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**Title:**

**Oxygen isotopic and chemical composition of chromites in micrometeorites: Evidence of ordinary chondrite precursors**

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**(MAPS)**

29 **Abstract**

30 We identified 66 chromite grains from 42 of ~5000 micrometeorites collected from Indian  
31 Ocean deep-sea sediments and the South Pole water well. To determine the chromite grains  
32 precursors and their contribution to the micrometeorite flux, we combined quantitative  
33 electron microprobe analyses and oxygen isotopic analyses by high-resolution secondary ion  
34 mass spectrometry. Micrometeorite chromite grains show variable O isotopic compositions  
35 with  $\delta^{18}\text{O}$  values ranging from  $-0.8$  to  $6.0\text{‰}$ ,  $\delta^{17}\text{O}$  values from  $0.3$  to  $3.6\text{‰}$ , and  $\Delta^{17}\text{O}$  values  
36 from  $-0.9$  to  $1.6\text{‰}$ , **seems majority of them are** similar to those of chromites from ordinary  
37 chondrites. **The oxygen isotopic compositions of olivine as a proxy to the chromite in**  
38 **chromite-bearing micrometeorites where we could not measure chromite** have  $\Delta^{17}\text{O}$  values  
39 **suggesting largely related to** ordinary chondritic **with some having carbonaceous**  
40 **chondrite precursors.** Furthermore, the chemical compositions of chromites in  
41 micrometeorites are close to those reported for ordinary chondrite chromites, **but some**  
42 **contribution from carbonaceous chondrites cannot be ruled out.** Consequently,  
43 carbonaceous chondrites cannot be a major contributor of chromite-bearing micrometeorites.  
44 Based on their oxygen isotopic and **elemental** compositions, we thus conclude with no  
45 ambiguity that chromite-bearing micrometeorites are **largely related to** fragments of  
46 ordinary chondrites **with small fraction from carbonaceous chondrites**, unlike other  
47 micrometeorites deriving **largely** from carbonaceous chondrites.

48

## 49 **1. Introduction**

50

51 The Earth's upper atmosphere accretes nearly 30,000 tons of **extraterrestrial** dust  
52 particles (from tens of micrometers to a few millimeters in size) every year: these particles  
53 are sourced either from collisions between asteroidal bodies or trails of cometary bodies  
54 during perihelion passage (Brownlee 2001). Most (~90%) of these micrometeorites are  
55 ablated during atmospheric entry, and only a small percentage reach the Earth's surface  
56 intact. They are collected from various environments such as deep-sea sediments (**DSS**),  
57 Antarctic ice, or in the **stratosphere** during entry and provide information on the varied  
58 objects that existed in the early solar system (Love and Brownlee 1993; Taylor et al. 1998;  
59 Peucker-Ehrenbrink and Ravizza 2000; Plane 2012; Prasad et al. 2013).

60

61 Ordinary chondrites are the most abundant meteorites, accounting for ~80% of all  
62 falls (Hutchison, 2004); of those falls, L and H chondrites dominate (~45% each) and ~10%  
63 are LL chondrites (Schmitz and Tassinari 2001). This subdivision may preferentially  
64 represent the ordinary chondrite component in the inner region of the asteroid belt, where  
65 meteorites break down more easily during collisional processes (Meibom and Clark 1999).  
66 However, micrometeorites are sourced to a large extent from bodies analogous to  
67 carbonaceous chondrites (>70–90%) and probably sample a more diverse population of  
68 carbonaceous-type asteroids than represented by meteorites (Love and Brownlee 1993;  
69 Beckerling and Bischoff 1995; Brownlee et al. 1997; Yada et al. 2005; Rudraswami et al.  
70 2015a). In addition, a few to ~30% of micrometeorites have asteroidal precursors related to  
71 ordinary chondrites, ~1–2% to iron meteorites, and fewer than a percent to HED bodies  
72 (Taylor et al. 2007; Suavet et al. 2010; Rudraswami et al. 2015a, b, 2016b).

73

74           The chemical compositions of micrometeorites are modified during atmospheric  
75 entry, complicating the identification of their precursors based solely on chemical  
76 composition. Since **oxygen diffuses** slower than **cations** (Ryerson et al. 1989), the oxygen  
77 isotopic characteristics of micrometeorites should be better preserved and thus represent a  
78 powerful tool for deciphering micrometeorite origins. For instance, oxygen isotopic  
79 investigations have indicated the contribution of ordinary chondrites (or precursors analogous  
80 to ordinary chondrites) to be only a few percent for micrometeorites sized 100–300  $\mu\text{m}$   
81 (Rudraswami et al. 2015b, 2016a), but ~30% for larger micrometeorites (~600–1000  $\mu\text{m}$ ). It  
82 should be noted, however, that this size range comprises much less than 1% of the total  
83 micrometeorite flux by mass (Suavet et al. 2010).

84

85           Chromite is a refractory, high-temperature mineral that is robust to acid treatments  
86 and weathering (Schmitz et al. 2001, 2003; Schmitz and Haggström 2006), and spherical to  
87 euhedral chromite grains tens of micrometers in size are largely found in ordinary chondrites.  
88 Based on their oxygen isotopic and chemical compositions, it has been proposed that  
89 micrometeorite chromites could have largely survived parent-body collisional events,  
90 frictional heating during atmospheric entry, and subsequent terrestrial alteration. However,  
91 chromite is rarely found in micrometeorites, and earlier studies reported only about a dozen  
92 chromite grains among ~500 spherules analyzed, which were conceivably linked to L/H  
93 chondrites (Van Ginneken et al. 2012; Prasad et al. 2015). The rarity of chromite grains  
94 characterized in micrometeorites limits the information we can obtain on their chemical and  
95 isotopic characteristics, and thus the micrometeorite sources in the asteroid belt. Here we  
96 determine the chemical and oxygen isotopic compositions of a suite of micrometeorite  
97 chromites from DSS and Antarctic ice, and compare their  $\Delta^{17}\text{O}$  values with those of ordinary  
98 chondrites to assess and distinguish the nature of micrometeorite precursors.

99

## 100 **2. Sampling method**

101

102 Micrometeorites were collected from Indian Ocean **DSS** and Antarctica.  
103 Micrometeorites from Indian Ocean DSS (74–76° E, 10–13° S) were collected using a grab  
104 sampler measuring 50 cm long × 50 cm wide × 15 cm deep with the capacity to lift 45 kg of  
105 sediments from the seafloor depth of ~5000 m (Rudraswami et al. 2011, 2012; Prasad et al.  
106 2013). Retrieved sediments were sieved using a ~200 µm mesh, and further dried and  
107 magnetically separated. The estimated terrestrial age of cosmic spherules from DSS at 0–15  
108 cm depth based on the peak tektite abundance from three sediment cores is ~0–50,000 a  
109 (Prasad et al. 2013). Antarctic micrometeorites were collected from the South Pole water well  
110 that supplies water to the Amundsen-Scott South Pole Station. The **24 m diameter** well is  
111 situated at ~100 m below the surface, contains ~5000 m<sup>3</sup> of melt water, and extends to 16 m  
112 depth below the well opening (Taylor et al. 1998, 2000). Particles from the well bottom were  
113 suctioned by a sample collector and sieved to various size fractions >50 µm. A binocular  
114 microscope was used to pick and mount samples in epoxy for analyses. Antarctic and DSS  
115 micrometeorites were mounted on 2 and 16 epoxy mounts, respectively, and polished to  
116 expose their surface diametrically. The sections were cleaned using alcohol and distilled  
117 water in an ultrasonic bath, then dried. Each section was carbon coated for observation under  
118 a scanning electron microscope (SEM) to identify chromites before chemical and isotopic  
119 characterization by electron and ion microprobe, respectively.

120

## 121 **3. Analytical techniques**

### 122 **3.1. Electron microscopy and microprobe analyses**

123

124 SEM and microprobe analyses were performed at the National Institute of  
125 Oceanography (Goa, India). A JEOL JSM-IT300LV SEM equipped with an energy  
126 dispersive spectrometer (AZtecEnergy EDS Microanalysis, Oxford instruments) was used to  
127 identify chromites in the micrometeorites and obtain back-scattered electron images.  
128 Chromite-bearing micrometeorites were further analyzed using a Cameca SX5 Electron  
129 Micro Probe Analyzer equipped with four spectrometers. Microprobe analyses were  
130 performed with ~15 kV accelerating voltage, ~12 nA beam current, and ~1–2  $\mu\text{m}$  beam  
131 diameter. The PAP model was used for matrix corrections (Pouchou and Pichoir 1991).  
132 Multiple analyses were performed on each spherule containing different mineral phases to  
133 obtain bulk chemical compositions by calculating the exposed area of different mineral  
134 phases in ImageJ or LISPIX. We note that the reported bulk compositions do not account for  
135 density differences among phases. For scoriaceous, barred, cryptocrystalline, or glassy  
136 micrometeorites, several analyses were performed using a ~5  $\mu\text{m}$  beam diameter and  
137 averaged to obtain the bulk chemical composition; the beam size was restricted to 5  $\mu\text{m}$  to  
138 avoid void spaces, vesicles, and pits. To improve the accuracy and statistical error on minor  
139 element measurements (Ca, V, Mn, Ti, Zn), analyses were performed with long counting  
140 times of 60 s on peak and 20 s on background. Replicate measurements of multiple standards  
141 were within 1% error for major elements and within a few percent for minor elements.  
142 Multiple analyses were performed at different spots in each chromite grain to constrain their  
143 chemical heterogeneity.

144

### 145 **3.2. Oxygen isotopic analyses**

146

147 Oxygen isotopic analyses of micrometeorite olivine (here representing the  
148 micrometeorite composition) and chromite phases were performed using a Cameca 1270 E7

149 at CRPG-CNRS (Nancy, France) using a Cs<sup>+</sup> beam with ~1 nA primary current and ~5 μm  
150 beam spot on the sample surface. We used a mass resolving power of ~2500 for <sup>16</sup>O and <sup>18</sup>O  
151 and ~7000 for <sup>17</sup>O to avoid <sup>16</sup>OH<sup>-</sup> interference in the <sup>17</sup>O peak. Secondary <sup>16</sup>O and <sup>18</sup>O ions  
152 were measured using a faraday cup while <sup>17</sup>O was measured using the electron multiplier in  
153 multi-collection mode. We corrected for instrumental mass fractionation in olivine grains  
154 using San Carlos olivine. Stillwater chromite (Schmitz et al., 2016) and UWCr-3 chromite  
155 standards were used to check the stability and reproducibility of the isotopic data (Heck et al.  
156 2010), and the Stillwater chromite was used as a running standard for unknown chromite  
157 grains. Typical count rates obtained on the Stillwater chromite standard were ~5 × 10<sup>8</sup> cps for  
158 <sup>16</sup>O, ~2 × 10<sup>5</sup> cps for <sup>17</sup>O, and ~1 × 10<sup>6</sup> cps for <sup>18</sup>O. Typical errors (2σ), accounting for  
159 measurement errors and the external reproducibility of the standard, are estimated to be  
160 ~0.7‰ for δ<sup>18</sup>O, ~0.6‰ for δ<sup>17</sup>O, and ~0.8‰ for Δ<sup>17</sup>O (= δ<sup>17</sup>O – 0.52 × δ<sup>18</sup>O, representing  
161 deviation from the terrestrial fractional line). All analytical spots were checked under SEM,  
162 and any that fell on cracks or grain boundaries were excluded.

163

#### 164 **4. Results**

165

166 **We examined ~3500 DSS micrometeorites and ~1500 Antarctic micrometeorites**  
167 **to identify chromite-bearing micrometeorites for further understanding the chemical**  
168 **and isotopic characteristics of these particles.** We found 46 chromites in 30 DSS  
169 micrometeorites and 20 chromites in 12 Antarctic micrometeorites; the chemical  
170 compositions and sizes of these chromites are reported in Table 1. Chromite grains varied  
171 from round to euhedral (Figs. 1 and 2). Most of the chromite-bearing micrometeorites  
172 displayed barred, cryptocrystalline, glass, or porphyritic type textures (Figs. 1 and 2). Only  
173 two chromite grains were observed in partially melted scoriaceous particles, and their small



174 **sizes** made their isotopic characterization challenging. Some chromites may have been  
175 altered, as their Si, Mg, Al, and Fe contents were slightly modified due to heating during  
176 atmospheric entry, but nonetheless seem to largely retain their elemental compositions. Fig. 3  
177 shows the **sizes** (maximum length) of chromite grains relative to **their major axes** of their  
178 host micrometeorites as well as the distribution of chromite grain sizes. Most chromites are  
179 **between ~5 and 100  $\mu\text{m}$**  in their maximum dimension, though some altered chromites are  
180 smaller, between a few and  $<10 \mu\text{m}$  (Fig. 2).

181

182 We selected 18 micrometeorites for oxygen isotopic analyses of chromite and olivine  
183 grains. In nine micrometeorites larger than  $20 \mu\text{m}$ , we analyzed the oxygen isotopic  
184 compositions of olivines and 17 chromites (Table 2); in the other nine, chromites were too  
185 small to analyze, so we measured the oxygen isotopic compositions of olivines only. The  
186  $\delta^{18}\text{O}$  and  $\delta^{17}\text{O}$  values of chromite grains range from  $-0.8$  to  $6.0\text{‰}$  and from  $0.3$  to  $3.6\text{‰}$ ,  
187 respectively, corresponding to  $\Delta^{17}\text{O}$  values of  $-0.9$  to  $1.6\text{‰}$  (Figs. 4–6). Micrometeorite  
188 olivines have the same limited range of  $\Delta^{17}\text{O}$  values, except **for a few that fall near**  
189 **carbonaceous chondrite**. The  $\Delta^{17}\text{O}$  values reported for micrometeorite olivines and  
190 chromites in Figs. 5 and 6 are averaged per micrometeorite, assuming that individual  
191 micrometeorites document a single precursor.

192

## 193 **5. Discussion**

194

195 Chromites in micrometeorites provide powerful constraints on heating during  
196 atmospheric entry and micrometeorite precursors. The mere presence of chromite is  
197 insufficient to distinguish between the different types of **chondrites** or metamorphic grades  
198 (Bunch et al. 1967; Johnson and Prinz 1991), though chromites can be used to validate

199 analogous micrometeorite precursors. For example, Prasad et al. (2015) used **chemical**  
200 **composition as analytical tool for the chromites in micrometeorites** to show that four of  
201 seven micrometeorites were related to L3–6 chondrites, and the remaining three to a  
202 combination of L/H-type chondrites. However, such a small number of chromite grains is not  
203 statistically robust enough to conclusively identify their **sources**. Here, we broaden the  
204 statistics from the different sampling sites (**DSS** and Antarctic ice), and include  
205 micrometeorites of a larger size range (50–500  $\mu\text{m}$ ) that arrived on Earth during the past  
206 ~50,000 years (Taylor et al. 1998; Prasad et al. 2015). Our detailed investigation of the  
207 oxygen isotopic compositions and **physical** and chemical properties of chromites will  
208 improve our understanding of the parent bodies of chromite-bearing micrometeorites and  
209 their contributions to the micrometeorite flux.

210

## 211 **5.1 Origin of chromite-bearing micrometeorites**

212

213 Chromite size **has not shown any great trend with respect to micrometeorite size,**  
214 **however, it seems to be** negatively correlated to chromite abundance; i.e., the chromite  
215 grains observed herein range in size from 4 to 153  $\mu\text{m}$ , but are largely dominated by ~5–50  
216  $\mu\text{m}$  grains from micrometeorites ~50–500  $\mu\text{m}$  in size (Fig. 3). Chromites are present in  
217 carbonaceous chondrites, but are typically smaller than those in ordinary chondrites (Johnson  
218 and Prinz, 1991). In L-type chondrites, chromite sizes vary according to the different  
219 metamorphic grades (L3, ~10–50  $\mu\text{m}$ ; L4, ~18–150  $\mu\text{m}$ ; L5, ~25–160  $\mu\text{m}$ ; and L6, ~30–600  
220  $\mu\text{m}$ ; Bridges et al. 2007), and the **sizes** of the largest chromite grains observed **increase** with  
221 increasing petrographic grade. Based on these size distributions, our results suggest that the  
222 chromite-bearing micrometeorites reported herein could derive from ordinary chondrites.  
223 However, chromite size alone is not diagnostic of chondrite type or metamorphic grade, and

224 these results must be coupled with the chemical and O isotopic compositions of chromites to  
225 convincingly relate them to specific chondrite types.

226

227 Chromite is the most abundant spinel group mineral in ordinary chondrites (up to 0.6  
228 wt%; Keil 1962) and the least abundant in carbonaceous chondrites (<0.01 wt%; Riebe  
229 2009). **In addition, chromites in ordinary chondrites have more varied chemical**  
230 **compositions than those in carbonaceous chondrites, likely due to the increased thermal**  
231 **metamorphism of ordinary chondrite parent bodies compared to carbonaceous ones.**  
232 The concentrations of **minor oxide** such as TiO<sub>2</sub>, MnO, Cr<sub>2</sub>O<sub>3</sub>, V<sub>2</sub>O<sub>5</sub>, or ZnO are therefore  
233 powerful tools for ascertaining the chondritic provenance of chromites, although chemical  
234 overlaps are observed. Chromites in H chondrites have very restricted TiO<sub>2</sub> contents ranging  
235 from ~1.5 to 3.0 wt%, LL chondrites have higher TiO<sub>2</sub> contents of ~2.5–4.5 wt%, and L  
236 chondrites show the widest range, from 0.5 to 3.5 wt% TiO<sub>2</sub> (Fig. 7). In general, the average  
237 TiO<sub>2</sub> content of equilibrated grains increases from H to L to LL chondrites. The least  
238 metamorphosed L3 chondrites have chromites with <2 wt% TiO<sub>2</sub>, similar to the much smaller  
239 chromites in carbonaceous chondrites (< 2 wt% TiO<sub>2</sub>; Fuchs et al. 1973; Johnson and Prinz,  
240 1991). Our data largely matches the range of chromite TiO<sub>2</sub> contents observed in ordinary  
241 chondrites, and to some extent that in carbonaceous chondrites.

242

243 Furthermore, chromites in ordinary **chondrites** are enriched in MnO (0.5–0.95 wt%)  
244 relative to those in carbonaceous chondrites (0.0–0.2 wt%; Bunch et al. 1967; Wlotzka 2005).  
245 Among ordinary chondrites, chromites in H chondrites are Mn-enriched (~0.9 wt%) relative  
246 to those in L (~0.7 wt%) and LL chondrites (~0.5 wt%; Bunch et al. 1967; Wlotzka 2005).  
247 Our results show that micrometeorite chromites are relatively rich in **MnO** (0.03–0.63 wt%,  
248 averaging  $0.32 \pm 0.16$  wt% MnO; Table 1, Fig. 8), suggesting that micrometeorites could

249 have derived from ordinary **with some from** carbonaceous chondrites. **Most of the data in**  
250 **Fig. 8 fall have shown a spread in data making difficult to assert the precursor. Apart**  
251 **from this, the diffusion of the minor element that has taken place during entry makes**  
252 **the matter worse to identify the precursor.** This is supported by (i)  $V_2O_3$  vs.  $Cr_2O_3$ , MnO,  
253 and  $TiO_2$  plots indicate a larger fraction of micrometeorite chromite grains plot in the area of  
254 ordinary chondrite chromites **with relatively small fraction in the carbonaceous chondrite**  
255 **range** (Fig. 8), and (ii) micrometeorite chromite ZnO concentrations up to 0.3 wt%, beyond  
256 the range of the systematically Zn-poor carbonaceous chondrite chromites (<0.1 wt% ZnO;  
257 Fuchs et al. 1973; Brearley and Jones 1998).

258

259 The oxygen isotopic compositions of micrometeorite chromites **allow** determination  
260 of the contribution of chromite-bearing **extraterrestrial** material to the Earth's surface. **The**  
261 **ordinary and enstatite chondrite have  $\Delta^{17}O$  lying between 0.1 and 1.5‰, while the**  
262 **carbonaceous chondrite have wider range with  $\Delta^{17}O < 0‰$ , for e.g. CV chondrite having -5 to -**  
263 **1‰, CO and CK having -5 to -4‰, CR having -2 to -1‰, CM having -4 to -1‰, respectively**  
264 **(Clayton et al., 1991, 1999)** Our results show that micrometeorite chromites have  $^{16}O$ -poor  
265 isotopic compositions similar to those measured in ordinary chondrites (Table 2; Clayton et  
266 al. 1991; Greenwood et al. 2007). One of our micrometeorites (SP005-P219) has a chromite  
267 grain with a slightly  $^{16}O$ -rich composition ( $\Delta^{17}O$  values ranging from -0.3 to -0.9‰), and  
268 thus probably derives from a carbonaceous chondrite (Table 2). Excluding this  
269 micrometeorite, **all other chromite grains observed seems to originate predominately**  
270 **with oxygen isotopic compositions** very similar to those of chromites in ordinary chondrites.  
271 **It may be difficult based on the oxygen isotope studies of chromites to narrow on**  
272 **specific population of ordinary chondrite.** Nevertheless, our results indicate that chromites

273 are dominantly related to ordinary chondrites, and that the contribution from carbonaceous  
274 chondrites is small (Figs. 4–6).

275

276 The O isotopic compositions of olivines in micrometeorites with chromite grains too  
277 small for ion microprobe analyses **indicate that most of the micrometeorites have**  
278 **ordinary chondrite compositions, while about six have shown  $\Delta^{17}\text{O} < 0$  (Fig. 6). The**  
279 **negative  $\Delta^{17}\text{O}$  values for these chromite-bearing micrometeorites point toward**  
280 **mainstream contribution from ordinary chondrite with some from carbonaceous**  
281 **chondrites.** Many of the micrometeorites have undergone alteration during atmospheric  
282 entry, as attested by their high  $\delta^{17,18}\text{O}$  values that result from exchange **with the**  
283 **stratospheric oxygen isotope composition of  $\delta^{18}\text{O} = 23.5\text{‰}$ , and  $\delta^{17}\text{O} = 11.8\text{‰}$  (Thiemens et al.,**  
284 **1995; Engrand et al. 2005; Yada et al. 2005; Suavet et al. 2010; Cordier et al. 2011;**  
285 **Rudraswami et al. 2015a, 2016a).** However, their  $\Delta^{17}\text{O}$  values are similar to those reported  
286 for chromite grains in ordinary chondrites, in contrast to many micrometeorites analyzed  
287 previously that were dominated by carbonaceous chondrite compositions (Clayton et al.  
288 1991; Engrand et al. 1999; Greenwood et al. 2007; Rudraswami et al. 2015a, 2016a).  
289 Excluding the **few** dataset that has shown us  $\Delta^{17}\text{O}$  in carbonaceous chondrite range, these  
290 results support the conclusion that chromite grains have O-isotopic compositions similar to  
291 ordinary chondrites. Though oxygen isotopic exchange between chromite-bearing  
292 micrometeorites and the atmosphere during entry resulted in  $\delta^{17,18}\text{O}$  values shifted towards  
293 atmospheric values in many olivine grains, the O isotopic compositions of chromite grains  
294 indicate that they are resistive and retain their precursor, i.e., ordinary chondritic,  
295 composition (Figs. 4–6).

296

## 297 **5.2 Implications for asteroid belt dynamics**

298

299           The chemical and mineralogical compositions of interplanetary dust particles and  
300 micrometeorites show strong similarities to those of carbonaceous chondrites, unlike  
301 meteorites that are dominated by ordinary chondrites (Brownlee et al. 1997; Rietmeijer 1998;  
302 Schmitz and Tassinari 2001). This discrepancy may be due to the dominance of ordinary  
303 chondrite bodies in the inner asteroid belt, where slight planetary perturbations can send  
304 larger asteroidal bodies into Earth resonant orbits, eventually reaching Earth as ordinary  
305 chondrite meteorites (Meibom and Clark 1999). This is not the case with micrometeorites;  
306 small dust particles generated by collisions can arrive in Earth resonant orbits from any  
307 region of the asteroid belt. It thus appears that the diversity of planetary bodies present in the  
308 asteroid belt is better represented in the micrometeorite flux, which exceeds that of meteorites  
309 and is therefore more statistically significant.

310

311           Although our study clearly indicates a genetic link between ordinary chondrites and  
312 **many** chromite-bearing micrometeorites, the latter constitute only ~1% of micrometeorites  
313 collected from DSS and Antarctic ice. Antarctic micrometeorites have terrestrial ages of  
314 ~1000 a (Taylor et al. 1998), whereas micrometeorites in **DSS** are as old as ~50,000 a (Prasad  
315 et al. 2013). In these two time spans (**Taylor et al., 1998; Prasad et al., 2013**), the flux of  
316 chromite-bearing micrometeorites has remained almost constant and no major collision event  
317 has been reported in the recent past. The abundance of micrometeorites related to ordinary  
318 chondrites is probably underestimated due to the non-systematic presence of chromite grains  
319 in micrometeorites derived from ordinary chondrites. Nevertheless, it seems that ordinary  
320 chondrites are rare in the asteroid belt, which is rather dominated by carbonaceous bodies as  
321 reflected in the chemical and isotopic compositions of micrometeorites (Brownlee et al. 1997;  
322 Meibom and Clark 1999; Taylor et al. 2007; Genge et al. 2008; Suavet et al. 2010;

323 Rudraswami et al. 2012, 2014, 2015b, 2016b). This could be due to either (i) a population  
324 deprived of S-type asteroids in the asteroid belt or (ii) an under-representation of dust related  
325 to ordinary chondrites in Earth resonant orbits.

326

327         The predominance of micrometeorites derived from carbonaceous chondrites could  
328 also result from the large differences in the physical properties of carbonaceous and ordinary  
329 chondrites, such as tensile strength, density, and porosity. Tensile strength is a critical  
330 parameter controlling the dust sizes generated during collisions; the greater the tensile  
331 strength, the larger the collisional debris (Flynn et al. 1999; Consolmagno et al. 2008).  
332 Furthermore, the lower porosity of ordinary compared to carbonaceous chondrites would  
333 generate larger particles during asteroid breakup. Disruptive impact experiments performed  
334 on different chondrite types revealed that carbonaceous chondrites produce more fragments  
335 in the micrometeorite mass range than ordinary chondrites (Flynn et al. 2009). These results  
336 suggest that the physical properties of carbonaceous chondrites (i.e., high porosity, low  
337 density and tensile strength) induce fragmentation into dust-sized particles during asteroidal  
338 collisions (Consolmagno et al. 2008). This is consistent with the large contribution of  
339 micrometeorites from carbonaceous chondrites, whereas there is a disparity in the ordinary  
340 chondrite contribution that varies from a few percent for smaller sizes (<300  $\mu\text{m}$ ) to ~30% for  
341 larger sizes (>600  $\mu\text{m}$ ) (e.g., Suavet et al. 2010; Rudraswami et al. 2015b, 2016b). The  
342 porosity (10–17%) and density (3.0–3.2  $\text{g}/\text{cm}^3$ ) of the higher petrographic grade L chondrites  
343 (L5 and L6) are similar to those of carbonaceous chondrites such as CO3 and CV3, and the  
344 increased porosity (up to 23%) and decreased density (up to 2.6  $\text{g}/\text{cm}^3$ ) at lower petrographic  
345 grades are being listed as similar to those reported for many primitive carbonaceous  
346 chondrites (Flynn et al. 1999). H and LL chondrites, however, have porosities much lower  
347 than those of L5–6 or H5–6 chondrites, even at lower petrographic (e.g., LL3) grades (Flynn

348 et al. 1999). Overall, the high porosity and low density of L-type chondrites compared to  
349 other ordinary chondrites favor fragmentation into smaller dust particles during collisions,  
350 although our present dataset does not allow us to conclusively relate micrometeorites to a  
351 petrographic grade or type of ordinary chondrite.

352

## 353 **6. Conclusions**

354

355 In-situ oxygen isotopic analyses of chromite-bearing micrometeorites revealed that  
356 chromites in micrometeorites are indistinguishable from those in ordinary chondrites. The  
357  $\Delta^{17}\text{O}$  values of most chromite-bearing micrometeorites here and in the literature are similar to  
358 those of ordinary chondrites, indicating that chromite-bearing micrometeorites **are largely**  
359 **derived** from ordinary chondrites (~70%) with small contribution (~30%) from  
360 carbonaceous chondrites. Chromite chemical compositions support an ordinary chondrite  
361 provenance despite the chemical compositions of some chromites being altered during  
362 atmospheric entry, as reflected by compositions enriched in Si, Mg, Al, and Fe. The two time  
363 spans analyzed herein (the last ~1000 and ~50,000 years in **DSS** and Antarctic ice, respectively)  
364 suggest that the contribution of chromite-bearing micrometeorites related to ordinary  
365 chondrites in the size range ~50–500  $\mu\text{m}$  has remained consistent at ~1% of the total  
366 micrometeorite flux during the last 50,000 years. The low overall abundance of  
367 micrometeorites related to ordinary chondrites likely indicates a small contribution of  
368 ordinary chondrites to dust particles produced in the asteroid belt.

369

370



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372

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378

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## FIGURE CAPTIONS

529

530

### 531 **Figure 1.**

532 Representative back-scattered electron images of chromite-bearing micrometeorites collected  
533 from Indian Ocean **DSS** and the South Pole water well (SPWW). Chromites are circled in  
534 each image. The chemical compositions of chromites unaffected by atmospheric entry are  
535 given in Table 1.

536

### 537 **Figure 2.**

538 Enlarged back-scattered electron images of chromites in micrometeorites.

539

### 540 **Figure 3.**

541 (a) Chromite sizes as a function of their host relict micrometeorites. (b) The size distribution  
542 of chromites from micrometeorites analyzed in this study.

543

### 544 **Figure 4.**

545 The oxygen isotopic compositions of olivines (representing micrometeorites) and chromites  
546 in chromite-bearing micrometeorites. Data points represent individual analyses. **Most of**  
547 **them are depleted in  $^{16}\text{O}$  and have  $\Delta^{17}\text{O}$  values similar to those of ordinary chondrites.**  
548 The TF and Carbonaceous Chondrite Anhydrous Mineral (CCAM) lines are shown for  
549 reference. **The error bars of many of the data points are masked by the size of the data**  
550 **points themselves.**

551

### 552 **Figure 5.**

553  $\Delta^{17}\text{O}$  versus  $\delta^{18}\text{O}$  values of chromites in chromite-bearing micrometeorites. **Chromite**  
554 **compositions are averaged per micrometeorite depending on the number of oxygen**  
555 **isotope analyses which varies from two to three chromite per micrometeorite, however,**  
556 **there are few that only represent single analyses.** Most of the data fall in the ordinary  
557 chondrite range, as delimited by the range of  $\Delta^{17}\text{O}$  values of LL, L, and H chondrites (green,  
558 blue, and red lines, respectively).

559

560 **Figure 6**

561 The distribution of average  $\Delta^{17}\text{O}$  values of 18 chromite-bearing micrometeorites (gray).  
562 Chromites were large enough to analyze in nine of those micrometeorites (black), and the  
563 values shown are averaged per micrometeorite.

564

565 **Figure 7.**

566 The distribution of  $\text{TiO}_2$  contents in chromites from (a) micrometeorites studied herein and  
567 (b) different chondrite types (carbonaceous, L, LL, H). Data for chromites from ordinary  
568 chondrites are from Bunch et al. (1967), Snetsinger et al. (1967), Johnson and Prinz (1991),  
569 and Wlotzka (2005). Data for chromites from carbonaceous chondrites are from Fuchs et al.  
570 (1973) and Johnson and Prinz (1991).

571

572 **Figure 8.**

573 Elemental distributions of chromites from micrometeorites studied herein (red), carbonaceous  
574 chondrites (yellow) and ordinary (L, LL, and H) chondrites (gray diamonds, inverted  
575 triangles, and circles, respectively). Data for chromites from ordinary chondrites are from  
576 Bunch et al. (1967), Snetsinger et al. (1967), Johnson and Prinz (1991), and Wlotzka (2005).  
577 Data for chromites from carbonaceous chondrites are from Fuchs et al. (1973) and Johnson

578 and Prinz (1991). **The rectangle and oval outline represent the spread in data of chromite**  
579 **from ordinary and carbonaceous chondrites, respectively. In figs. a, c, d, f, the H**  
580 **chondrite has shown narrow spread which can be recognized and is marked with**  
581 **smaller rectangle with ordinary chondrite.**

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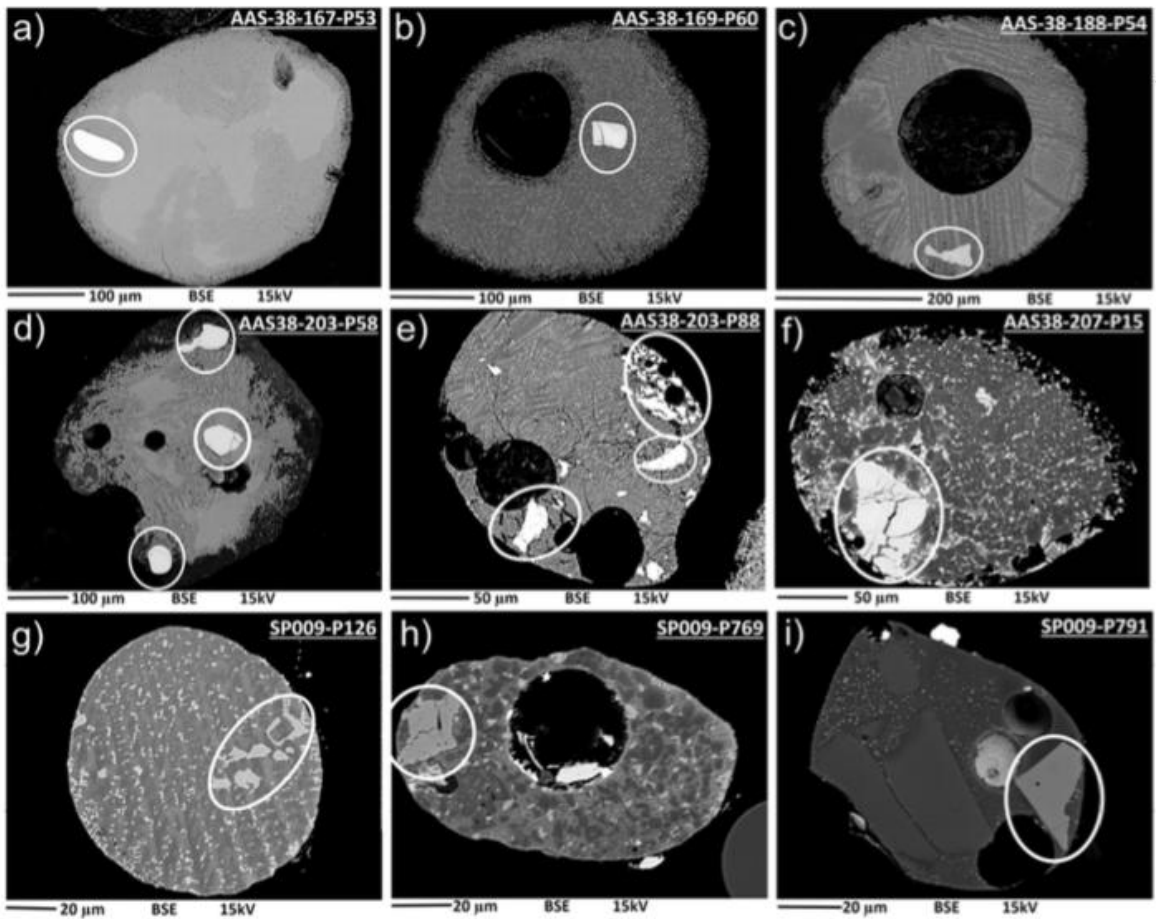
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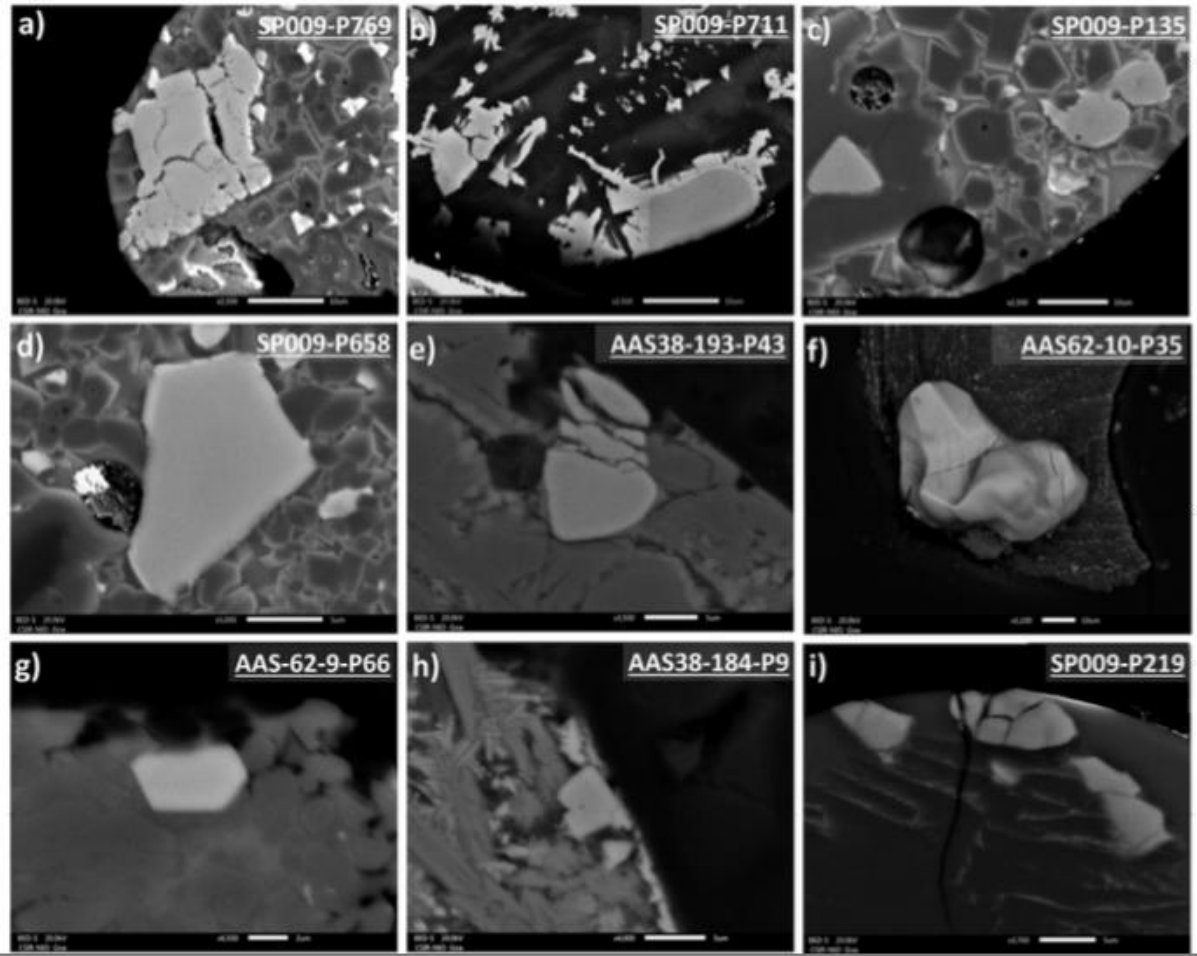
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592 Fig. 1

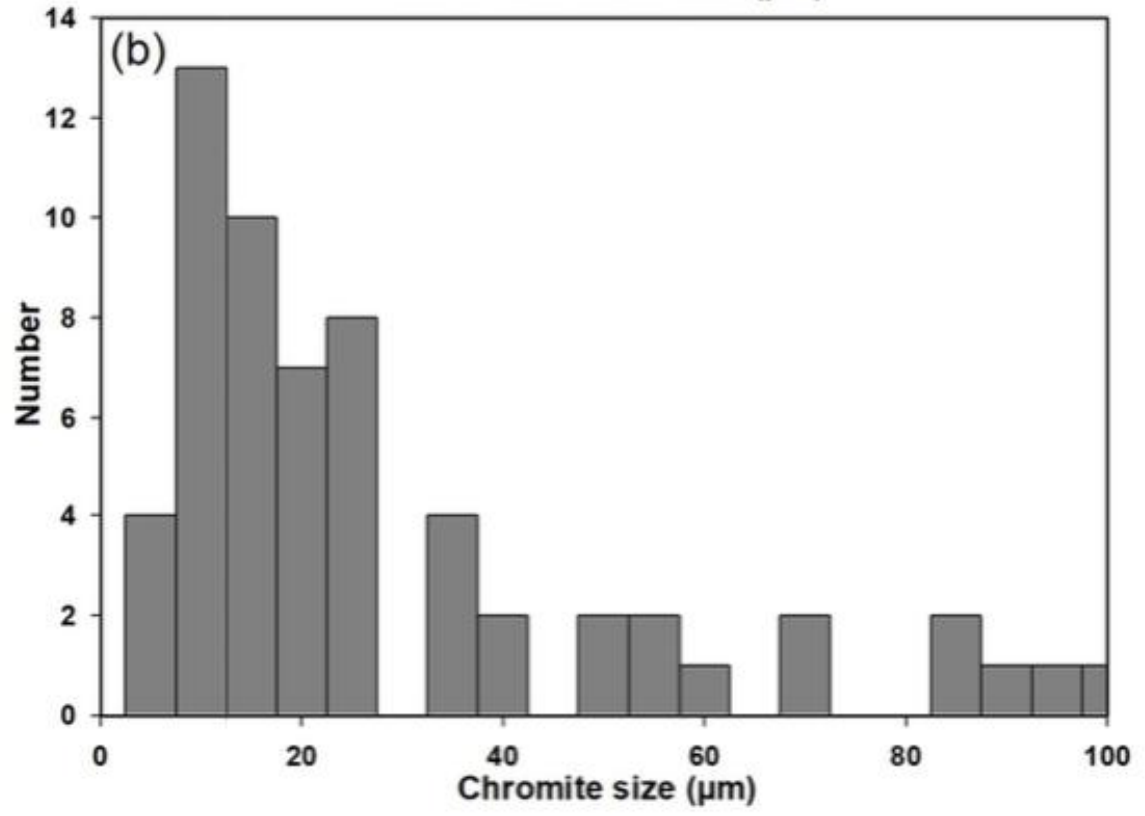
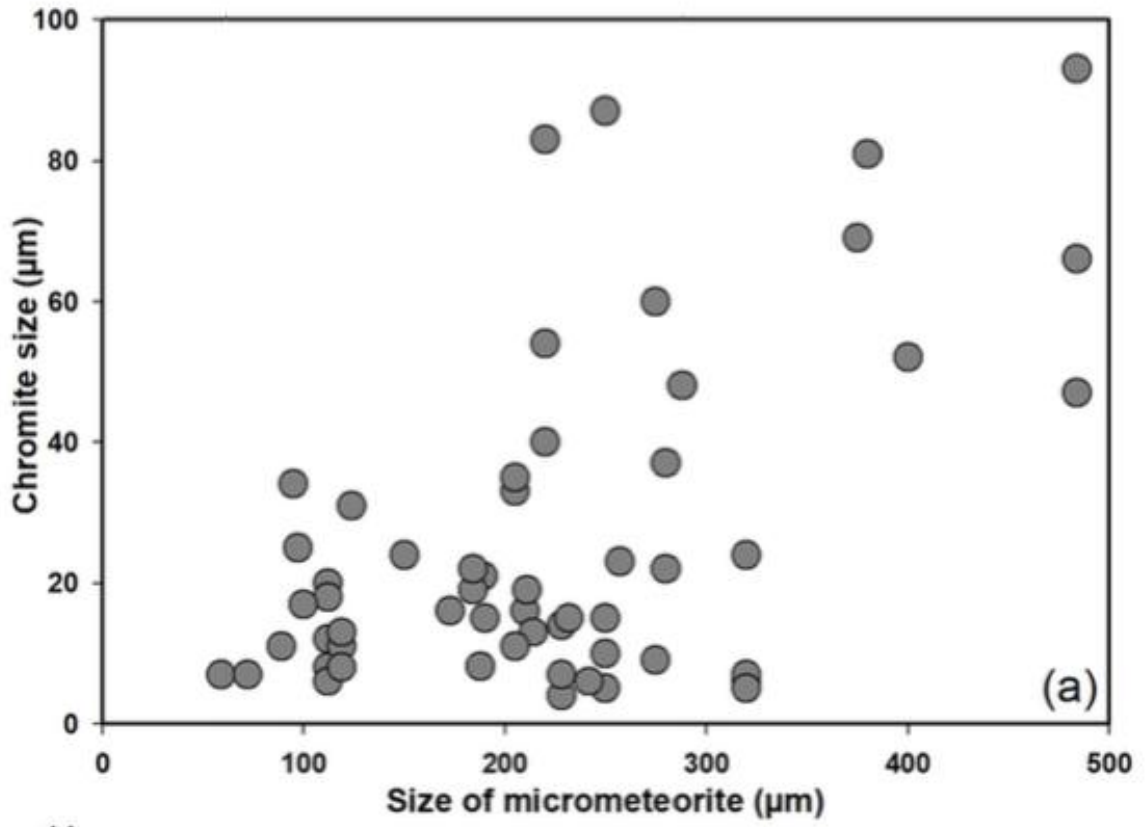
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595 Fig. 2

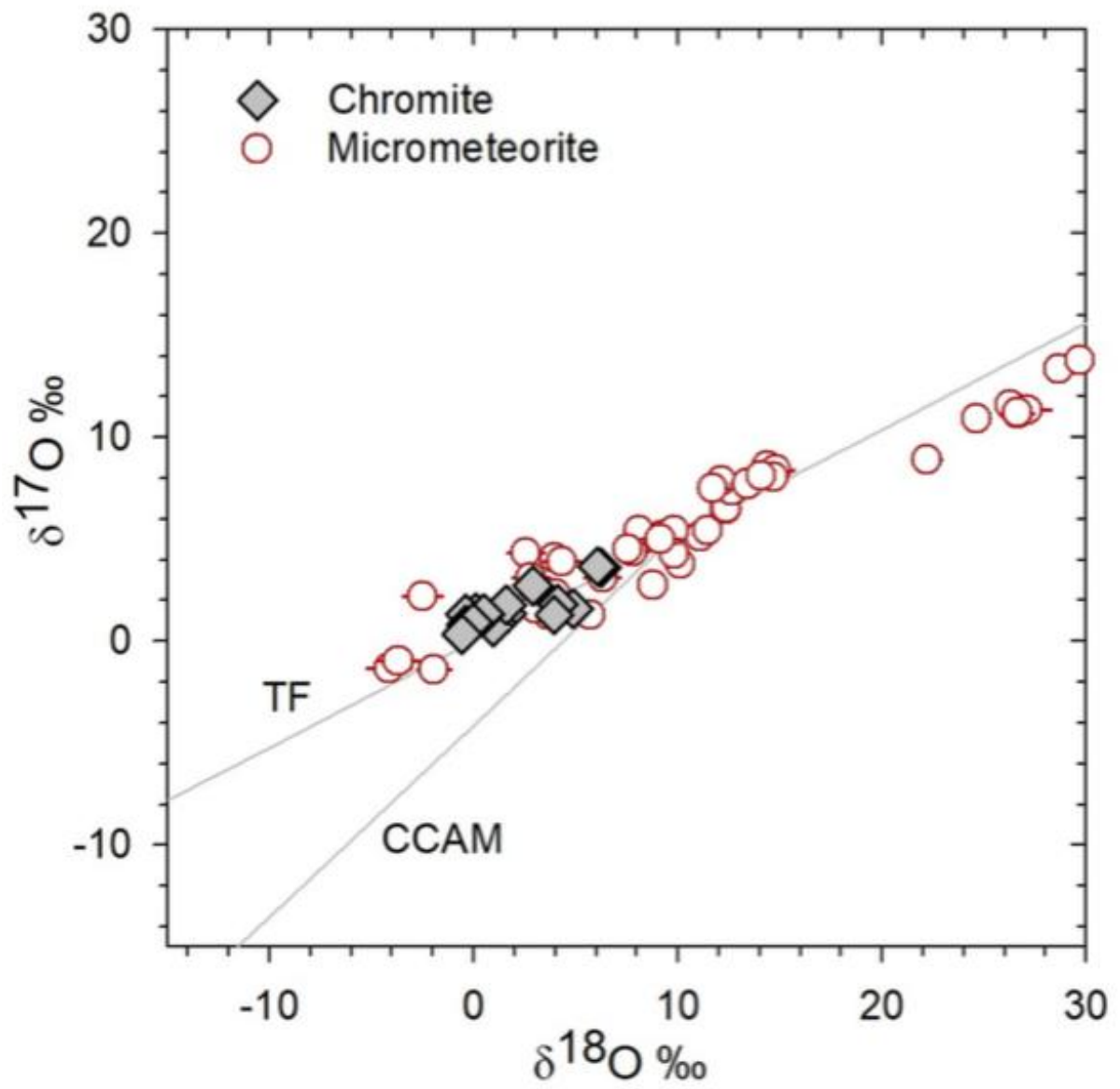
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598 Fig. 3

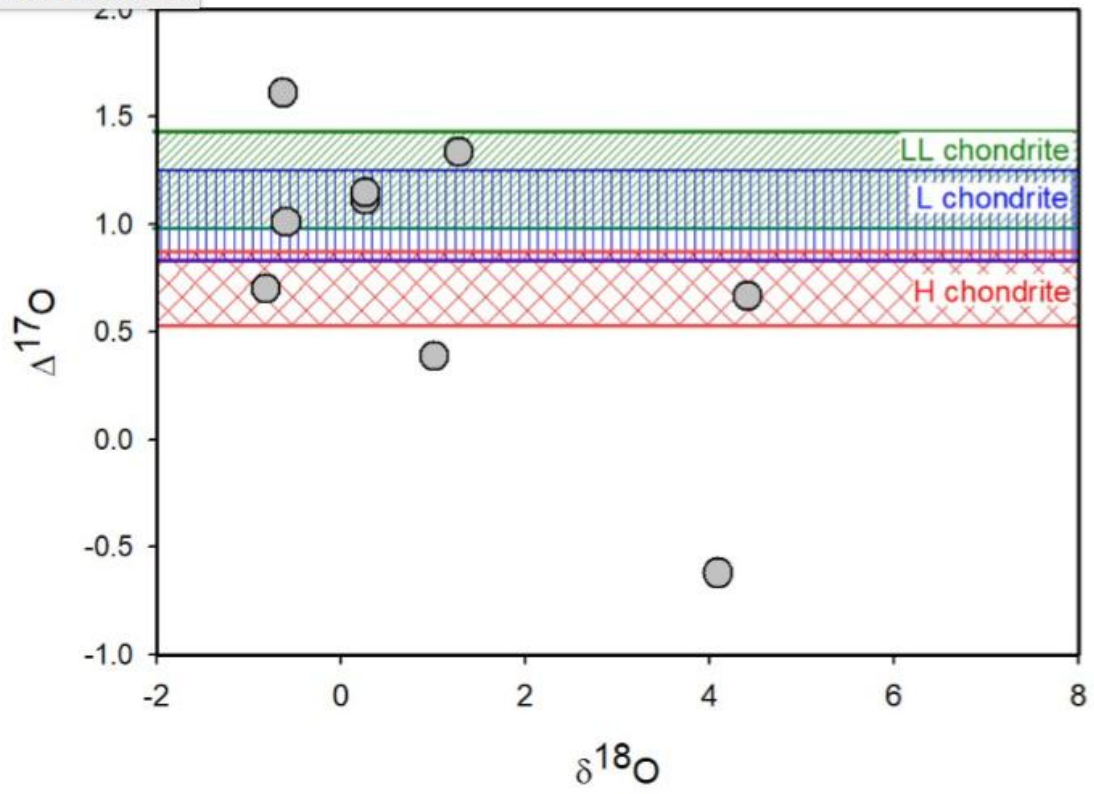
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601 Fig.4

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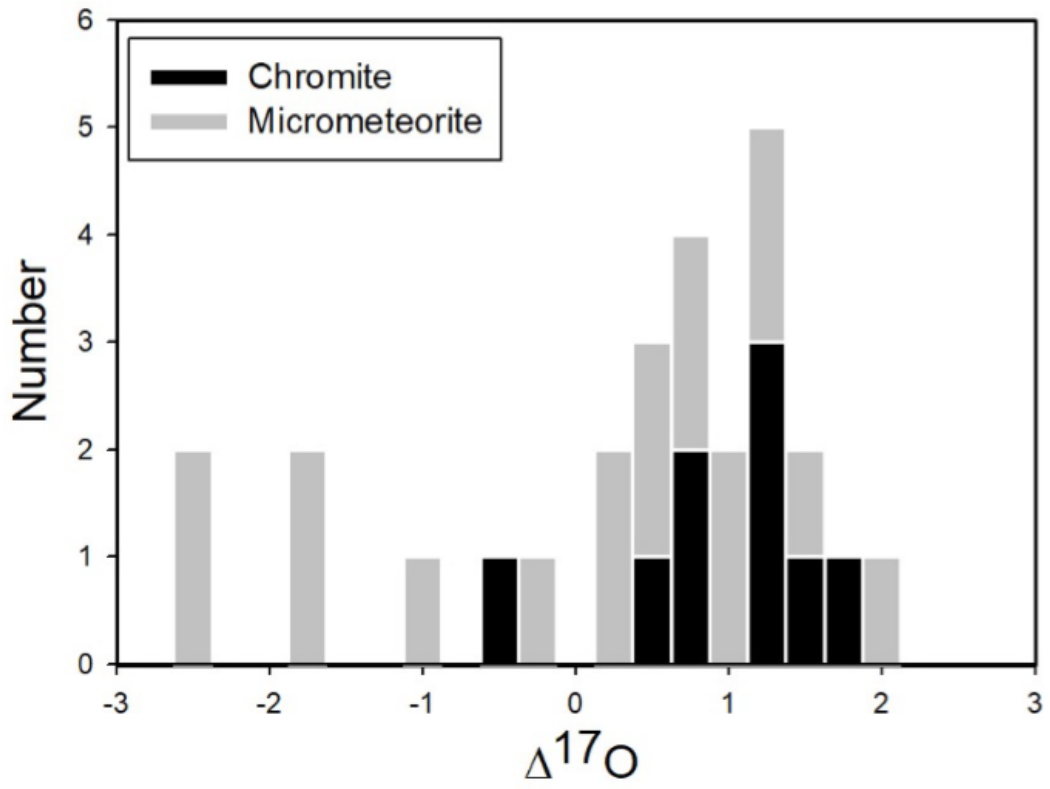


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603 Fig. 5

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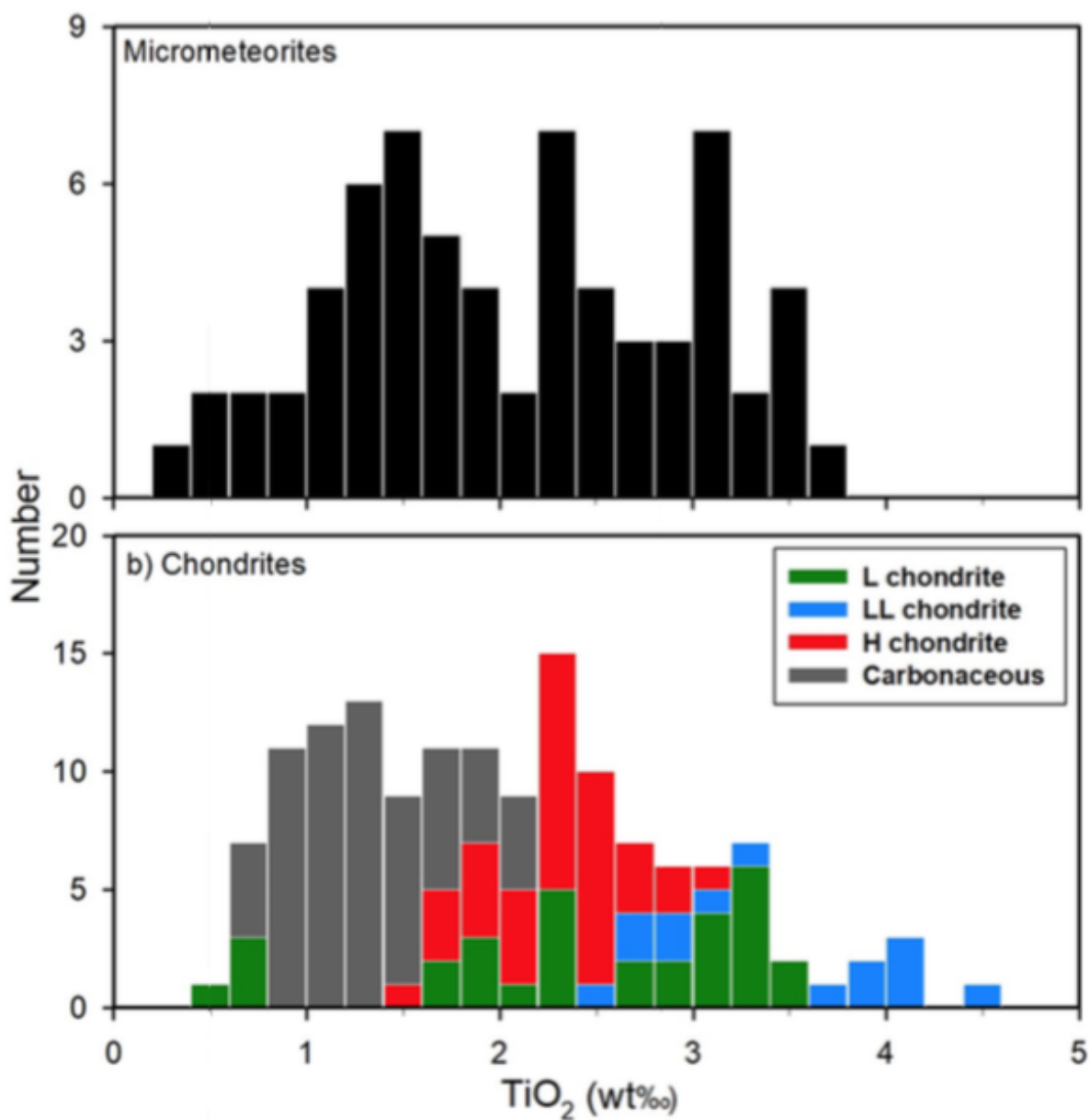




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606 Fig.

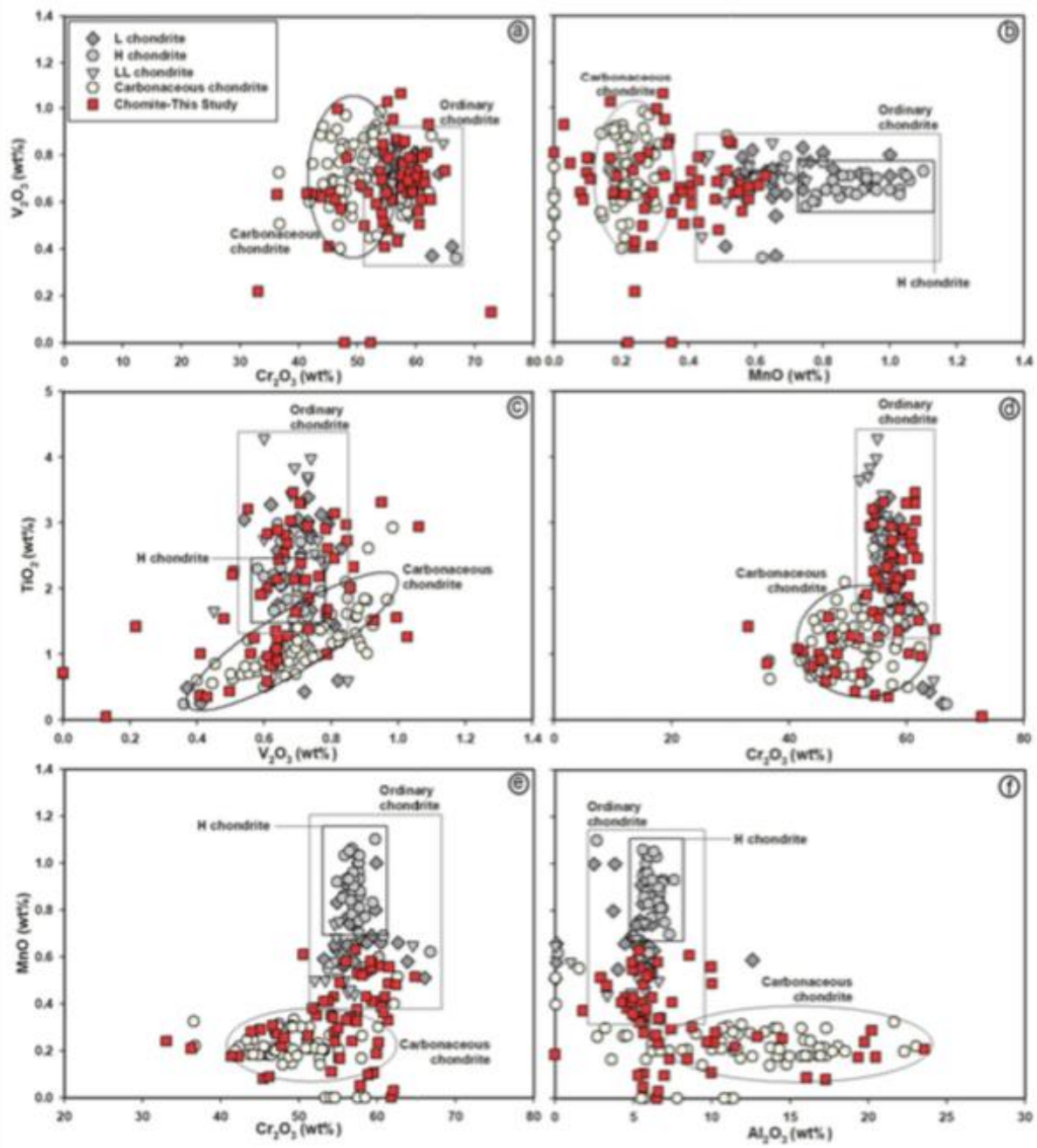
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609 Fig.7

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613 Fig. 8

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Table 1: Chemical composition (wt%) of the chromite grains from micrometeorites.

Sr. No	Cosmic spherule#	Type	Spherule size (μm) <sup>#</sup>	Chromite size(μm)*	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	V <sub>2</sub> O <sub>3</sub>	ZnO	Total
1	AAS-38-143-P141A	Barred	150	24	11.31	1.78	0.99	0.06	2.53	57.48	0.37	22.23	0.66	0.22	97.63
2	AAS-38-167-1-P20	Barred	280	37	6.50	5.62	0.10	0.00	3.46	61.45	0.49	22.79	0.69	0.00	101.09
				22	11.62	5.67	0.09	0.01	3.30	61.43	0.33	17.54	0.71	0.00	100.70
3	AAS-38-167-1-P59	Porphyritic	210	16	6.71	10.12	0.70	0.04	0.37	54.63	0.24	25.78	0.41	0.00	99.00
4	AAS-38-167-P53	Barred	380	81	2.51	6.16	0.05	0.00	2.73	57.55	0.53	28.51	0.85	0.24	99.14
5	AAS-38-169-P60	Barred	400	52	6.91	9.70	0.29	0.04	0.35	56.85	0.24	24.82	0.43	0.00	99.63
6	AAS-38-170-P89	Porphyritic	188	8.1	8.81	20.20	1.30	0.18	1.01	45.10	0.29	21.83	0.41	0.00	99.13
7	AAS-38-177-P51	Porphyritic	228	4	8.86	23.58	0.83	0.01	0.86	36.29	0.21	28.65	0.63	0.06	99.98
8	AAS-38-180-P73	Barred	320	24	3.29	6.55	0.03	0.01	2.01	56.04	0.58	28.55	0.61	0.23	97.90
9	AAS-38-180-P107	Barred	650	23	12.30	5.69	0.18	0.01	3.14	54.61	0.28	20.07	0.81	0.15	97.24
10	AAS-38-182-P25	Porphyritic	228	14	8.69	9.96	0.15	0.00	1.01	60.39	0.56	18.58	0.56	0.01	99.89
				7	10.68	4.47	1.26	0.07	2.26	54.47	0.43	23.07	0.51	0.00	97.22
11	AAS-38-184-P28	Barred	288	153	9.36	5.46	0.07	0.03	2.69	60.67	0.41	21.78	0.67	0.19	101.33
				48	12.36	4.61	0.59	0.02	2.21	60.58	0.39	19.99	0.51	0.10	101.32
12	AAS-38-184-P9	Barred	320	6	8.69	8.45	0.53	0.00	1.26	55.14	0.17	23.42	1.03	0.00	98.69
				7	9.35	6.02	0.79	0.08	1.36	58.56	0.54	21.78	0.63	0.00	99.10
				7	10.53	5.60	0.63	0.06	2.18	57.86	0.05	20.02	0.76	0.19	97.88
				5	11.86	7.31	0.67	0.10	1.62	55.28	0.17	20.12	0.79	0.33	98.23
13	AAS-38-188-P54	Barred	375	69	6.44	5.72	0.03	0.01	3.21	54.21	0.35	29.28	0.55	0.09	99.90
14	AAS-38-193-P40	Porphyritic	250	10	16.53	6.48	0.33	0.00	2.46	61.82	0.00	11.18	0.81	0.30	99.91
				15	16.70	6.57	0.69	0.02	1.86	60.20	0.24	10.67	0.73	0.24	97.92
				5	17.68	6.97	0.46	0.01	2.12	58.97	0.10	10.67	0.72	0.20	97.91
				5	16.83	6.58	0.65	0.09	1.52	62.10	0.03	10.80	0.93	0.36	99.90

15	AAS-38-193-P43	Porphyritic	214	13	10.13	0.00	0.00	0.03	3.30	59.95	0.19	23.75	0.71	0.12	98.18
16	AAS-38-193-P45		242	6	15.91	0.10	0.40	0.01	0.05	72.81	2.97	6.46	0.13	0.01	98.84
17	AAS-38-195-P80A	Barred	257	23	7.94	5.14	1.17	0.01	0.71	52.26	0.35	28.93	0.00	0.00	96.50
18	AAS-38-203-P58	Barred	484	93	5.86	5.43	0.07	0.01	3.03	61.56	0.56	23.44	0.68	0.17	100.81
				66	4.99	4.97	0.86	0.04	2.44	59.34	0.55	25.44	0.64	0.18	99.46
				47	7.23	4.91	0.16	0.00	2.82	59.20	0.58	23.39	0.66	0.13	99.07
19	AAS-38-203-P88	Barred	205	33	10.14	4.86	0.55	0.02	2.89	59.40	0.41	21.41	0.64	0.09	100.41
				35	5.42	5.37	0.94	0.03	2.38	57.29	0.63	25.37	0.71	0.27	98.41
				11	7.15	4.99	1.08	0.04	2.14	58.65	0.43	24.77	0.69	0.19	100.13
20	AAS-38-204-P58	Cryptocrystalline	189	21	13.22	5.65	0.36	0.01	2.91	59.61	0.11	17.74	0.78	0.11	100.49
21	AAS-38-207-P15	Porphyritic	250	87	4.83	6.18	0.13	0.03	2.61	61.04	0.43	24.77	0.79	0.21	101.02
22	AAS-38-207-P117	Porphyritic	250	100	7.63	6.74	0.19	0.01	2.32	56.65	0.34	24.99	0.87	0.24	99.99
23	AAS-62-5-P77	Barred	190	15	6.54	5.47	0.23	0.04	3.31	56.11	0.33	23.67	0.95	0.29	96.95
24	AAS-62-10-P35	Barred	275	60	8.53	5.86	0.35	0.03	2.01	58.11	0.52	21.17	0.86	0.18	97.62
25	AAS-62-26-P86	Porphyritic	184	19	16.42	5.31	0.90	0.01	1.68	58.86	0.10	14.73	0.79	0.30	99.10
				22	8.09	2.92	0.44	0.16	1.38	64.87	0.51	19.71	0.73	0.13	98.93
26	AAS-62-26-P132	Porphyritic	220	83	7.21	5.40	0.15	0.01	2.94	57.42	0.32	23.40	1.06	0.32	98.24
				54	8.62	7.47	0.15	0.04	2.94	53.85	0.41	24.77	0.73	0.16	99.13
				40	8.50	6.61	0.21	0.00	2.97	54.40	0.34	22.98	0.84	0.20	97.06
27	AAS-62-32-P102	Porphyritic	173	16	2.76	8.75	0.79	0.02	1.56	46.66	0.31	37.66	1.00	0.00	99.49
28	AAS-62-32-P106	Scoriaceous	232	15	5.45	11.46	0.60	0.05	0.72	47.83	0.22	32.69	0.00	0.00	99.02
29	AAS-62-51-P4	Porphyritic	211	19	11.22	19.74	0.27	0.03	1.42	33.06	0.24	30.64	0.22	0.00	96.84
30	AAS-62-51-P52	Porphyritic	275	9	6.74	10.25	1.46	0.01	0.82	43.94	0.28	31.97	0.62	0.00	96.09
31	SP009-P126	Cryptocrystalline	112	8	7.49	7.41	0.22	0.11	2.14	55.04	0.29	24.83	0.64	0.02	98.20
				12	7.13	4.22	0.93	0.06	1.91	53.25	0.41	26.85	0.59	0.04	95.39
				20	8.47	5.81	1.98	0.09	1.24	51.81	0.38	24.69	0.64	0.00	95.11
				6	9.30	6.45	1.37	0.12	1.25	47.25	0.27	27.83	0.57	0.01	94.42
				18	9.00	9.98	0.51	0.11	1.64	54.21	0.11	23.06	0.70	0.00	99.31

32	SP005-P135	Porphyritic	119	11	8.58	17.27	0.58	0.00	0.92	45.49	0.08	25.21	0.64	0.05	98.82
				13	7.95	19.34	0.56	0.00	1.04	42.28	0.18	25.40	0.63	0.00	97.38
				8	7.82	20.47	0.41	0.00	1.08	41.41	0.18	25.97	0.64	0.00	97.97
33	SP005-P219	Glass	89	12	8.39	8.57	1.46	0.54	1.28	50.55	0.61	27.87	0.67	0.05	99.99
				10	6.75	9.45	1.10	1.00	1.62	47.36	0.66	27.73	0.45	0.00	96.13
				7	6.51	9.02	1.41	0.36	1.02	50.25	0.57	29.06	0.47	0.02	98.69
34	SP005-P325	Porphyritic	59	7	10.03	10.03	0.75	0.07	1.54	55.26	0.49	18.77	0.48	0.00	97.42
35	SP005-P530	Glass	72	7	13.05	4.97	0.10	0.03	2.83	60.86	0.36	13.56	0.61	0.00	96.37
36	SP005-P658	Porphyritic	100	17	4.29	14.51	0.34	0.04	1.00	48.20	0.26	28.87	0.79	0.00	98.29
37	SP005-P711	Porphyritic	97	25	7.86	12.93	0.22	0.13	0.44	51.21	0.26	24.42	0.50	0.00	97.97
38	SP005-P769	Porphyritic	124	31	6.39	16.05	0.59	0.00	0.58	46.21	0.09	27.31	0.61	0.07	97.91
39	SP005-P791	Porphyritic	95	34	4.61	3.31	0.21	0.02	0.97	62.48	0.48	26.38	0.61	0.00	99.07
40	SP007-P72	Relict bearing	132	7	6.80	12.14	0.84	0.13	1.59	46.40	0.12	30.45	0.90	0.01	99.36
41	SP007-P2	Unmelted	153	14	2.81	6.01	0.28	0.05	2.03	53.25	0.10	33.88	1.00	0.30	99.71
42	SP007-P29	Relict bearing	74	6	9.55	13.69	0.29	0.05	1.21	49.56	0.31	24.34	0.28	0.01	99.27

# indicate spherule size as diameter

\* indicate chromite size measured along the maximum length.

All measurements are in wt%

Table 2. Oxygen isotopic composition of chromites and the olivine phases in micrometeorites. All the values of the oxygen isotopic composition are reported in ‰.

#	Name	Type	Spot#	$\delta^{18}\text{O}$	$2\sigma$	$\delta^{17}\text{O}$	$2\sigma$	$\Delta^{17}\text{O}$	$2\sigma$
1	SP005-P126	Glass	1	5.8	0.6	1.3	0.5	-1.7	0.6
			2	8.8	0.7	2.7	0.5	-1.8	0.6
			3	10.2	0.6	3.8	0.5	-1.5	0.6
			4	9.9	0.7	4.3	0.4	-0.9	0.5
			5	11.2	0.8	5.2	0.4	-0.7	0.5
			6	11.5	0.5	5.4	0.5	-0.5	0.5
2	SP005-P219	Glass	*1	4.7	0.9	1.5	0.4	-0.9	0.6
			*2	3.9	0.7	1.7	0.4	-0.3	0.6
			*3	3.7	0.6	1.2	0.4	-0.7	0.5
			4	3.7	0.8	1.3	0.5	-0.6	0.6
			5	6.4	0.9	3.1	0.3	-0.2	0.6
3	AAS-38-203-P58	Barred	*1	1.4	0.7	1.3	0.4	0.6	0.5
			*2	0.9	0.5	0.8	0.5	0.3	0.5
			*3	0.7	0.7	0.6	0.4	0.3	0.6
			4	12.4	0.7	6.5	0.5	0.0	0.6
			5	12.4	0.7	6.5	0.5	0.1	0.6
4	AAS-38-203-P88	Barred	*1	6.0	0.7	3.6	0.5	0.4	0.6
			*2	1.4	0.6	1.7	0.4	1.0	0.5
			*3	5.8	0.6	3.6	0.4	0.6	0.5
			4	7.9	0.8	4.4	0.4	0.3	0.6
			5	8.2	0.7	5.5	0.5	1.2	0.6
			6	9.4	0.7	5.2	0.5	0.4	0.6
5	AAS-38-207-P15	Barred	*1	2.7	0.4	2.7	0.6	1.3	0.6
			*2	-0.1	0.4	1.3	0.6	1.4	0.6

			3	7.6	0.7	4.5	0.5	0.6	0.6
			4	9.9	0.6	5.4	0.5	0.3	0.6
6	AAS-38-169-P60	Barred	*1	-0.6	0.9	1.3	0.4	1.6	0.6
			2	12.7	0.8	7.4	0.5	0.8	0.7
			3	12.2	0.6	7.9	0.5	1.5	0.6
7	AAS-38-188-P54	Barred	*1	0.3	0.6	1.2	0.5	1.1	0.6
			2	13.5	0.8	7.7	0.5	0.7	0.6
			3	11.8	0.8	7.5	0.5	1.4	0.6
8	AAS-38-167-1-P20	Barred	*1	0.3	0.5	1.3	0.6	1.1	0.6
			2	14.5	0.8	8.6	0.5	1.1	0.6
			3	14.9	0.8	8.4	0.5	0.7	0.7
9	AAS-38-167-P53	Barred	*1	-0.6	0.6	0.7	0.4	1.0	0.5
			*2	-0.2	0.6	0.9	0.5	1.0	0.6
			3	14.7	0.7	8.1	0.5	0.4	0.6
			4	14.2	0.6	8.1	0.5	0.8	0.6
10	AAS-38-204-P58	Barred	*1	-0.8	0.8	0.3	0.5	0.7	0.6
			2	-1.9	0.8	-1.4	0.5	-0.4	0.7
			3	-4.1	1.1	-1.3	0.6	0.8	0.8
11	SP005-P135	Porphyritic	1	26.5	0.8	11.5	0.4	-2.3	0.6
			2	26.4	0.7	11.6	0.4	-2.1	0.5
			3	30.7	0.6	13.6	0.4	-2.3	0.5
			4	28.7	0.7	13.4	0.4	-1.6	0.6
			5	29.8	0.6	13.8	0.4	-1.7	0.5
12	SP005-P658	Porphyritic	1	22.3	0.7	8.9	0.5	-2.7	0.6
			2	27.2	1.2	11.4	0.7	-2.7	0.9
13	SP005-P711	Glass	1	26.7	0.8	11.2	0.4	-2.7	0.6
			2	26.7	0.7	11.2	0.4	-2.6	0.5
14	SP005-P769	Porphyritic	1	24.7	0.7	10.9	0.5	-1.9	0.6
15	SP005-P770	Unmelted	1	3.0	0.6	2.8	0.3	1.2	0.4



			2	2.9	0.5	2.8	0.4	1.3	0.5
16	SP007-P72	Relict bearing	1	-3.6	1.0	-1.0	0.5	0.9	0.7
			2	3.1	0.9	1.6	0.5	0.0	0.7
			3	9.2	1.0	5.0	0.6	0.2	0.8
17	SP007-P2	Unmelted	1	4.0	0.7	4.1	0.5	2.0	0.6
			2	4.4	0.9	3.9	0.5	1.6	0.7
			3	-2.4	1.0	2.2	0.6	3.5	0.8
			4	2.6	0.9	4.3	0.3	3.0	0.6
18	SP007-P29	Relict bearing	1	3.3	0.6	2.5	0.5	0.8	0.6
			2	4.1	0.7	2.4	0.5	0.2	0.6
			3	2.9	0.9	3.1	0.6	1.6	0.7

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\* marked are the oxygen isotope analyzed for chromite grain.