Fig. 10**; not unlike the type I-CO to type I-CR chondrule recycling  
410 scenario of Marrocchi et al., 2022) which would have been too fine-grained to survive as  
411 relicts. The agglomeratic <sup>16</sup>O-rich objects reported in CR chondrites could represent weakly  
412 melted versions thereof (Schrader et al., 2018). The oxygen and silicon isotopic  
413 heterogeneities observed within type II chondrules containing Mg-rich olivine relics also  
414 imply open-system formation with evolving isotopic compositions being controlled by gas-  
415 melt interaction processes, in agreement with their substantially enriched volatile contents  
416 relative to type I chondrules.

417 In terms of astrophysical setting, it appears that the formation of type I chondrules and  
418 their recycling into type II chondrules require repetitive heating mechanisms producing  
419 different oxygen fugacities. Such processes must be extremely localized for producing type II  
420 chondrules without recycling all type I chondrules, implying that chondrites comprise objects  
421 affected by a variable number of melting episodes. These spatially-limited processes are also  
422 illustrated by our data on CR chondrites where two chondrule populations characterized by  
423 different sizes and oxygen isotopic compositions were recently reported (Marrocchi et al.,  
424 2022). The larger,  $^{16}\text{O}$ -poor type I-CR chondrules appear to have formed late out from  
425 smaller,  $^{16}\text{O}$ -rich type I-CO chondrules that initially populated the CR reservoir (Marrocchi et  
426 al., 2022; Tenner et al., 2019). Adequate chondrule-forming scenarios in that respect are those  
427 of the “nebular” brand, e.g., bow shocks induced by eccentric planetary embryos (Morris et  
428 al., 2012), lightning (Johansen & Okuzumi 2017) or the short-circuit instability (McNally et  
429 al. 2013).

430

## 431 **5- Concluding remarks**

432

433 We have determined the oxygen isotope compositions of Mg-rich relict and host  
434 grains in type II chondrules in the carbonaceous chondrites Los Vientos 123 (CO3.05),  
435 Catalina 008 (CO3.1), El Médano 463 and 465 (CO3), Renazzo (CR2.4) and Dar al Gani 574  
436 (CR2). Our main results are:

437 1- Type II chondrules are characterized by large, mass-independent, oxygen isotope  
438 variations with olivine O-isotopic composition in CO and CR chondrites ranges respectively  
439 from  $-13.1$  to  $+15.2$  ‰ and  $-11.3$  to  $8.1$  ‰ for  $\delta^{18}\text{O}$ ; and from  $-14.2$  to  $5.8$  ‰ and  $-13.1$  to  
440  $4.4$  ‰, in the case of  $\delta^{17}\text{O}$ . These ranges are primarily due to Mg-rich relicts generally  $^{16}\text{O}$ -  
441 richer than the hosts.

442           2- The Mg-rich relicts overlap the oxygen isotopic composition of host olivine grains  
443 in type I chondrules, with the same dominant peaks shown by their respective host chondrites.  
444 All analyzed relicts in CR chondrites plot around  $-6\text{‰}$  or  $-2\text{‰}$  for  $\Delta^{17}\text{O}$  values similar to the  
445 two generations of type I CR chondrules previously identified by Marrocchi et al. (2022).

446           From this, we drew the following inferences:

447           1- The oxygen isotopic composition of Mg-relicts in type II chondrules supports an  
448 origin from Mg-rich type I chondrules. This points toward a genetic link between both types  
449 of chondrules with type II being derived from type I chondrules *via* oxidation shocks inducing  
450 the dissolution of Fe-Ni metal beads and the subsequent crystallization of FeO-rich olivine  
451 overgrowths. The oxygen isotopic heterogeneity observed within type II chondrules  
452 containing Mg-rich olivine relict grains also implies a formation of their precursors under  
453 open-system conditions.

454           2- Combined with the presence of AOA-like  $^{16}\text{O}$ -rich relict olivine grains and large  
455 and variable nucleosynthetic anomalies previously reported in type I chondrules, our data  
456 support a nebular origin of both type I and II chondrules.

457           3- As illustrated by the presence of CR type II chondrules with Mg-rich relict grains  
458 having  $\Delta^{17}\text{O}$  characteristics of the two chondrule generations observed in CR chondrites, our  
459 data imply that the nebular process at the origin of chondrules must be extremely localized for  
460 producing type II chondrules without recycling all type I chondrules.

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CRPG contribution #XXXX.

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502 **Figure caption**

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**Fig 1:** Backscattered electron images of relic-bearing type II chondrules from LoV 123 (CO3.05), Médano 465 (CO3) and (e-f) Renazzo (CR2.4). (a) LoV123\_Ch02 is a relict-bearing chondrule with at least ~12 Mg-rich relict grains of various size sharply delineated from their enclosing Fe-rich olivine grains. (b) LoV123\_Ch10 show abundant metal beads in the mesostasis and inside host as well as relict olivines. The central large Mg-rich relict crystal contains three rounded metal beads. (c) Ren\_Ch02 is a lobate chondrule, presumably compound as suggested by the sulfide delineating the protuberance at bottom. The latter has a cluster of small Mg-rich relicts, but a bigger grain appears on the left side of the whole chondrule (possibly in another adhesion, i.e. another component chondrule; Wasson et al., 1995). (d) LoV123\_Ch07 with a large (~100  $\mu\text{m}$ ) enstatite relict, with some olivine chadacrysts and sparse metal beads and an augitic overgrowth. (e) Ren\_Ch03 is a relatively large porphyritic chondrule with the most  $^{16}\text{O}$ -rich relict grain at  $\Delta^{17}\text{O} = -7.5$  ‰. (f) The lobate chondrule

517 Ren\_Ch02 display a cluster of Mg-rich olivine phenocrysts whereas each one is surrounded  
518 by thin layer of Fe-rich olivine. Tro = Troilite; Kam = Kamacite; Chr = Chromite; Gyp =  
519 gypsum; Fa = Fayalite; Fo = forsterite; Meso = mesostasis.

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521 **Fig. 2:** Backscattered electron images of relic-bearing type II chondrules from LoV 123  
522 (CO3.05), Médano 465 (CO3). (a-b) LoV123\_Ch18 displays several Mg-rich olivine crystals  
523 sparsely distributed over its area and in the center a metal-bearing IBA chondrule relict  
524 intruded by an olivine-microlite rich mesostasis of the host. (c) LoV123\_Ch11 is a large Fe-  
525 rich chondrule (~500  $\mu\text{m}$ ) containing a central region with large (>200  $\mu\text{m}$ ) partly embayed  
526 euhedral olivine phenocrysts, a nonporphyritic right bottom region and two relict-bearing  
527 olivine clusters at the top, one with coarse forsterites (near the middle) and another with a  
528 olivine-chadacryst-bearing enstatite crystal. Possibly the latter was an independent partly  
529 melted droplet which collided with a coarser-grained one. (d) LoV123\_Ch15, fine grained  
530 (“agglomeratic”; e.g. Schrader et al. 2018) type II chondrule with a sulfide-rich outer region  
531 and a large, elongate type IAB porphyritic chondrule-textured relict (~120  $\mu\text{m}$ ), with partly  
532 oxidized metal beads. (e) EM465\_Ch04 display a type I POP-textured relict, with (olivine  
533 chadacryst-laden) enstatite dominating toward its margin (the top protuberance may be an  
534 adhesion merged with the main type I chondrule during its original formation episode) and  
535 olivine grains displaying thin Fe-rich margins. Other magnesian relict grains occur sparsely  
536 throughout the host. Some porosities are filled by (light gray) gypsum. (f) EM465\_Ch05  
537 shows a cluster of Mg-rich relicts on the right, possibly a late adhesion on the main chondrule,  
538 and other sparsely distributed relicts, possibly making a second cluster near the lower left .  
539 The porosity is filled by anhedral massive gypsum. Spot analysis in SIMS is indicated as  
540 orange and blue circles for relict and host olivines. Tro = Troilite; Kam = Kamacite; Chr =  
541 Chromite; Gyp = gypsum; Fa = Fayalite; Fo = forsterite; Meso = mesostasis.

542

543 **Fig 3:** (a) Triple oxygen isotope plot of the olivine crystals in the 13 analyzed Fe-rich  
544 chondrules. Relict grains show mass-independent variations plotting along the Primary  
545 Chondrule Mineral (PCM) line. (b-e)  $\Delta^{17}\text{O}$  values vs. (b)  $\text{Al}_2\text{O}_3$  (c)  $\text{CaO}$ , (d)  $\text{Cr}_2\text{O}_3$ , (e)  $\text{MnO}$   
546 and (f) Olivine Fa content ( $=\text{Fe}/[\text{Mg} + \text{Fe}] \times 100$  mol%) in log scale. The estimated  
547 composition of type I and type II chondrules and the Terrestrial Fractionation line (TFL;  
548 Clayton et al., 1991) are shown for reference.

549

550 **Fig 4:** Oxygen three-isotope diagrams for type II chondrules from (a–h) CO and (i–m) CR  
551 chondrites. Reference lines are Terrestrial Fractionation (TF; Clayton et al., 1991), and the  
552 Primitive Chondrule Minerals (PCM; Ushikubo et al., 2012). The error bars are smaller than  
553 marker size.

554

555 **Fig. 5:** Curves show probability density function of  $\Delta^{17}\text{O}$  of type I host olivines and type II  
556 Mg-relict grains in both CO (a) and CR chondrites (b). Data from this study, Schrader et al.  
557 (2013); Tenner et al. (2013, 2015); Fukuda et al., (2022); Kunihiro et al. (2004) and Libourel  
558 et al. (2022, 2023).

559

560 **Fig 6.** The Mg# -  $\Delta^{17}\text{O}$  value of relict and host olivines in type I and type II chondrules from  
561 CO (a) and CR (b) chondrites. Fa content ( $=100 \times \text{Fe}/[\text{Mg} + \text{Fe}]$ ) is plotted in log scale  
562 revealing a transition and overlapping between olivine grains in type I chondrules and relict  
563 grains in type II chondrules for carbonaceous chondrites. The probability density function of  
564 relict and host grains in type I and II chondrules are show to the right of each chondrite group.  
565 Errors are  $2\sigma$ . Data of type I chondrules in carbonaceous chondrites are from Schrader et al.  
566 (2013); Kunihiro et al. (2004); Tenner et al. (2013); Hertwig et al. (2018); Chaumard et al.

567 (2018); Marrocchi et al. (2018, 2019, 2022); and Libourel et al. (2022, 2023). The TFL is  
568 shown as blue line for reference.

569

570 **Fig. 7:** The  $\Delta^{17}\text{O}$  value plotted against  $\text{Al}_2\text{O}_3$  (a),  $\text{CaO}$  (b),  $\text{Cr}_2\text{O}_3$  (c), and  $\text{MnO}$  (d) for relict  
571 and host olivines in type I and II chondrules from CO, CV, CM and C2-an carbonaceous  
572 chondrites. The TFL is shown as blue line for reference. Errors are  $2\sigma$ . Data of type I and II  
573 chondrules of CO, CV, CM and C2-an carbonaceous chondrites from Kunihiro et al. (2004);  
574 Tenner et al. (2013); Libourel et al. (2022,2023); Hertwig et al. (2018); Chaumard et al.  
575 (2018); Marrocchi et al. (2018, 2019). Data of type II chondrules are show in blue and  
576 skyblue for this study and literature data, respectively.

577 **Fig. 8:** The  $\Delta^{17}\text{O}$  value plotted against  $\text{Al}_2\text{O}_3$  (a),  $\text{CaO}$  (b),  $\text{Cr}_2\text{O}_3$  (c), and  $\text{MnO}$  (d) for relict  
578 and host olivines in type I and II chondrules from CR carbonaceous chondrites. The TFL is  
579 shown as blue line for reference. Errors are  $2\sigma$ . Data of type I and II chondrules from  
580 Schrader et al. (2013) and Marrocchi et al. (2022). Data of type II chondrules are show in  
581 green and light green for this study and literature data, respectively.

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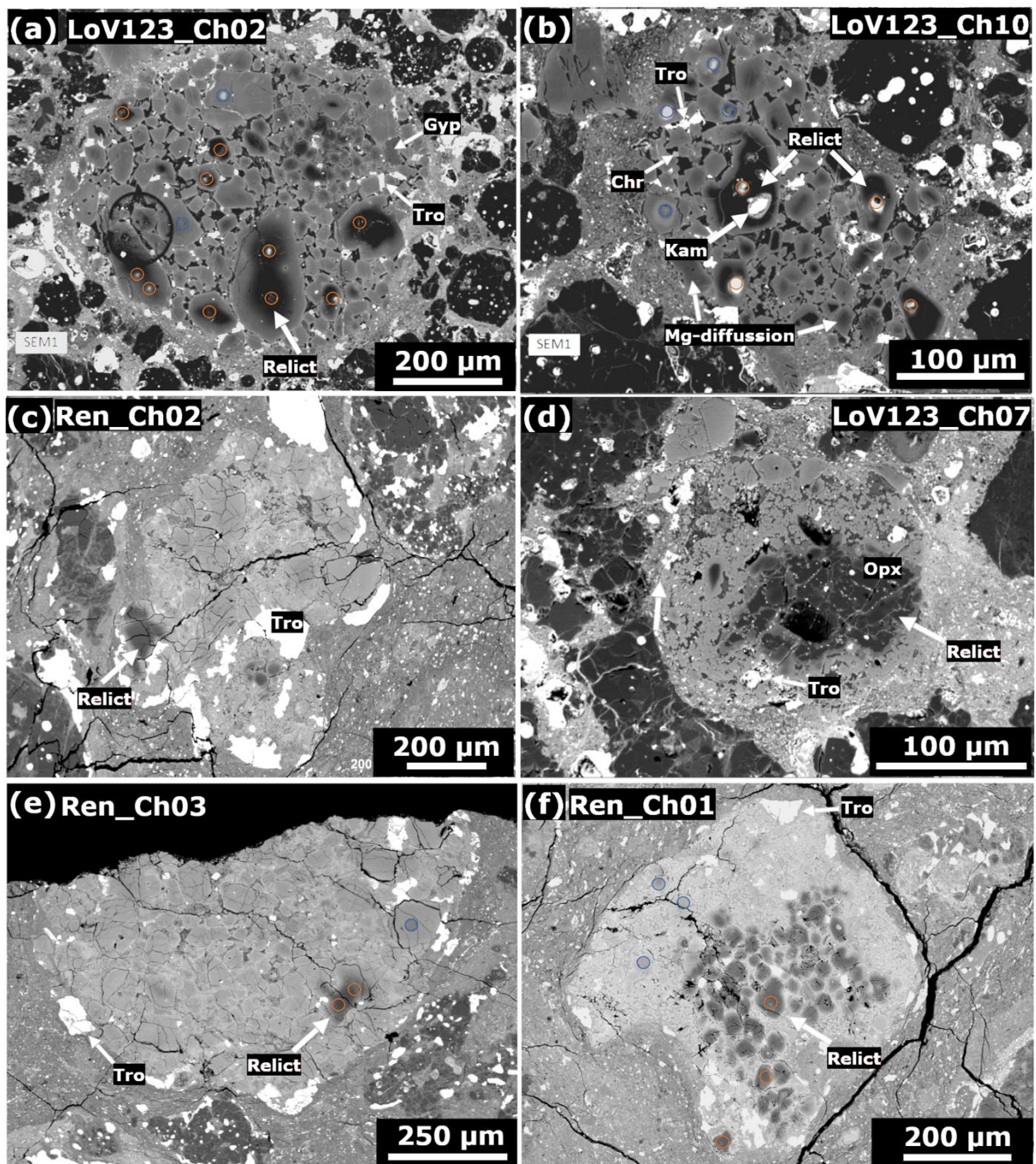
583 **Fig. 9:** Schematic representation of formation of type I and II chondrules in CO chondrites.  
584 Previously condensed  $^{16}\text{O}$ -rich AOAs mixed with NC-like dust before experienced  
585 subsequent melting and gas-melt interactions. This lead to the formation of olivine-rich type I  
586 chondrules characterized by  $^{50}\text{Ti}$ - $^{54}\text{Cr}$  anomalies and the presence of  $^{16}\text{O}$ -rich olivine grains.  
587 Depending on the duration of gas-melt interaction, PO, POP or PP type I chondrules are  
588 formed. Later heating event under oxidizing conditions induced the formation of type II  
589 chondrules. Depending on duration of the oxidation shock, Mg-rich olivine grains can be  
590 either conserved or fully dissolved.

591



592 **Fig. 10:** Schematic representation of formation of type I and II chondrules in CR chondrites.  
593 Similarly to CO chondrules, small type I CR chondrules result from the melting of a mix of  
594 <sup>16</sup>O-rich AOAs and NC-like dust followed by gas-melt interactions. A second generation of  
595 large type I chondrules were also formed through the recycling of CI-like dust, inducing the  
596 presence of two chondrule generations in CR chondrites. Both type of type I CR chondrules  
597 were then recycled into type II chondrules with Mg-rich relict grains having  $\Delta^{17}\text{O}$   
598 characteristics of the two generations of type I chondrule. This implies that the origin of  
599 chondrules must be extremely localized for producing type II chondrules without recycling all  
600 type I chondrules.

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Fig. 1

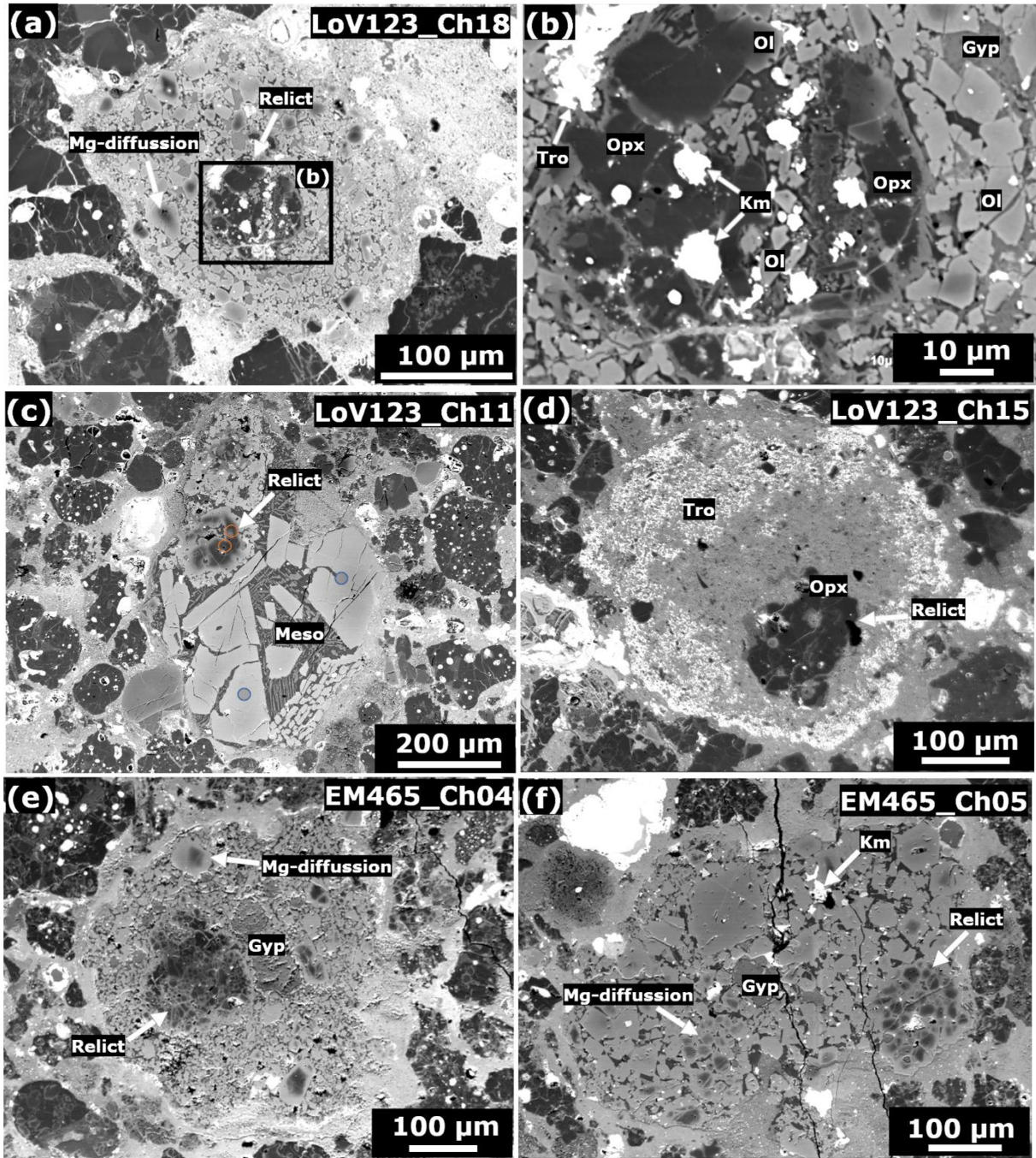
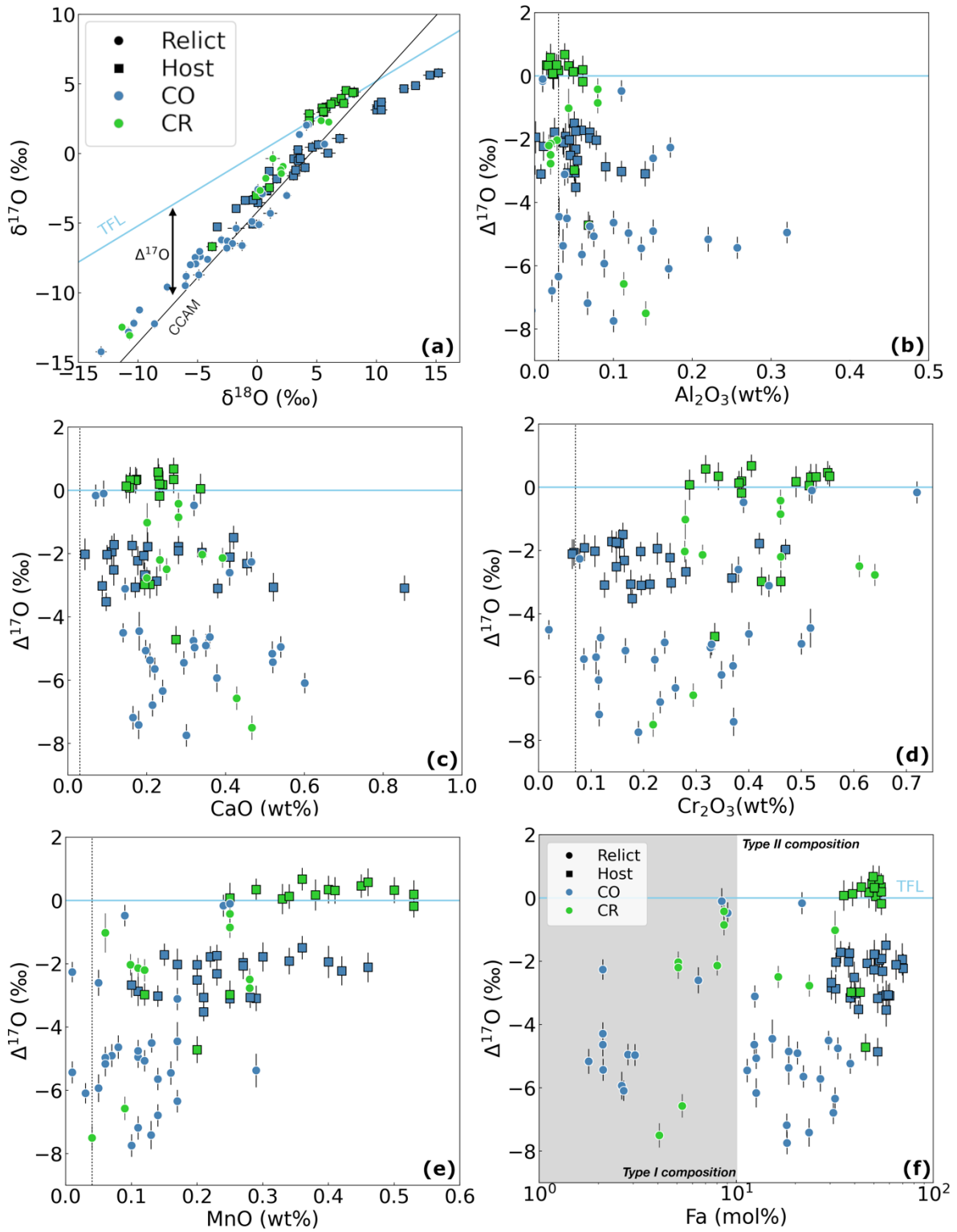


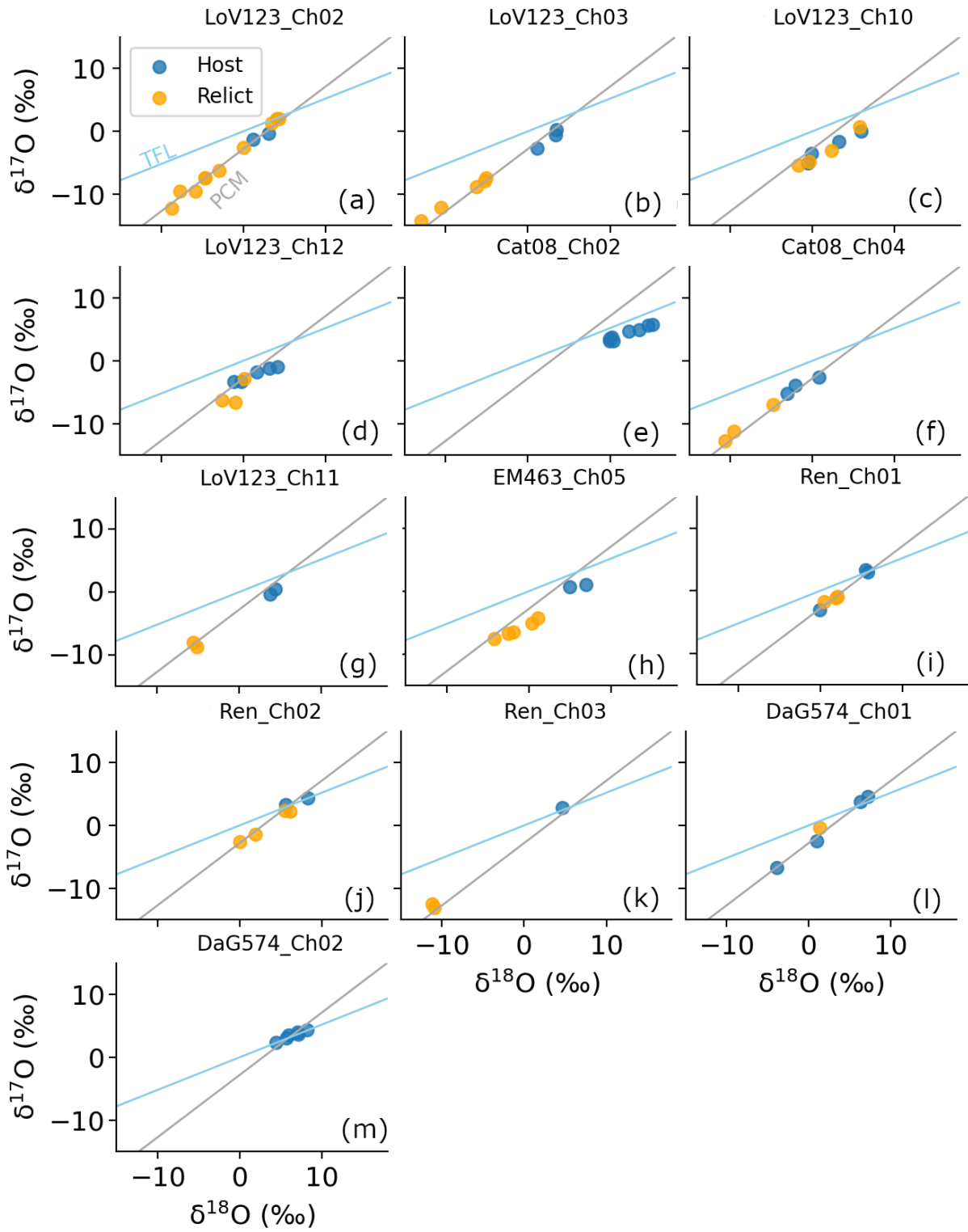
Fig. 2

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**Fig. 4**

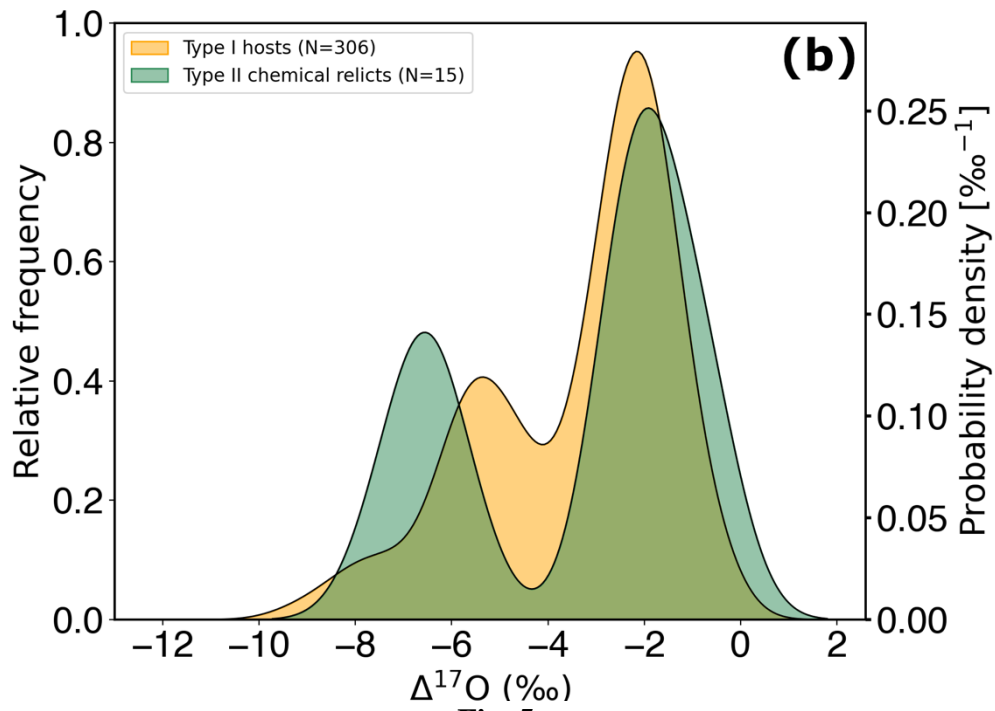
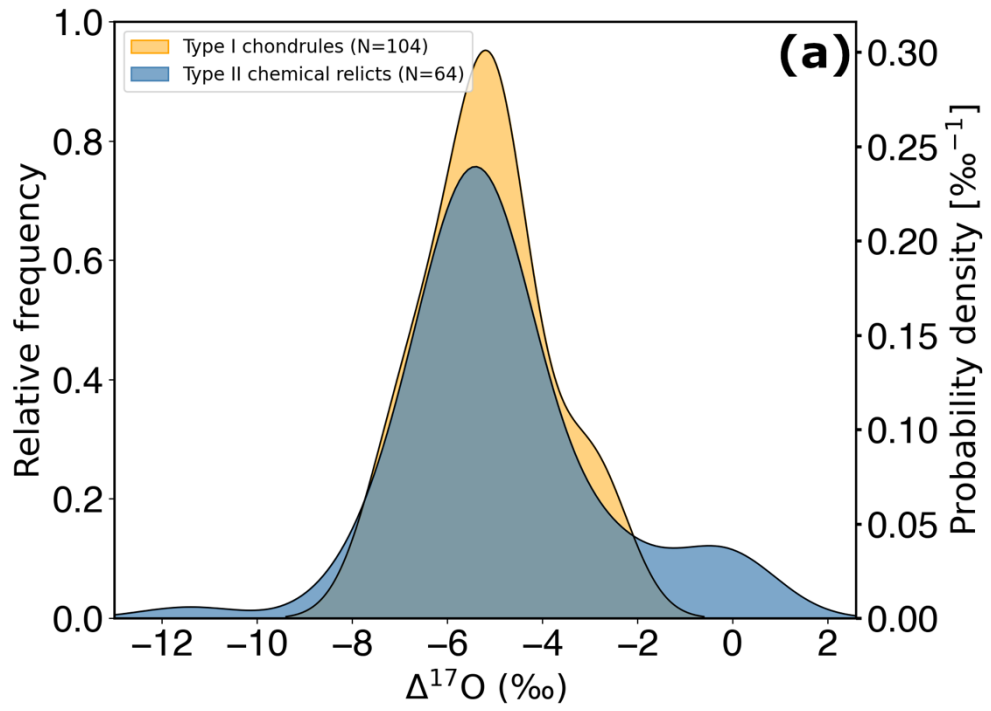
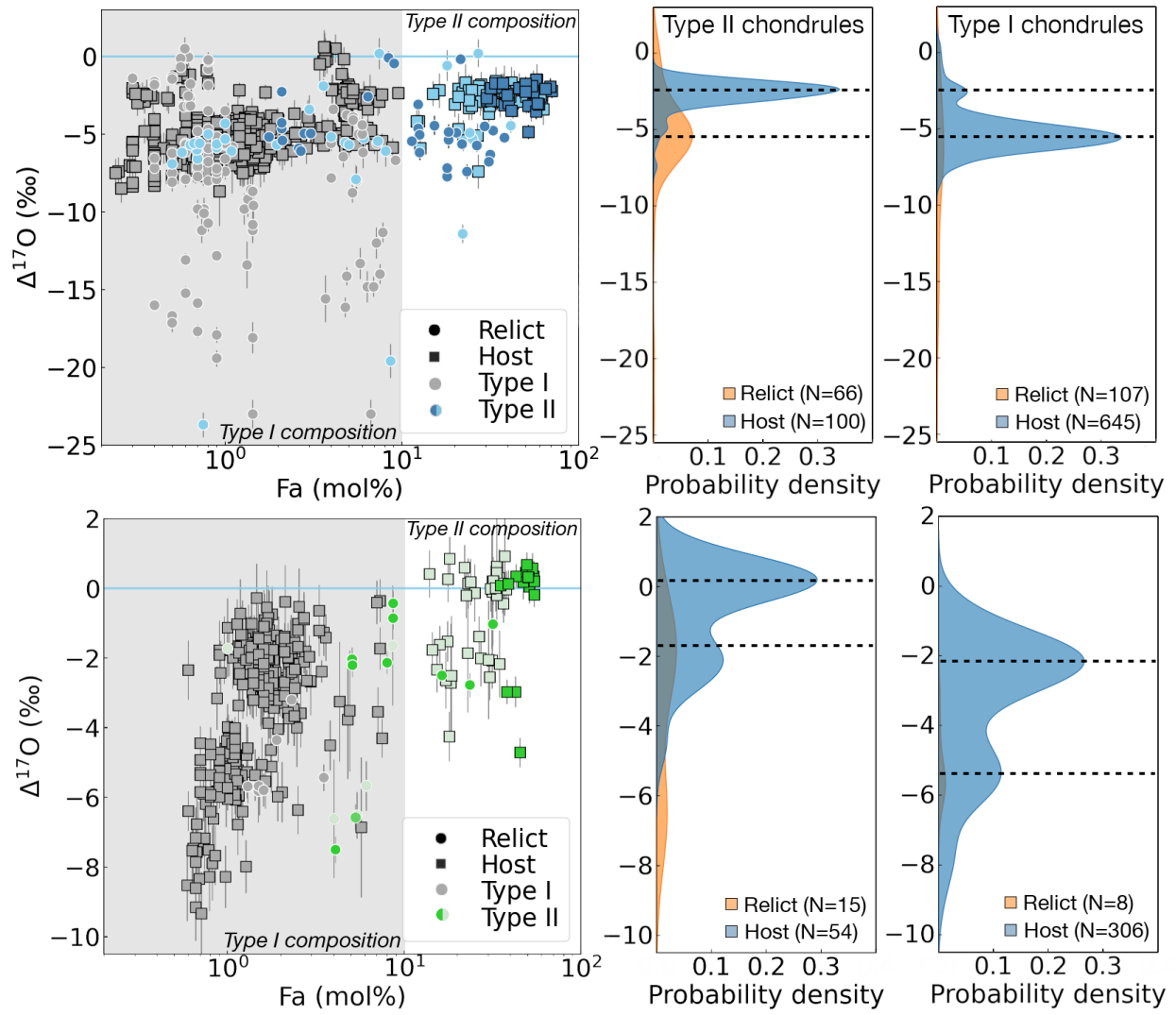


Fig. 5

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**Fig. 6**

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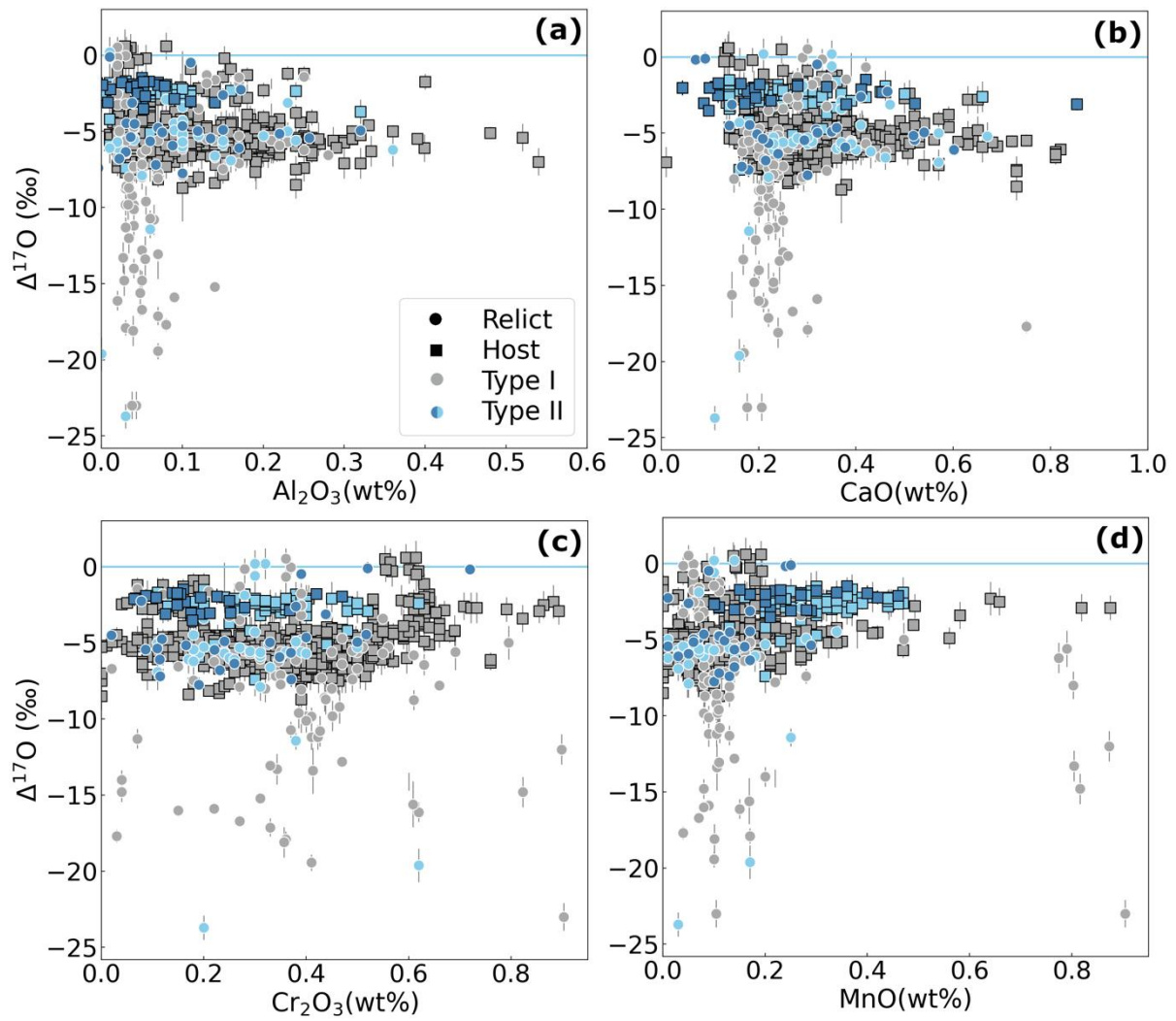
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**Fig. 7**

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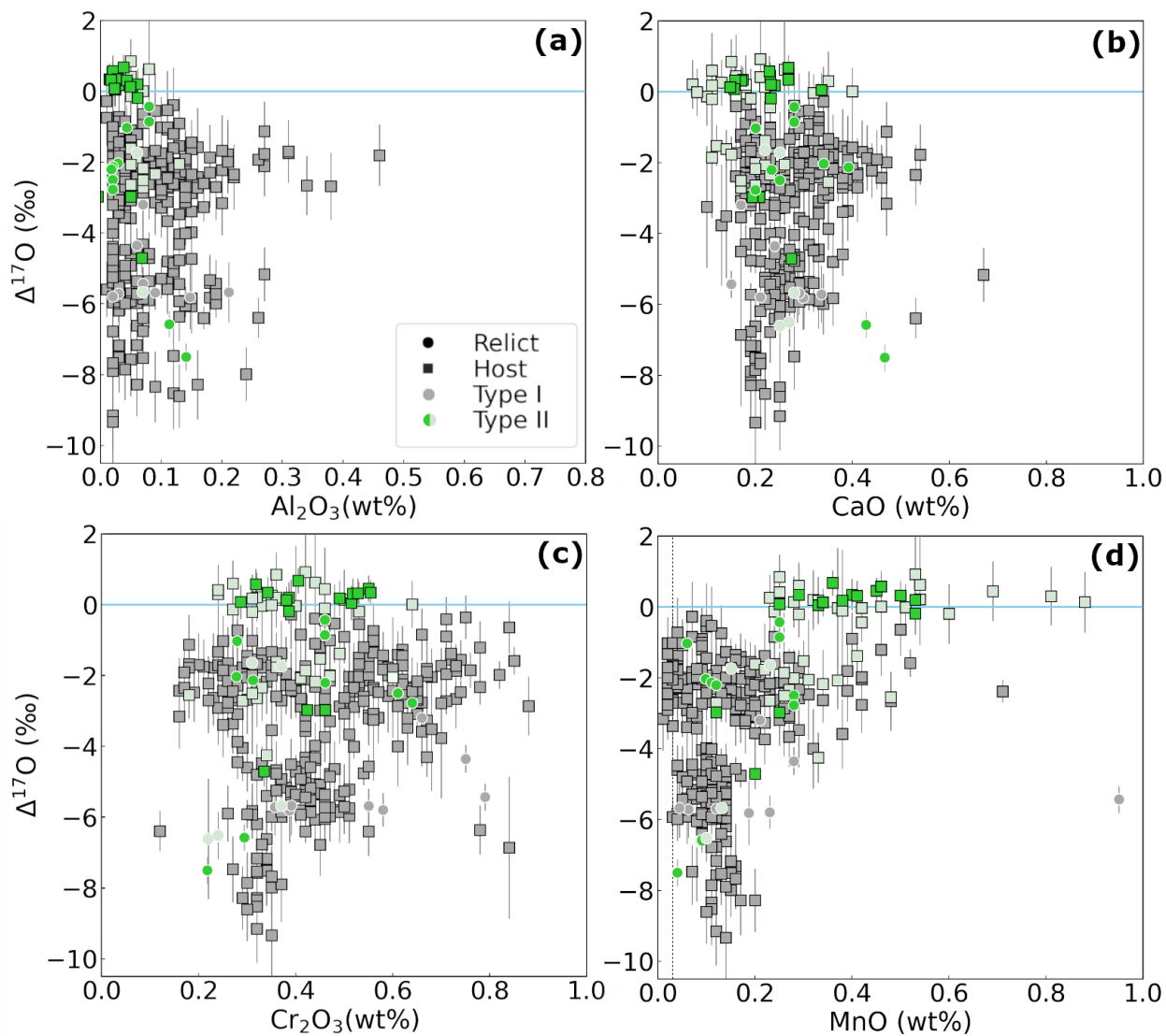


Fig. 8

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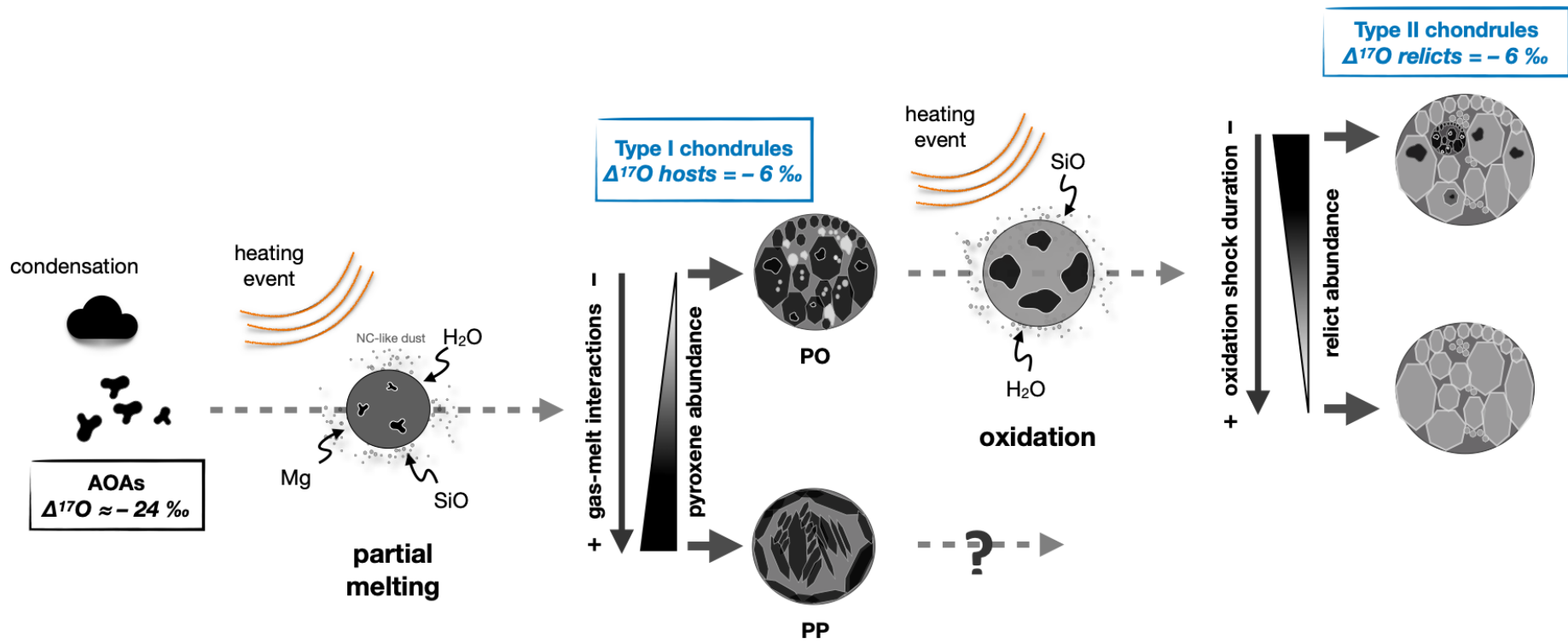


Fig. 9

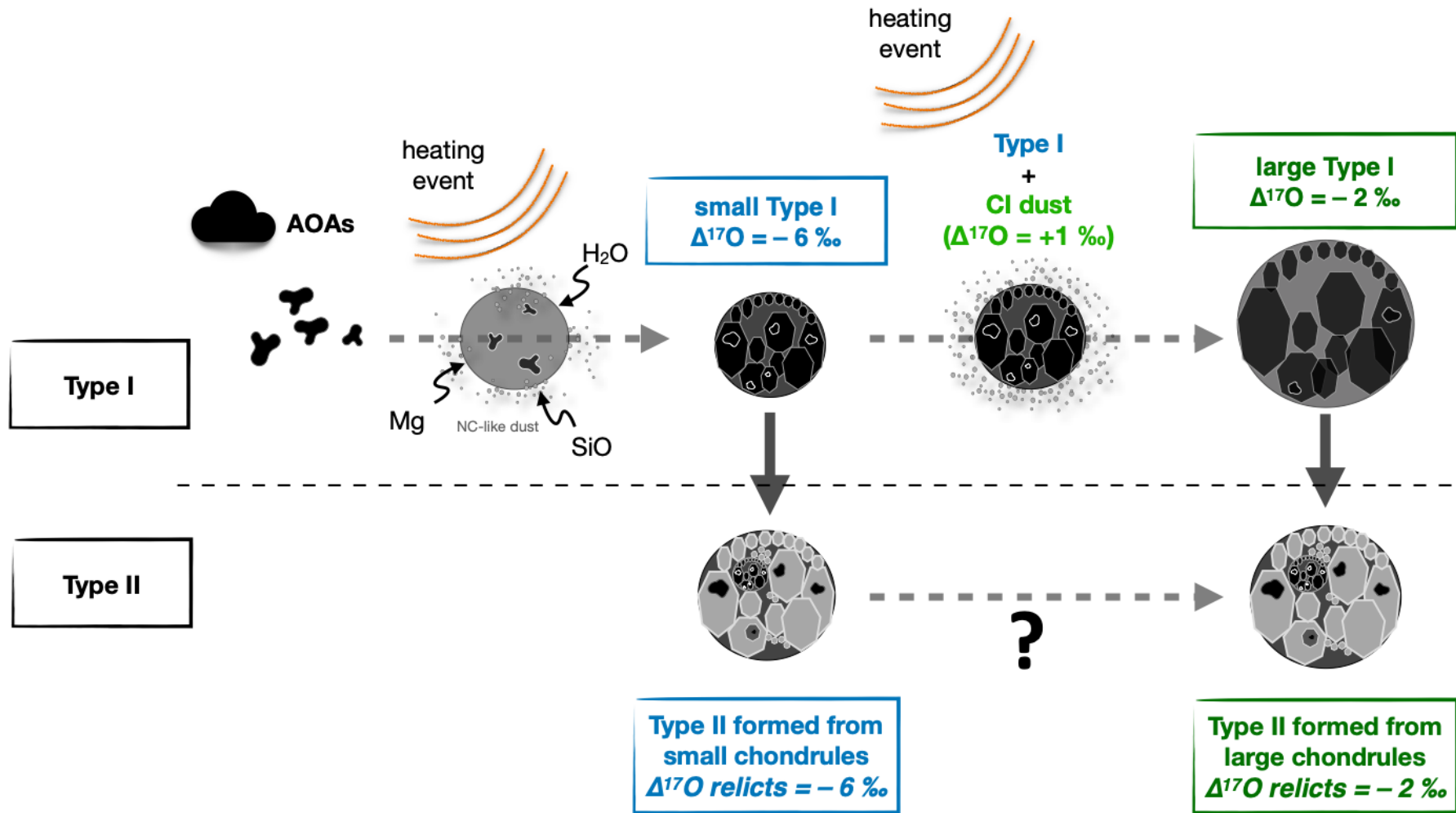


Fig. 10

Table 1. Mean major and minor composition of 688 spot analysis in host and relict olivine grains among the 13 studied FeO-rich chondrules.

Class	Meteorite	Chondrule	Grain type	N	Mg# (mol%)	MgO	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	CaO	TiO <sub>2</sub>	Cr <sub>2</sub> O <sub>3</sub>	MnO	FeO	
CO	<i>LoV123</i>	<i>Ch_02</i>	Host	82	51.66	35.52	0.08	37.64	0.35	0.01	0.34	0.23	26.00	
			Relict	53	82.78	50.29	0.07	41.34	0.25	0.04	0.37	0.16	8.27	
		<i>Ch_12</i>	Host	44	49.40	33.93	0.14	37.03	0.47	0.01	0.30	0.24	27.40	
			Relict	20	87.83	52.17	0.09	41.59	0.41	0.03	0.33	0.09	5.92	
		<i>Ch_03</i>	Host	72	45.09	31.63	0.15	36.56	0.50	0.02	0.26	0.27	30.04	
			Relict	23	72.86	46.04	0.03	39.72	0.34	0.02	0.27	0.14	13.40	
		<i>Ch_10</i>	Host	22	42.87	30.00	0.28	36.00	0.45	0.02	0.37	0.23	31.22	
			Relict	14	90.20	52.33	0.11	41.74	0.33	0.04	0.49	0.04	4.49	
		<i>Ch_11</i>	Host	49	29.54	22.05	0.01	34.34	0.18	b.d.	0.27	0.42	40.98	
	Relict		7	84.77	50.41	0.07	40.69	0.23	0.04	0.29	0.14	7.32		
	<i>Cat 008</i>	<i>Ch_02</i>	Host	108	51.32	34.98	0.07	37.49	0.22	0.01	0.18	0.28	26.40	
			Host	50	48.16	33.62	0.06	37.21	0.17	0.01	0.14	0.23	28.57	
			Relict	20	84.62	51.20	0.10	41.63	0.37	0.05	0.13	0.08	7.47	
	<i>EM463</i>	<i>Ch_05</i>	Host	41	52.77	35.85	0.13	37.95	0.17	0.01	0.16	0.25	25.33	
			Relict	52	88.64	52.40	0.17	41.67	0.39	0.05	0.14	0.07	5.36	
	CR	<i>Renazzo</i>	<i>Ch_01</i>	Host	4	52.17	35.76	0.01	37.50	0.26	0.02	0.41	0.31	25.52
				Relict	3	93.94	54.93	0.02	41.96	0.32	0.03	0.35	0.11	2.75
			<i>Ch_02</i>	Host	3	53.29	36.07	0.02	37.44	0.19	0.04	0.46	0.37	24.54

		Relict	4	81.57	49.41	0.03	41.02	0.23	0.01	0.55	0.27	8.77
	<i>Ch_03</i>	Host	3	46.16	32.38	0.02	36.86	0.26	0.01	0.38	0.43	29.30
		Relict	3	83.45	49.82	0.08	41.41	0.36	0.06	0.30	0.13	8.28
	<i>DaG 574</i>											
	<i>Ch_01</i>	Host	4	55.97	37.99	0.05	38.25	0.23	0.01	0.44	0.24	23.24
		Relict	2	69.09	44.43	0.08	39.39	0.23	0.07	0.39	0.11	15.42
	<i>Ch_02</i>	Host	5	54.17	37.16	0.04	38.11	0.17	b.d.	0.42	0.40	24.58

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b.d.:below detection limit

Table 2. Compilation of mean Mg#s and oxygen isotope ratios of 88 spot analysis in the 13 FeO-rich chondrules from the carbonaceous chondrite LoV 123 (CO3.05), Cat 008 (CO3.1), EM 463 (CO3.2), Renazzo (CR2.4), and DaG 574 (CR2).  $\delta^{17}\text{O}$  and  $\delta^{18}\text{O}$  are relative to VSMOW (Vienna Standard Mean Ocean Water).

Class	Chondrite	Chondrule	Grain type	N analysis	$\delta^{18}\text{O}$ (‰)	$2\sigma$	$\delta^{17}\text{O}$ (‰)	$2\sigma$	$\Delta^{17}\text{O}$ (‰)	$2\sigma$	Mg# (mol%)		
CO	LoV123	Ch02	Relict	10	-2.27	0.31	-4.94	0.33	-3.75	0.37	84.74		
			Host	2	2.03	0.33	-0.81	0.29	-1.87	0.33	48.29		
		Ch03	Relict	5	-7.96	0.37	-10.12	0.32	-5.98	0.38	69.62		
			Host	3	2.56	0.39	-0.97	0.29	-2.30	0.35	43.91		
		Ch10	Relict	4	1.48	0.43	-3.14	0.35	-3.91	0.42	94.61		
			Host	4	2.17	0.60	-2.53	0.35	-3.66	0.47	45.09		
		Ch11	Relict	2	-5.26	0.40	-8.34	0.34	-5.61	0.40	87.39		
			Host	2	4.12	0.58	0.06	0.38	-2.08	0.49	30.16		
		Ch12	Relict	3	-1.13	0.36	-5.25	0.33	-4.67	0.38	93.97		
			Host	5	1.50	0.41	-2.14	0.34	-2.92	0.40	61.91		
		Cat008	Ch02	Host	8	12.04	0.49	4.31	0.30	-1.95	0.40	53.85	
				Ch04	Relict	3	-8.50	0.31	-10.34	0.29	-5.92	0.33	83.31
					Host	3	-1.44	0.32	-3.95	0.27	-3.20	0.32	53.06
		EM463	Ch05	Relict	6	-2.04	0.45	-6.37	0.34	-5.31	0.41	89.51	
				Host	2	6.02	0.67	0.87	0.36	-2.26	0.50	61.63	
		CR	Renazzo	Ch01	Relict	3	1.61	0.35	-1.28	0.28	-2.12	0.34	93.94
Host	3				3.75	0.55	1.10	0.35	-0.85	0.45	50.71		

<i>DaG574</i>	<i>Ch02</i>	Relict	4	3.40	0.36	0.14	0.29	-1.63	0.35	85.73
		Host	2	6.78	0.47	3.85	0.41	0.32	0.43	52.03
	<i>Ch03</i>	Relict	2	-11.02	0.36	-12.76	0.32	-7.03	0.37	95.31
		Host	1	4.36	0.49	2.85	0.36	0.58	0.44	46.87
	<i>Ch01</i>	Relict	1	1.30	0.61	-0.35	0.53	-1.02	0.62	68.32
		Host	4	2.79	0.43	-0.21	0.30	-1.66	0.37	55.97
	<i>Ch02</i>	Host	6	6.41	0.47	3.48	0.34	0.15	0.42	52.74

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