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# The Tarda Meteorite: A Window Into the Formation of D-type Asteroids

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## Abstract

Dynamic models of solar system evolution suggest that D-type asteroids formed beyond Saturn's orbit and represent invaluable witnesses of the prevailing conditions in the outer solar system. Here, we report a comprehensive petrographic and isotopic characterization of the carbonaceous chondrite Tarda, a recent fall recovered in the Moroccan Sahara. We show that Tarda shares strong similarities with the D-type-derived chondrite Tagish Lake, implying that Tarda represents a rare sample of D-type asteroids. Both Tarda and Tagish Lake are characterized by the presence of rare <sup>16</sup>O-rich chondrules and chondrule fragments, high C/H ratios, and enrichments in deuterium, <sup>15</sup>N, and <sup>13</sup>C. By combining our results with literature data on carbonaceous chondrites related to C-type asteroids, we show that the outer solar system at that time was characterized by large-scale oxygen isotopic homogeneities in (i) the water-ice grains accreted by asteroids and (ii) the gas controlling the formation of FeO-poor chondrules. Conversely, the zone in which D-type asteroids accreted was significantly enriched in deuterium relative to the formation regions of C-type asteroids, features likely inherited from unprocessed, D-rich, molecular-cloud materials.

31 **Keywords:** asteroids, Trans-Neptunian objects, carbonaceous chondrites, isotopic abundances

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55 **1- Introduction**

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57 Asteroids are small bodies orbiting the Sun that result from the complex evolution of  
58 planetesimals that formed early during the history of the protoplanetary disk (Delbo et al.  
59 2017). Most known asteroids are presently located in the main asteroid belt, between the  
60 orbits of Mars and Jupiter (heliocentric distances of  $\sim 2\text{--}3.2$  AU; DeMeo & Carry 2014).

61 **Asteroids are characterized by spectroscopically distinct features that, in general,**  
62 **correspond to distinct mineralogical and chemical compositions (DeMeo & Carry 2014).**

63 D-type asteroids are dark bodies whose mineral compositions are poorly known due to the  
64 low reflection intensities of their surfaces (Gartrelle et al. 2021). Nonetheless, spectral  
65 features indicate the presence of water ice, organics, phyllosilicates, and anhydrous minerals  
66 (e.g., Mg-rich olivine; Barucci et al. 2018; Gartrelle et al. 2021). Although rare in the main  
67 asteroid belt ( $\sim 2\%$ ; DeMeo & Carry 2014), D-type asteroids are the most abundant (i) at the  
68 outer edge of the main belt (i.e.,  $\sim 3.0\text{--}3.2$  AU) and (ii) among Jupiter Trojans (i.e., 5.2 AU;  
69 66–84% of all Trojans). D-type asteroids could have formed beyond the orbit of Neptune and  
70 potentially as far as the Kuiper belt (i.e., 30–50 AU; Levison et al. 2009; Vokrouhlický et al.  
71 2016). Numerical simulations suggest that the dynamic evolution of the giant planets' orbits  
72 led to the capture of D-type asteroids from a primordial trans-Neptunian disk (Morbidelli et  
73 al. 2005) and their subsequent implantation into the outer main asteroid belt and at the Jupiter  
74 Trojan orbit (Levison et al. 2009; Vokrouhlický et al. 2016). D-type asteroids thus represent  
75 invaluable witnesses of the conditions that prevailed in the outer circumsolar disk 4.56 Ga.

76 Chondrites are leftover solids from the evolution of the circumsolar disk. Their  
77 diversity attests to the different asteroid populations currently observed in the solar system.  
78 For instance, carbonaceous chondrites are genetically linked to water-rich C-type asteroids,  
79 whereas ordinary chondrites are related to dry S-type asteroids. Samples of D-type asteroids  
80 have not been unequivocally confirmed, with the possible exception of three specific

81 meteorites: WIS 91600 (Hiroi et al. 2005), MET 00432 (Nakamura et al. 2013), and Tagish  
82 Lake (**Brown et al. 2000**). Among them, the Tagish Lake chondrite has been studied in detail  
83 because a significant amount (~10 kg) of it was quickly recovered after its fall (Hiroi et al.  
84 2001). Although Tagish Lake might not be representative of the surface compositions of D-  
85 type asteroids, as previously suggested by Izawa et al. (2015), it may represent the aqueously  
86 altered cores of these peculiar bodies (Vernazza et al. 2017). A genetic link between Tagish  
87 Lake and D-type asteroids has also been proposed based on (i) its weak magnetic  
88 paleointensity (**Bryson et al., 2020**; Weiss et al. 2021) and (ii) the systematic presence of  $^{13}\text{C}$ -  
89 rich carbonates (Fujiya et al. 2019). In addition, Tagish Lake is characterized by high  
90 abundances of carbon and presolar grains, and large deuterium and  $^{15}\text{N}$  enrichments  
91 (Nakamura-Messenger et al. 2006), implying its formation in a cold region of the disk (Brown  
92 et al. 2000). Despite the fundamental importance of Tagish Lake, our knowledge of the  
93 characteristics of the outer solar system at the time of its formation is limited by the rarity of  
94 samples derived from D-type asteroids in meteorite collections.

95         The Tarda chondrite fell in the Moroccan Sahara on 2020 August 25, and the first  
96 pieces of it were collected the following day. Around 4 kg were ultimately recovered, and  
97 initial petrographic and geochemical analyses suggest that Tarda corresponds to a type-2  
98 ungrouped carbonaceous chondrite (Chennaoui Aoudjehane et al., 2021). More specifically,  
99 Tarda is characterized by a bulk oxygen isotopic composition (i) lying between those of CI  
100 and CY chondrites (Clayton & Mayeda 1984; King et al. 2019; Chennaoui Aoudjehane et al.,  
101 2021) and (ii) similar to that estimated for Tagish Lake (Brown et al. 2000). Here, we report a  
102 comprehensive description of the Tarda chondrite. Our results demonstrate that Tarda shares  
103 numerous similarities with Tagish Lake and thus corresponds to a D-type asteroid formed in  
104 the outer part of the solar system. We use our data to discuss the peculiar characteristics of  
105 bodies formed beyond the orbit of Saturn 4.56 Ga.

106

## 107 **2- Material and methods**

108

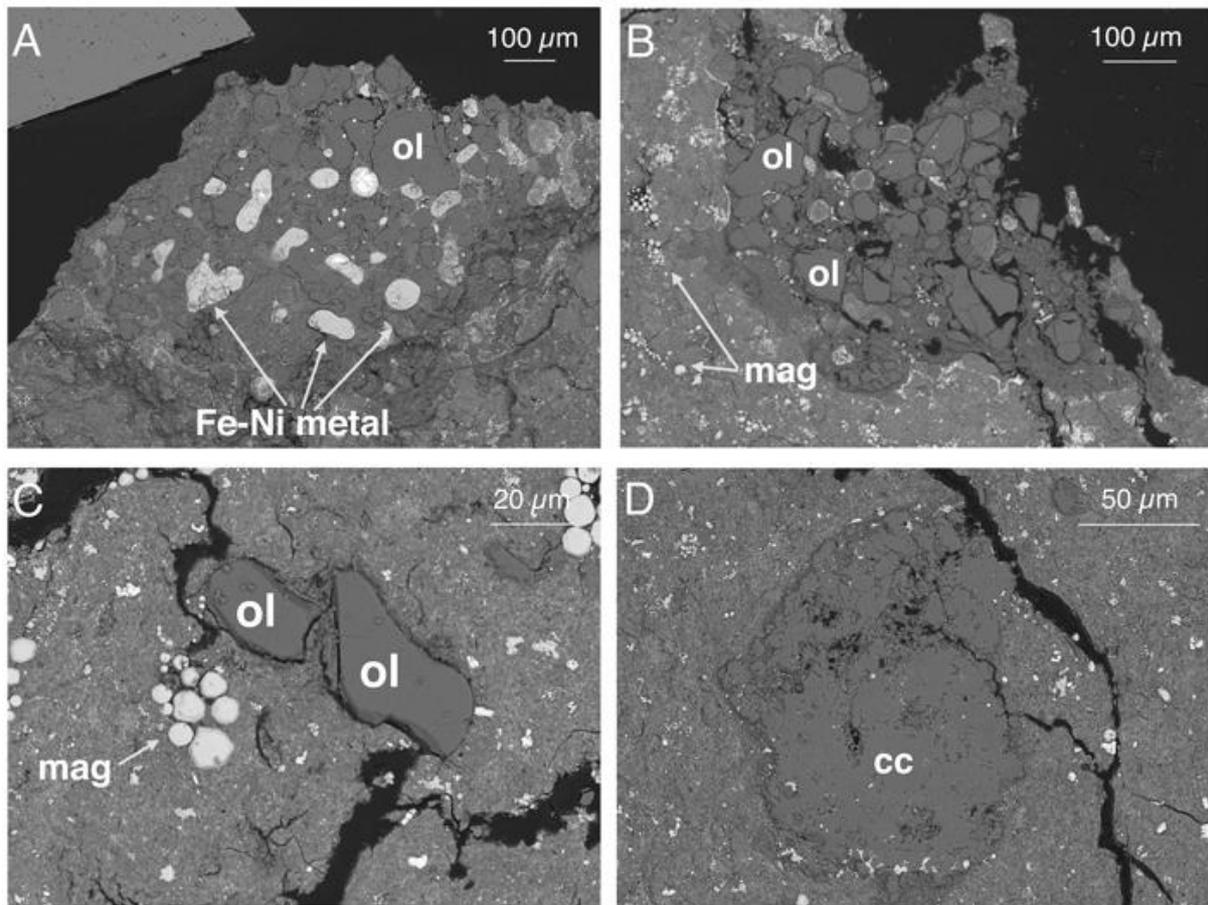
109 We characterized the Tarda carbonaceous chondrite based on (i) petrographic  
110 observations (**scanning** electron microscope and electron microprobe), (ii) bulk mineralogical  
111 and chemical analyses (X-ray diffraction and inductively coupled plasma-sector field mass  
112 spectrometry), and (iii) both *in situ* (i.e., phase-specific, secondary ion mass spectrometry)  
113 and bulk isotopic measurements (elemental analyzer/isotope ratio mass spectrometry). All  
114 analytical techniques are reported in the Supplementary Information. Isotopic compositions  
115 are reported as per-mil variations relative to that of a standard using delta notation as  $\delta^X E =$   
116  $((^{X}E/^{Y}E)_{\text{sample}} / (^{X}E/^{Y}E)_{\text{standard}} - 1) \times 1,000 \text{ ‰}$ , where E indicates the element, and X and Y are  
117 the mass numbers of the heavy and light isotopes, respectively.

118

## 119 **3- Results**

120

121 Our observations of Tarda revealed an abundant fine-grained matrix containing  
122 porphyritic chondrules and isolated olivine grains (hereafter IOGs; Fig. 1). All observed  
123 olivines are forsterites with Mg# (=  $\text{Mg}/[\text{Mg} + \text{Fe}] \times 100$ ) ranging from 98.7 to 99.3 (Table  
124 S1). No calcium-aluminum-rich inclusions (CAIs) or amoeboid olivine aggregates were  
125 observed in the two surveyed sections. Magnetite was frequently observed as framboidal  
126 clusters in the fine-grained matrix (Fig. 1C). A few carbonates (dolomite) were also observed  
127 (Fig. 1D). Crystalline phases identified in diffraction patterns were magnetite, dolomite, Fe-  
128 sulfides, and olivine (Fig. 2). We attribute the broad diffraction peaks observed at  $19^\circ$  and  $60^\circ$   
129 ( $2\theta$  Cu  $K\alpha_1$ ; Fig. 2) to the presence of fine-grained phyllosilicates (King et al. 2019).

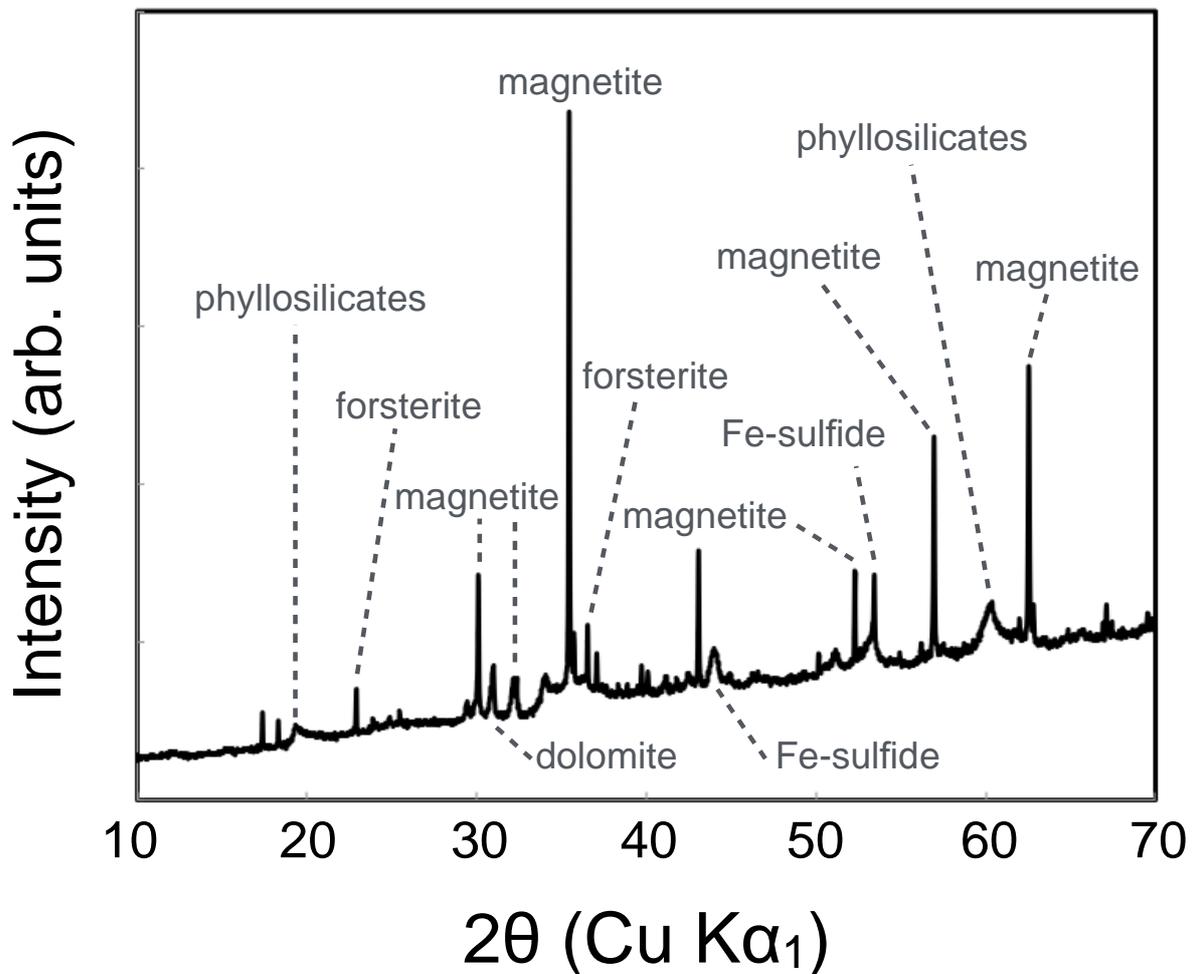


130

131 Fig. 1: Back-scattered electron images of (A, B) porphyritic, FeO-poor chondrules and  
 132 isolated (C) olivine (ol) and (D) dolomite (cc) grains in the Tarda carbonaceous chondrite.  
 133 Framboidal magnetite (mag) grains are also visible in (C).

134

135 Bulk chemical compositions obtained for two aliquots of Tarda showed drastically  
 136 different results (Fig. S1; Table S2). The first aliquot was enriched in rare earth elements  
 137 (REEs) relative to CI chondrites (Fig. S1A; Barrat et al. 2012), with a flat REE pattern, and  
 138 had a bulk composition enriched in refractory elements and depleted in volatile elements (Fig.  
 139 S1B), similar to that of Tagish Lake (Friedrich et al. 2002; Pourmand et al. 2012). The second  
 140 aliquot showed an extreme enrichment in ultra-refractory elements that could result from  
 141 either (i) a higher abundance of refractory inclusions than in the first aliquot or (ii)  
 142 contamination during crushing; therefore, we only consider the first aliquot in the following  
 143 discussion.



144

145

146 Fig. 2: Position-sensitive X-ray diffraction pattern of the Tarda carbonaceous chondrite. The  
 147 presence of phyllosilicates at 19 and 60° 2θ suggests that Tarda did not experience  
 148 dehydration during the evolution of its parent body.

149

150 The two analyzed aliquots of Tarda contained 8.54 and 8.57 wt.% H<sub>2</sub>O, equivalent to

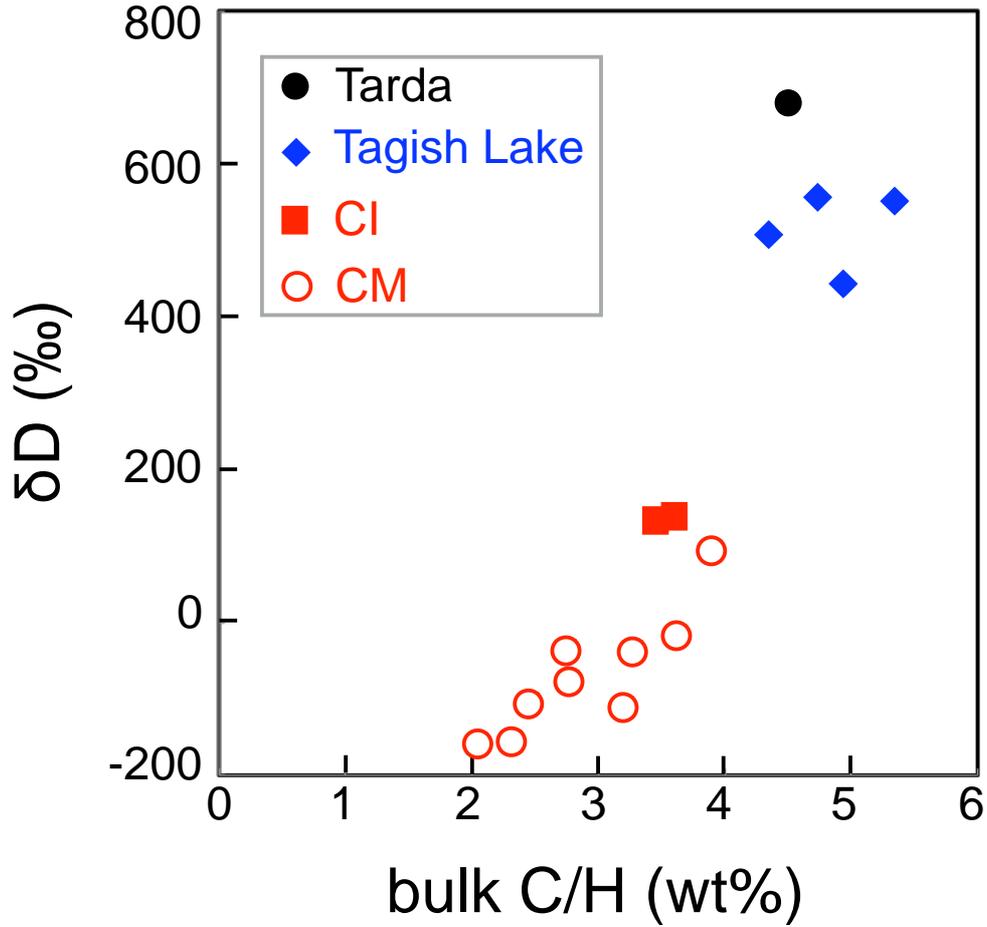
151 0.948 and 0.952 wt.% H, respectively, and had respective H isotopic values of δD = 678.4 ‰

152 and 681.6 ‰ (Fig. 3, Table 1). Three other aliquots were separated for analyses of C and N

153 abundances and isotopic compositions; these aliquots contained 4.06 wt.% C and 0.29 wt.% N

154 and had isotopic compositions of δ<sup>13</sup>C = 10.9 ‰ and δ<sup>15</sup>N = 55.3 ‰, respectively (Table 1).

155



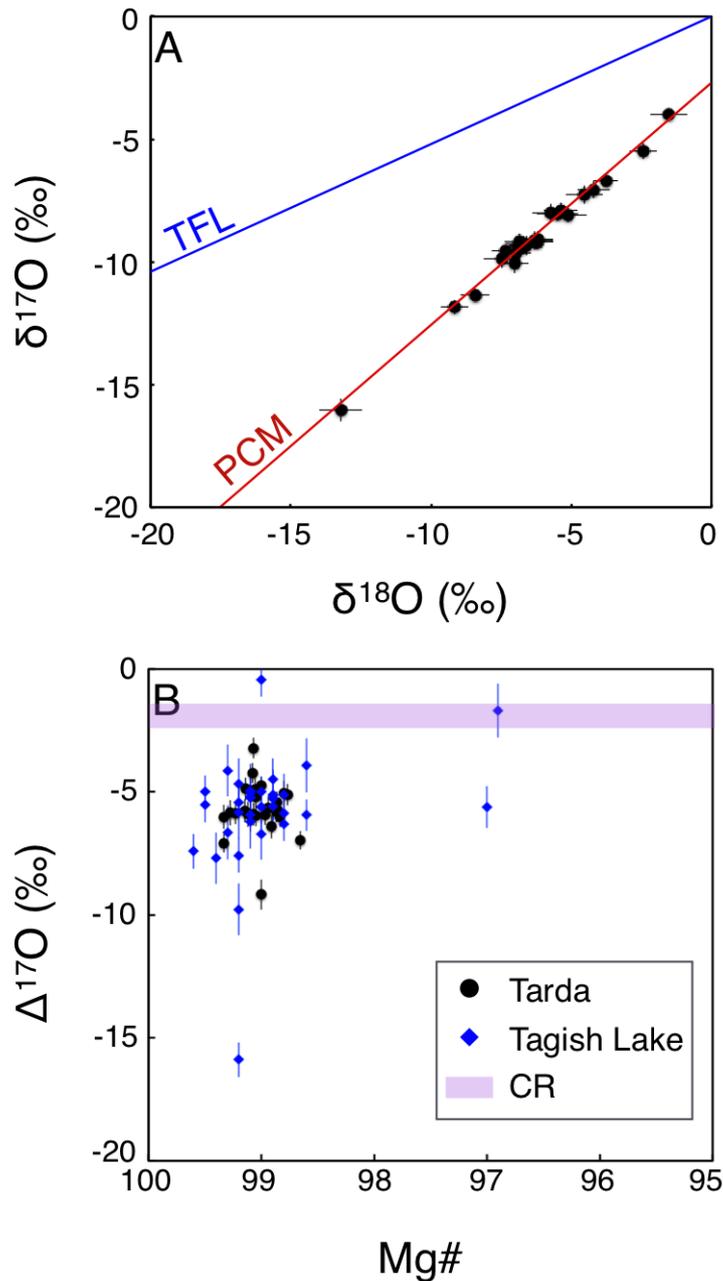
156

157 **Fig. 3:** Comparison of the bulk D/H (as  $\delta D$ ) vs. C/H ratios of Tarda and Tagish Lake, as well  
 158 as those of CM and CI chondrites (data measured after pre-degassing of the samples; Vacher  
 159 et al., 2016, 2020).  
 160

	H (wt%)	$\delta D$	C (wt%)	$\delta^{13}C$	N (wt%)	$\delta^{15}N$
Tarda 1	0.948	678.4				
Tarda 2	0.952	681.6				
Tarda 3			4.00	11.3	0.28	54.7
Tarda 4			4.06	10.7	0.28	55.3
Tarda 5			4.11	10.7	0.30	55.9

161 **Table 1:** Bulk hydrogen, carbon and nitrogen abundances and isotopic compositions of Tarda

162 The oxygen isotopic compositions of Mg-rich chondrules and IOGs define a linear  
163 correlation (Fig. 4A,  $\delta^{17}\text{O} = [0.991 \pm 0.142] \times \delta^{18}\text{O} - [2.8 \pm 0.8]$ ,  $r^2 = 0.98$ ) and plot along the  
164 primitive chondrule minerals line (Ushikubo et al., 2012), with  $\delta^{18}\text{O}$  and  $\delta^{17}\text{O}$  ranging from  
165  $-13.2$  to  $-1.5$  ‰ and from  $-16.1$  to  $-4.0$  ‰, respectively (Fig. 4A, Table S1).



166

167 **Fig. 4:** (A) Oxygen isotopic compositions and (B) oxygen isotopic fractionations of  
168 chondrule olivines and isolated olivine grains in Tarda and Tagish Lake (Ushikubo &  
169 Kimura, 2021). The range of oxygen isotopic compositions of host olivine grains in CR  
170 chondrules is also shown (purple rectangle). The primitive chondrule minerals line (PCM)  
171 and terrestrial fractionation line (TFL) are shown for reference.

172 Excluding chondrule Ch-1, all other individual chondrules and IOGs are characterized by  
173 limited O isotopic variabilities but show average  $\delta^{18}\text{O}$  and  $\delta^{17}\text{O}$  values ranging from  $-7.1$  to  
174  $-2.6$  ‰ and from  $-9.8$  to  $-5.4$  ‰, respectively (Table S1). The O isotopic fractionations of  
175 chondrule olivines and IOGs, expressed as  $\Delta^{17}\text{O} = \delta^{17}\text{O} - 0.52 \times \delta^{18}\text{O}$ , range from  $-9.2$  to  
176  $-3.2$  ‰, but most have  $\Delta^{17}\text{O}$  values between  $-5$  and  $-6$  ‰ (Fig. 4B; Table 1). Concentrations  
177 of  $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$ ,  $\text{CaO}$ ,  $\text{MnO}$  and  $\text{NiO}$  range from  $0.04$ – $0.23$  wt.%,  $0.05$ – $0.09$  wt.%,  $0.11$ – $0.41$   
178 wt.%,  $0.07$ – $0.31$  wt.%, and  $0.008$ – $0.010$  wt%, respectively (Table 1).

179

## 180 **4- Discussion**

181

### 182 **4-1- Tarda's genetic relationship with other known chondrite types**

183

184 Among chondrites, the Tarda meteorite shows peculiar characteristics that led to its  
185 classification as C2 ungrouped. The bulk oxygen isotopic compositions of fragments of Tarda  
186 plot below the terrestrial **fractionation** line and show a bi-modal distribution characterized by  
187  $\Delta^{17}\text{O}$  values near those of either CI or CY chondrites (King et al. 2019; Chennaoui  
188 Aoudjehane et al., 2021). In addition, the  $^{54}\text{Cr}$  isotopic composition of Tarda is close to that  
189 estimated for CR chondrites (Dey et al. 2021). However, our results demonstrate that Tarda  
190 has no genetic link with CI, CY, or CR chondrites for six reasons. First, chondrules and IOGs  
191 are rare but not uncommon in Tarda (Fig. 1; Jacquet et al., 2021), whereas no  
192 (pseudomorphosed)-chondrule has yet been reported in CI chondrites (Piralla et al. 2020).  
193 Second, compared to CI chondrites, the bulk chemical composition of Tarda is significantly  
194 enriched in REEs and refractory elements and depleted in volatile elements (Fig. S1, Table  
195 S2). Third, the diffraction pattern of Tarda reveals phyllosilicates (Fig. 2) that comprise  
196 around 72 % of the bulk (King et al. 2021), implying that Tarda did not experience

197 dehydration as did CY chondrites (King et al. 2019). Fourth, the hydrogen isotopic  
198 composition of Tarda ( $\delta D = +680 \text{ ‰}$ ; Fig. 3) **is D-rich compared** to those reported for CI  
199 and CY chondrites,  $+135 \text{ ‰}$  and  $-106 \text{ ‰}$ , respectively (Fig. 3; Vacher et al. 2020). Fifth,  
200 Tarda is strongly enriched in  $^{13}\text{C}$  ( $\delta^{13}\text{C} = +10.9 \text{ ‰}$ ) compared to CI and CY chondrites ( $\delta^{13}\text{C}$   
201  $= -11.8$  and  $-12.9 \text{ ‰}$ , respectively; Alexander et al. 2012; Vacher et al. 2020). Finally, the  
202  $\Delta^{17}\text{O}$  values of chondrule olivines and IOGs are around  $-6 \text{ ‰}$  (Fig. 4B), significantly  
203 different from those reported for CR anhydrous silicates (i.e.,  $\Delta^{17}\text{O} \approx -2 \text{ ‰}$ ; Tenner et al.  
204 2018). These features demonstrate that Tarda is not related to CR, CI, or CY chondrites, but  
205 instead represents a specific type of carbonaceous chondrite with bulk  $\Delta^{17}\text{O}$  values plotting  
206 near the TFL.

207 Interestingly, **the bulk oxygen isotopic composition of Tagish Lake ( $\Delta^{17}\text{O} = -0.83 \pm$**   
208  **$0.26 \text{ ‰}$ ; Brown et al. 2000) is relatively close to that of Tarda ( $-0.13 \pm 0.15 \text{ ‰}$ ;**  
209 **Chennaoui Aoudjehane et al. 2021)**, suggesting a potential link with this peculiar chondrite.  
210 Indeed, several observations corroborate this hypothesis. Chondrule olivines and IOGs in  
211 Tarda show  $\Delta^{17}\text{O}$  values similar to those reported for olivines in Tagish Lake, with values  
212 around  $-6 \text{ ‰}$  (Fig. 4B; Ushikubo & Kimura 2021). In addition, both chondrites are  
213 characterized by large D-enrichments;  $\delta D = +680 \text{ ‰}$  in Tarda and  $+442.3$  to  $+556.36 \text{ ‰}$  in  
214 Tagish Lake (Alexander et al. 2012; Vacher et al. 2020). Furthermore, Tarda and Tagish Lake  
215 plot in the same field in the  $\delta D$  vs. C/H diagram (Fig. 3, Table 1) and have similar,  
216 isotopically heavy bulk  $\delta^{13}\text{C}$  ( $+10.9$  and  $+4.7 \text{ ‰}$ , respectively; Vacher et al. 2020) and  $\delta^{15}\text{N}$   
217 compositions ( $+55.3$  and  $+66.2 \text{ ‰}$ , respectively; Alexander et al. 2012). Finally, the bulk  
218 chemical composition and REE pattern of Tarda are similar to those determined for Tagish  
219 Lake (Friedrich et al. 2002; Pourmand et al. 2012; Fig. S1; Table S2). Our data therefore  
220 demonstrate that Tarda is genetically related to Tagish Lake and thus represents a new sample  
221 of D-type asteroids.

## 222 **4-2- Implications for the isotopic characteristics of the D-type asteroid accretion region**

223

224 The peculiar characteristics of both Tarda and Tagish Lake provide a window into the  
225 characteristics of the region in which D-type asteroids accreted and the isotopic structure of  
226 the outer solar system. We now discuss our results in light of previous results on Tagish Lake.

227 The low abundances of chondrules and IOGs in both Tagish Lake and Tarda could  
228 result from intensive fluid circulation processes, as observed in some CM1 chondrites.  
229 However, the limited volatile-depletion observed in Tarda suggests that chondrules were  
230 never a significant constituent of Tarda (Fig. S1B). Conversely, such a low degree of volatile-  
231 depletion could be interpreted as the result of (i) ineffective anhydrous silicate formation in  
232 the D-type asteroid accretion region or (ii) limited large-scale transport from other regions of  
233 the disk. Interestingly, the  $\Delta^{17}\text{O}$  values of chondrule olivines in Tarda and Tagish Lake (i.e., ~  
234  $-6\text{‰}$ ) are similar to the large majority of FeO-poor chondrules and IOGs reported in other  
235 carbonaceous chondrites, with the exception of CR chondrites (i.e.,  $\Delta^{17}\text{O} \approx -2\text{‰}$ ; see Tenner  
236 et al. 2018 for a compilation). Assuming transport between reservoirs in the disk, this would  
237 suggest that chondrules in the D-type asteroid-forming region originated from a C-type  
238 reservoir. Alternatively, local chondrule formation would imply large-scale oxygen isotopic  
239 homogeneity because chondrule olivines formed *via* interactions between (partially) molten  
240 chondrule precursors and the ambient gas (e.g., Marrocchi et al. 2018, 2019; Tenner et al.  
241 2018; Ushikubo & Kimura 2021).

242 Interestingly, the peculiar  $^{26}\text{Al}$  and  $^{54}\text{Cr}$  isotopic signatures of CR chondrules have  
243 been interpreted as resulting from (i) the incorporation of  $^{26}\text{Al}$ -poor primordial materials  
244 inherited from the molecular cloud and (ii) their formation beyond the orbits of the giant  
245 planets (van Kooten et al. 2016). These authors suggested a similar outer solar system origin  
246 for the  $^{16}\text{O}$ - and  $^{26}\text{Al}$ -poor chondrules and chondrule fragments sampled from the Jupiter-

247 family comet Wild 2 by the Stardust mission, which are generally interpreted as having  
248 formed late in the inner circumsolar disk and radially transported to the cometary accretion  
249 region (Ogliore et al., 2012). Consequently, they proposed that chondrule formation was not  
250 limited to the innermost part of the solar system, but instead occurred throughout the disk,  
251 including the region in which D-type asteroids accreted. If correct, this implies that the O  
252 isotopic composition of the gas that interacted with FeO-poor chondrules was homogeneous  
253 at the scale of the C- and D-type asteroid accretion regions.

254 Both Tarda and Tagish Lake are dominated by phyllosilicates (Brown et al. 2000;  
255 King et al. 2021), implying that D-type asteroids accreted water-ice grains with Earth-like O  
256 isotope compositions (i.e.,  $\Delta^{17}\text{O} \approx 0 \text{ ‰}$ ). Indeed, the water released during the pyrolysis of  
257 Tagish Lake had a terrestrial oxygen isotopic composition (Baker et al. 2002). Similar to CI  
258 chondrites (Piralla et al. 2020), neither Tarda nor Tagish Lake show any evidence of  $^{17,18}\text{O}$ -  
259 rich water formed *via* the self-shielding of  $^{16}\text{O}$ -rich nebular  $\text{CO}_{(\text{g})}$  by UV light in the  
260 molecular cloud or outer solar system (e.g., Krot et al. 2020). This implies that, at the time  
261 when chondritic parent bodies formed, the outer solar system was characterized by oxygen  
262 isotopic compositions similar to those of the terrestrial planets such as Earth and Mars.  
263 However, these peculiar isotopic characteristics do not preclude the occurrence of self-  
264 shielding processes because carbonaceous chondrites accreted relatively late during the disk's  
265 evolution (i.e.,  $\geq 2.5$  Myr after the formation of CAIs; Sugiura & Fujiya 2014). Hence,  $^{17,18}\text{O}$ -  
266 rich water-ice grains could have experienced rapid thermal processing and O isotopic re-  
267 equilibration with amorphous silicates—the main constituent of chondritic matrices (Le  
268 Guillou et al. 2015)—as recently experimentally demonstrated (Yamamoto et al. 2018). This  
269 would have shifted the O isotopic composition of water toward terrestrial values, as inferred  
270 from the  $\Delta^{17}\text{O}$  values of aqueously formed minerals in other carbonaceous chondrites (e.g.,  
271 Doyle et al. 2015). Nevertheless, the bulk O isotopic compositions of Tarda, Tagish Lake, and

272 other carbonaceous chondrites indicate that water in the outer solar system (beyond several  
273 tens of astronomical units) had homogenous, Earth-like, oxygen isotopic compositions.

274 Another peculiar feature of Tarda is its strong enrichment in D (Fig. 3; Vacher et al.  
275 2020), which is consistent with the D-rich bulk and *in situ* compositions of Tagish Lake  
276 (Nakamura-Messenger et al. 2006; Patzek et al. 2020; Vacher et al. 2020). **D-rich signatures**  
277 **of chondrites** are generally interpreted as resulting from either (i) the accretion of D-rich  
278 organics and/or water-ice grains (Vacher et al. 2020) or (ii) the aqueous oxidation of Fe-Ni  
279 metal beads followed by H<sub>2</sub>-loss and Rayleigh-type isotopic fractionation (Sutton et al. 2017).  
280 **The latter process is however ineffective for enriching water-rich chondrites such as Tarda in**  
281 **deuterium as their D/H ratios could not be buffered due to their large amount of initial water**  
282 **(Vacher et al., 2020).** In addition, this is inconsistent with the higher H concentration and  
283 isotopic composition of Tarda relative to Tagish Lake (Fig. 3), as the opposite isotopic  
284 characteristics would be expected (Vacher et al., 2021). Our data thus imply that the region of  
285 D-type asteroid formation was characterized by a significant D-enrichment relative to that of  
286 C-type asteroids (the only exception being CR chondrites, peculiar chondrites proposed to  
287 have formed in the outer part of the disk; van Kooten et al. 2016). The D enrichments of D-  
288 type asteroids are likely inherited from D-rich molecular cloud materials (i.e., organic and  
289 water-ice grains) that were not reprocessed by high-temperature thermal events, consistent  
290 with the low abundance of chondrules in Tarda and Tagish Lake. This conclusion is  
291 consistent with the occurrence in Tagish Lake of organic globules similar to those observed in  
292 cometary particles whose isotopic compositions are interpreted as being inherited from the  
293 cold molecular cloud from which the solar system formed (Nakamura-Messenger et al. 2006).

294

295

296

297 **5- Conclusions**

298

299 Our petrographic and isotopic surveys of the Tarda carbonaceous chondrite revealed  
300 that it shares important similarities with the Tagish Lake chondrite. Both likely originate from  
301 D-type asteroids, which are considered to have formed at large heliocentric distances beyond  
302 the current orbit of Saturn. By comparing our isotopic data with those from chondrites related  
303 to C-type asteroids, we showed that the outer solar system at the time of chondrite formation  
304 was characterized by large-scale O isotopic homogeneities in (i) the gas that drove the  
305 formation of FeO-poor chondrules and (ii) the water-ice grains accreted by carbonaceous  
306 asteroids. It also appears that the formation region of D-type asteroids is significantly  
307 enriched in deuterium relative to that of C-type asteroids due to the accretion of unprocessed,  
308 D-rich materials from the molecular cloud.

309

310 **Research data**

311 Original data from this study are available on the Ordar database;  
312 <http://dx.doi.org/10.24396/ORDAR-63>.

313

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315

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320

321

322 **Appendices**

323 **Materiel and method**

324

325 *Mineralogical and Petrographic Observations*

326 We surveyed two homemade thick sections of Tarda (Tarda #1 and #2) in reflected  
327 light. Scanning electron microscope (SEM) observations and Energy Dispersive X-ray (EDX)  
328 spectral analyses were performed at CRPG with a JEOL JSM-6510 equipped with an EDX  
329 Genesis X-ray detector and operating with a 3 nA primary beam at 15 kV. Quantitative  
330 analyses of the mineralogical compositions of chondrule olivine grains were made with a  
331 CAMECA SX-100 electron microprobe (SCMEM) at the University of Lorraine. A 20 nA  
332 focused beam, accelerated to 15 kV potential difference, was used for spot analyses of  
333 silicates. Detection limits in silicates were: (i) 0.03 wt% for SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, CaO and MgO,  
334 (ii) 0.04 wt% for MnO and TiO<sub>2</sub> and (iii) 0.07 wt% for NiO, Cr<sub>2</sub>O<sub>3</sub> and FeO.

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336 *X-Ray Diffraction*

337 500 mg of Tarda were gently crushed in an agate mortar for determining its X-ray  
338 diffraction (XRD) patterns. The measurements were performed using a Panalytical X'Pert Pro  
339 diffractometer equipped with a Cu tube, a Ge(111) incident-beam monochromator ( $K\alpha_1 =$   
340  $1.5406 \text{ \AA}$ ), 0.02 rad Soller slits, programmable divergence and anti-scatter slits, the irradiated  
341 area was fixed to 10mm × 10mm and an X'Celerator fast detector. The X'Celerator detector  
342 was used as "scanning line detector (1D)" with 2.122° active length. Phase identification was  
343 realized using the Panalytical software "X'Pert Highscore Plus" with the pdf2 files as  
344 crystallographic database.

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347 *Bulk chemistry*

348 Two fragments were prepared and the results are listed in Table S2. Both samples  
349 were crushed in into powder in an agate mortar. The second sample (Tarda 2) corresponds to  
350 the fraction that was used for determining the X-ray diffraction pattern. Trace element  
351 concentrations were measured with a Thermo® ICP-MS iCapQ (Tarda 1, CRPG) and a  
352 Thermo® Element2 HR-ICP-MS at CRPG (Tarda 2, IUEM). 120 mg of powder were  
353 digested on a hot plate heated to 125°C, using sequential mixtures of HF/HNO<sub>3</sub>, HNO<sub>3</sub> and  
354 HCl. Concentrations were determined following the procedure described by Barrat et al.  
355 (2012, 2016). The reproducibility is always much better than 5%.

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357 *Bulk hydrogen, carbon and nitrogen isotope measurements*

358 The hydrogen, carbon and nitrogen concentration and isotopic composition of Tarda  
359 has been determined using a Thermo Scientific EA IsoLink —DeltaV IRMS System at  
360 CRPG. The procedure was similar to that detailed in Vacher et al. (2020). After crushing in an  
361 agate mortar, two aliquots (3.36 and 4.29 mg, respectively) were loaded into tin capsules,  
362 which were degassed for 48 hours at 120°C for removing adsorbed atmospheric water before  
363 hydrogen measurements (Vacher et al., 2016, 2020, Marrocchi et al., 2020; Piani et al., 2020).  
364 We express the hydrogen isotopic compositions in delta units relative to that of Standard  
365 Mean Ocean Water (SMOW,  $D/H_{SMOW} = 155.76 \times 10^{-6}$ ) with  $\delta D [‰] = [(D/H_{sample} /$   
366  $D/H_{SMOW}) - 1] \times 1,000$ . Reproducibilities estimated from reference materials are better than  
367 10% ( $2\sigma$ ) for H concentration and 5 ‰ for  $\delta D$ . Aliquots of 5 to 10 mg were wrapped in Tin  
368 foil and used for C and N measurements. The capsule was loaded into an auto-sampler  
369 connected to the EA system and pumped for 20 min before oxidation on a reactor made of a  
370 quartz tube filled with Cr<sub>2</sub>O<sub>3</sub>. The tin capsule oxidation led to an exothermic reactions (up to  
371 180°C) releasing N<sub>2</sub> and CO<sub>2</sub> that were separated on a chromatographic column at 70°C. For

372 nitrogen analyses,  $2\sigma$  errors are expected to be 10% for [N] and 2‰ for  $\delta^{15}\text{N}$ . Errors on [C]  
373 are estimated to be 2 % and 2 ‰ for  $\delta^{13}\text{C}$ .

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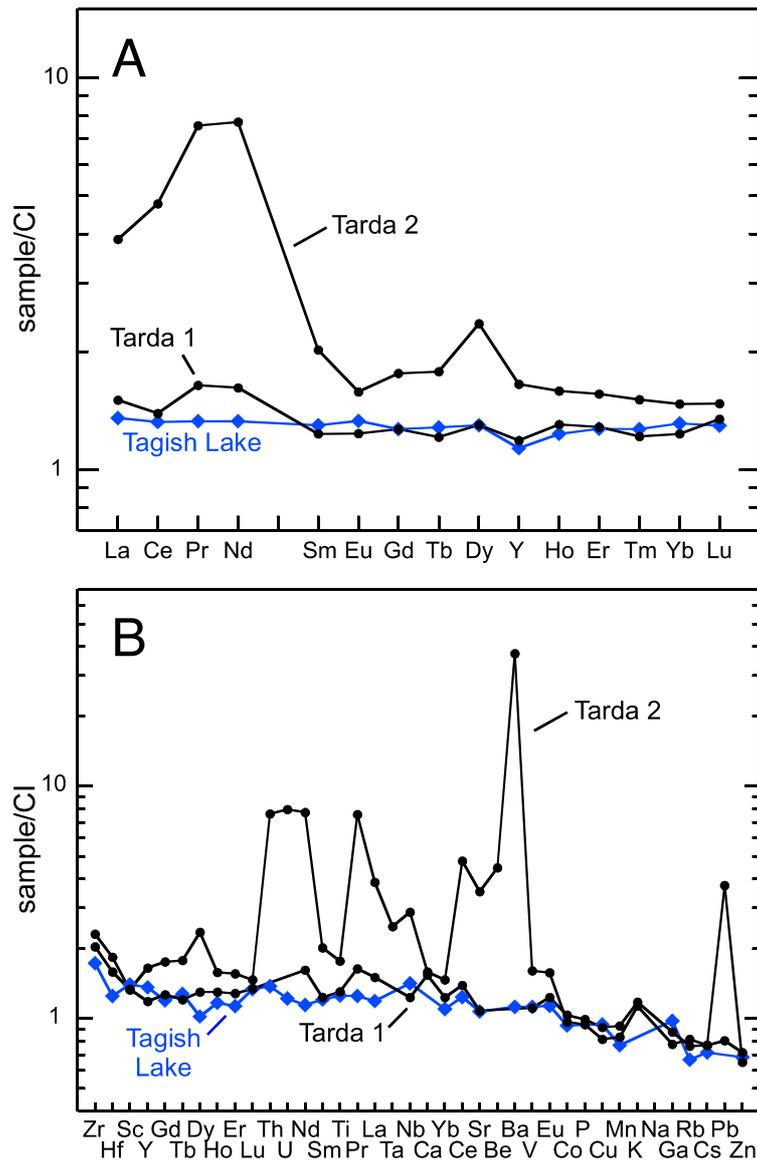
#### 375 *In situ oxygen isotopic compositions*

376 Olivine oxygen isotopic compositions of chondrule olivine grains were determined at  
377 CRPG using a CAMECA IMS 1270 E7.  $^{16}\text{O}^-$ ,  $^{17}\text{O}^-$  and  $^{18}\text{O}^-$  ions produced by a  $\text{Cs}^+$  primary  
378 beam of 500 pA ( $\sim 4 \mu\text{m}$ ) were measured in multi-collection mode using two off-axis faraday  
379 cups and the axial electron multiplier (EM). A normal-incidence electron gun was used for  
380 charge self-compensation. To remove interference from  $^{16}\text{OH}^-$  on the  $^{17}\text{O}^-$  peak and maximize  
381 the flatness atop the  $^{16}\text{O}^-$  and  $^{18}\text{O}^-$  peaks, the entrance ( $\sim 100 \mu\text{m}$ ) and axial exit ( $\sim 200 \mu\text{m}$ )  
382 slits were adjusted to obtain a Mass Resolving Power ( $\text{MRP} = M/\Delta M$ ) of  $\sim 6000$  for  $^{17}\text{O}^-$  on  
383 the axial EM.  $^{16}\text{O}^-$  and  $^{18}\text{O}^-$  were measured on L'2 and H1 (**slit 1,  $\text{MRP} \approx 2500$ ; Bouden et**  
384 **al., 2021**). For removing the carbon coating at the surface, samples were sputtered before each  
385 measurement for 90 s over an area of  $2 \times 2 \mu\text{m}$ . 40 cycles of 5 s each were acquired to obtain  
386 counting statistics on the order of  $\pm 0.6\text{‰}$  ( $2\sigma$ ) for  $\delta^{18}\text{O}$  and  $0.4\text{‰}$  ( $2\sigma$ )  $\delta^{17}\text{O}$ . Three terrestrial  
387 standards were measured to define the mass fractionation line (Diopside, magnetite and San  
388 Carlos olivine) and to correct instrumental fractionation **due to** the matrix effect of olivine.  
389 Typical measurement errors of  $\sim 0.4\text{--}0.7 \text{‰}$  for  $\delta^{18}\text{O}$ ,  $\delta^{17}\text{O}$  and  $\Delta^{17}\text{O}$  ( $2\sigma$ ) account for internal  
390 errors on each measurement and the external reproducibility of the standard.

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395 **Fig. S1:** (A) REE and (B) bulk trace element patterns of Tarda and Tagish Lake (Pourmand et  
 396 al. 2012) normalized to the average composition of Orgueil (Barrat et al. 2012).

chondrule	$\delta^{18}\text{O}$	$2\sigma$	$\delta^{17}\text{O}$	$2\sigma$	$\Delta^{17}\text{O}$	$2\sigma$	SiO <sub>2</sub>	FeO	Al <sub>2</sub> O <sub>3</sub>	CaO	MnO	MgO	Cr <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	NiO	Total	Fo#
detection limit							0.03	0.07	0.03	0.03	0.04	0.03	0.07	0.04	0.07		
Ch-1	-5.11	0.67	-8.10	0.30	-5.44	0.46	42.47	1.14	0.04	0.19	0.14	55.75	0.50	bdl	bdl	100.2	98.9
	-4.21	0.59	-7.06	0.34	-4.87	0.46	42.06	0.87	0.04	0.22	0.11	56.40	0.46	0.06	bdl	100.2	99.1
	-5.48	0.73	-8.04	0.28	-5.19	0.47	42.31	0.96	0.08	0.24	0.17	56.22	0.34	bdl	0.08	100.4	99.1
	-6.23	0.59	-9.17	0.26	-5.93	0.40	42.57	1.04	0.09	0.31	0.22	55.86	0.45	bdl	bdl	100.5	99.0
	-5.37	0.60	-7.90	0.30	-5.11	0.44	42.30	1.24	0.11	0.24	0.23	55.87	0.52	0.07	bdl	100.6	98.8
	-		-														
Ch-2	13.22	0.78	16.04	0.47	-9.17	0.62	42.19	1.01	0.04	0.11	0.18	56.00	0.53	0.05	bdl	100.1	99.0
	-6.59	0.62	-9.33	0.40	-5.90	0.52	42.36	0.89	0.13	0.14	0.12	56.34	0.21	0.07	bdl	100.3	99.1
	-4.53	0.66	-7.26	0.39	-4.90	0.52	42.48	0.95	0.11	0.26	0.15	55.78	0.39	bdl	bdl	100.1	99.1
	-5.73	0.67	-8.01	0.37	-5.04	0.51	42.39	1.21	0.13	0.37	0.11	56.04	0.45	bdl	bdl	100.7	98.8
	-6.21	0.58	-9.18	0.31	-5.95	0.43	42.31	0.96	0.21	0.18	0.07	56.17	0.57	0.09	bdl	100.6	99.1
	-6.70	0.65	-9.25	0.32	-5.77	0.46	42.15	0.86	0.05	0.25	0.26	56.07	0.42	bdl	bdl	100.1	99.1
Ch-3	-7.47	0.67	-9.90	0.35	-6.01	0.49	42.51	0.67	0.04	0.27	0.14	56.12	0.26	bdl	bdl	100.0	99.3
	-6.20	0.57	-9.08	0.33	-5.86	0.45	42.36	0.77	0.06	0.16	0.09	55.72	0.40	bdl	bdl	99.6	99.2
	-		-														
	-7.02	0.50	10.06	0.40	-6.41	0.48	42.48	1.11	0.12	0.21	0.19	56.49	0.39	bdl	0.10	101.1	98.9
	-7.34	0.49	-9.57	0.27	-5.75	0.37	42.67	1.14	0.04	0.38	0.14	55.34	0.17	bdl	bdl	99.9	98.9
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	-8.43	0.51	11.35	0.26	-6.96	0.37	42.38	1.36	0.04	0.41	0.10	56.04	0.48	bdl	bdl	100.8	98.7
	-6.74	0.71	-9.41	0.28	-5.90	0.46	42.22	0.94	0.07	0.16	0.21	56.11	0.51	bdl	bdl	100.2	99.1
	-6.31	0.65	-9.13	0.38	-5.85	0.51	42.36	0.73	0.06	0.24	0.20	56.30	0.42	0.06	bdl	100.4	99.3
	-		-														
IOG-1	-9.16	0.49	11.85	0.28	-7.09	0.38	42.20	0.67	0.11	0.27	0.14	55.88	0.39	bdl	bdl	99.7	99.3
IOG-2	-6.86	0.53	-9.37	0.33	-5.80	0.43	42.33	1.14	0.13	0.22	0.31	55.97	0.62	bdl	bdl	100.7	98.9

	-6.85	0.52	-9.20	0.37	-5.64	0.46	42.55	1.07	0.08	0.22	0.28	56.07	0.28	bdl	bdl	100.6	98.9
	-6.95	0.51	-9.64	0.29	-6.03	0.39	42.41	1.18	0.09	0.38	0.14	56.23	0.37	bdl	bdl	100.8	98.8
IOG-3	-1.53	0.67	-4.01	0.25	-3.22	0.42	42.74	0.94	0.11	0.31	0.08	56.03	0.39	bdl	bdl	100.6	99.1
	-2.43	0.49	-5.50	0.33	-4.24	0.41	42.39	0.93	0.16	0.28	0.16	56.24	0.42	0.08	bdl	100.7	99.1
	-3.77	0.43	-6.69	0.25	-4.73	0.34	42.47	1.01	0.23	0.17	0.17	56.08	0.35	bdl	bdl	100.5	99.0

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**Table S1:** Oxygen isotopic compositions and chemical compositions of chondrule and isolated olivine grains in Tarda

lab.		Tarda	
		Tarda 1 CRPG	2 IUEM
SiO <sub>2</sub>	wt%	27.09	
TiO <sub>2</sub>	wt%	0.098	0.133
Al <sub>2</sub> O <sub>3</sub>	wt%	2.084	
FeO	wt%	26.34	
MnO	wt%	0.228	0.206
MgO	wt%	18.89	
CaO	wt%	1.81	1.87
Na <sub>2</sub> O	wt%	0.60	
K <sub>2</sub> O	wt%	0.08	0.075
P <sub>2</sub> O <sub>5</sub>	wt%	0.23	0.219
L.O.I.	wt%	17.5	
Be	µg/g	n.d.	0.101
Sc	µg/g	7.84	7.79
V	µg/g	58.25	84.40
Cr	µg/g	3283	n.d.
Co	µg/g	539	504
Ni	µg/g	11648	n.d.
Cu	µg/g	117	104
Zn	µg/g	217	197
Ga	µg/g	8.31	7.37
Ge	µg/g	25.91	n.d.
As	µg/g	3.90	n.d.
Rb	µg/g	1.78	1.91
Sr	µg/g	8.38	27.28
Y	µg/g	1.86	2.58
Zr	µg/g	7.2	8.14
Nb	µg/g	0.357	0.831
Mo	µg/g	1.89	n.d.
Sb	µg/g	0.37	n.d.
Sn	µg/g	1.17	n.d.
Cs	µg/g	0.145	0.145
Ba	µg/g	n.d.	91.64
La	µg/g	0.3541	0.910
Ce	µg/g	0.8362	2.87
Pr	µg/g	0.1494	0.687
Nd	µg/g	0.7512	3.58
Sm	µg/g	0.1888	0.309
Eu	µg/g	0.0725	0.0927
Gd	µg/g	0.2614	0.363
Tb	µg/g	0.0454	0.0669

Dy	μg/g	0.3305	0.600
Ho	μg/g	0.0738	0.0898
Er	μg/g	0.2135	0.259
Tm	μg/g	0.0319	0.0395
Yb	μg/g	0.2075	0.248
Lu	μg/g	0.0331	0.0363
Hf	μg/g	0.171	0.197
Ta	μg/g	0.0245	0.0369
W	μg/g	n.d.	0.52
Pb	μg/g	2.16	10.03
Bi	μg/g	0.09	n.d.
Th	μg/g	0.0581	0.215
U	μg/g	n.d.	0.0613

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Table S2: REE and bulk trace element patterns of Tarda normalized to the average composition of Orgueil. They have been measured in two different laboratories (CRPG and IUEM).

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