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1 **The isotopic composition of volatiles in the unique Bench Crater carbonaceous**
2 **chondrite impactor found in the Apollo 12 regolith**

3
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26 **Abstract**

27 Projectiles striking the Moon have modified its crust and delivered volatile elements to its
28 interior and surface. Direct evidence of impactor origins is recorded by the rare occurrence of
29 sub-cm sized meteorite fragments identified in Apollo samples and lunar meteorites. The
30 Bench Crater meteorite is a millimetre-sized carbonaceous chondrite collected in regolith on
31 the rim of Bench impact crater at the Apollo 12 landing site. Transmission electron
32 microscopy has previously shown that Bench Crater contains abundant hydrated silicates,
33 establishing the survivability of hydrated material impacting the lunar surface. To provide
34 further information on the volatile inventory of the Bench Crater meteorite, we report here
35 the isotope compositions of hydrogen, nitrogen, carbon and oxygen. This is the first direct
36 isotopic analysis of meteoritic material delivered to the lunar surface and provides context for
37 volatile and organic element signatures in lunar regolith samples, and the survivability of
38 volatile material delivered to planetary surfaces during impact bombardment. The Bench
39 Crater meteorite is characterised by δD values ranging between -36 ± 40 and 200 ± 40 ‰,
40 and bulk average $\delta^{13}C$ of -13 ± 30 ‰, and $\delta^{15}N$ of -40 ± 36 ‰ (all uncertainties at the 2σ
41 confidence level). The oxygen isotope compositions measured *in situ* in matrix silicates and
42 magnetite in Bench Crater are consistent with those measured in matrix and magnetite in CI
43 and CM chondrite falls. Altogether, these new H, C, N and O isotope data, coupled to
44 mineralogical and geochemical observations, suggest that Bench Crater may have been
45 derived from an asteroidal parent body not represented in the terrestrial meteorite collection.
46 This is a crucial outcome in the current context of sample-return missions to carbonaceous
47 asteroids, and more broadly for investigating the flux of material delivered to the Earth-Moon
48 system through time.

49

50 **Keywords:** Moon, Meteorite, Light stable isotopes, Regolith, Volatiles, Carbonaceous
51 chondrite

52

53 **1. Introduction**

54 A key driver of future lunar scientific exploration is to determine the source(s) of water ice
55 and volatiles found on the Moon's surface at the present day (Li *et al.*, 2018), and to
56 understand past origins of water and volatiles in the Earth-Moon system (NRC, 2007).
57 Potential caches of water and other volatiles at the lunar surface are being targeted by
58 spacecraft missions for both scientific and exploration objectives (*e.g.*, Carpenter *et al.*, 2014;
59 Colaprete *et al.*, 2016; Barber *et al.*, 2017). Such volatile reservoirs at the lunar surface are of
60 key astrobiological interest (Cockell, 2010; Martins *et al.*, 2013) and may also prove to be
61 useful for *in situ* resource utilisation (Anand *et al.*, 2012) for the next generation of lunar
62 surface exploration.

63

64 Over the past decade, laboratory measurements of hydroxyl and water locked in volcanic
65 picritic glass beads and melt inclusions they host, in the phosphate mineral apatite, and in
66 nominally anhydrous minerals have also allowed investigation of the diversity and budgets of
67 volatile reservoirs in the lunar interior (see McCubbin *et al.*, 2015 for a review). Lunar
68 surface volatile budgets have been constrained by spectral identifications of OH bound in
69 regolith soils (*e.g.*, Pieters *et al.*, 2009), concentrations of volatiles within the regolith of
70 permanently shadowed polar craters (*e.g.*, Colaprete *et al.*, 2009), and in Apollo regolith
71 glasses and impact breccias (*e.g.*, Liu *et al.*, 2012). However, the origin of these different
72 reservoirs is poorly constrained: they are likely a mixture of both indigenous and exogenous
73 sources (*e.g.*, McCubbin *et al.*, 2015 and references therein; Barnes *et al.*, 2016).

74

75 Unravelling the geochemical and isotopic records of volatiles at the lunar surface is
76 complicated by (i) limited direct measurements of end-member compositions (*i.e.* impactor
77 types, solar wind-derived volatiles, and interior sources), (ii) few complete volatile inventory
78 analyses of lunar soil and regolith samples (Steele *et al.*, 2010; Liu *et al.*, 2012; Stephant and
79 Robert, 2014; Füri and Marty, 2015; Füri *et al.*, 2012, 2017, 2018; Curran *et al.*, 2020), and
80 (iii) complications with calculating isotopic contributions from spallogenically-derived
81 components (e.g., Stephant and Robert 2014; Füri *et al.*, 2017). To address the first of these
82 challenges, we have determined the isotopic composition of the volatile elements hydrogen,
83 carbon, nitrogen and oxygen in a carbonaceous chondrite meteorite fragment from the Moon.
84 This study, therefore, provides the first ground-truth for the composition of asteroid-derived
85 volatiles hosted by the lunar regolith.

86

87 **2. Sources of lunar impactors**

88 The types of meteoritic material that are recovered today on the Earth (e.g., The Meteoritical
89 Bulletin, 2020) might also be representative of the sources of material striking the Moon,
90 contributing to the addition of volatiles to the lunar regolith. There are, however, two
91 significant knowledge gaps preventing us from making this assessment. Firstly, weakly
92 consolidated – and likely the most volatile-rich – meteorites (and micrometeorites) are largely
93 contaminated (especially volatile elements) or destroyed during descent through the Earth's
94 atmosphere and are poorly sampled, or unavailable in the Earth's meteorite collection (Trigo-
95 Rodriguez and Blum, 2009; Flynn *et al.*, 2017). Thus, knowledge of their contribution to the
96 meteoritic volatile inventory is incomplete. Secondly, the flux and nature of meteoritic debris
97 may have changed with time with the dynamical evolution of small bodies in the Solar
98 System, and meteoritic fragments found in the lunar regolith provide us with a
99 complementary and often older record compared to terrestrial meteorites (Joy *et al.*, 2016;

100 Heck *et al.*, 2017). To address both of those existing shortcomings we need to examine the
101 Moon's surficial regolith for volatile-rich meteoritic relics (Joy *et al.*, 2012 and references
102 therein). Retention of such projectile material at the lunar surface depends upon impact
103 velocity, impact angle, and impactor and target material properties including strength and
104 porosity (Avdellidou *et al.*, 2016). Theoretical calculations indicate that asteroids deliver the
105 majority of lunar near-surface volatiles compared with cometary dust particles (Svetsov and
106 Shuvalov, 2015). To date, all impactor debris found on the Moon have been very small,
107 ranging from a few microns to only a few mm in size (see summary in Joy *et al.*, 2016), yet
108 provide a vital ground-truth for characterisation of volatile resources by future *in situ* mission
109 analysis of the lunar regolith, and samples returned to the Earth.

110

111 **3. Geological setting and characteristics of the Bench Crater meteorite**

112 In this study, we characterised the petrography, mineralogy and geochemistry of a fragment
113 of the Bench Crater carbonaceous chondrite meteorite (McSween, 1976; Fitzgerald and
114 Jones, 1977; Zolensky *et al.*, 1996; Zolensky, 1997) (Fig. 1). The meteorite was identified
115 from a range of small (0.6 to 3 mm) rock particles extracted from soil sample 12037 (Fig. S-
116 1), collected from the rim of a 75 m impact crater on the nearside of the Moon at the Apollo
117 12 landing site (3.01°S 23.4°W) (Figs. S-2 and S-3, and Supplementary Information note 1).

118

119 The 12037 bulk soil is sub-mature, meaning that it underwent medium levels of solar wind
120 exposure at the lunar surface compared with other Apollo soil samples (the sample has an
121 I_p/FeO soil maturity index value of 21; Morris *et al.*, 1983). The duration of exposure of this
122 12037 soil to the space environment has been estimated to be 10-20 Myr based upon the
123 density of cosmic ray tracks and nitrogen spallation ages (Arrhenius *et al.*, 1971; Becker and
124 Clayton, 1978). This exposure age is younger than the proposed Apollo 12 landing site Bench

125 impact crater formation episode, thought to be \sim <99 Ma (Arvidson *et al.*, 1975) and likely
126 <55 Ma (Burnett *et al.*, 1975). It may be that the Bench Crater meteorite represents part of the
127 impactor that made this crater, but it may also have been delivered after this event. In any
128 case, the Bench Crater meteorite likely impacted the Moon's surface in the last 100 million
129 years.

130

131 **4. Methods**

132 Key aspects of the methods are described here and a full description of methodology is
133 outline in Supplementary Materials note 2. Small pieces of the Bench Crater meteorite in
134 section 12037,188 were removed (Fig. S-1) with a needle. Microtomed sections were
135 prepared and analysed using the NASA Johnson Space Center (JSC) JEOL 2200FS field
136 emission gun (FEG) transmission electron microscope (TEM) coupled to an Oxford energy-
137 dispersive X-ray (EDX) spectroscopy system to check the presence of hydrated phases
138 (Supplementary note S-2.2) and determine the composition of matrix materials (Table S-1).
139 Two $15 \times 15 \mu\text{m}$ areas (Area 1 and Area 2) of fragments pressed into gold foil were spatially
140 mapped for H, C, and N isotope compositions and two $10 \times 10 \mu\text{m}$ areas (Area 3 and 4) were
141 spatially mapped for their H isotope composition in separate sessions using the NASA JSC
142 NanoSIMS 50L ion microprobe (Table 1 and Supplementary note S-2.4).

143

144 After removing a small sub-split of the sample for NanoSIMS work, we also analysed the
145 whole polished grain mount of Bench Crater using the NASA JSC JEOL 7600f FEG
146 scanning electron microscope (SEM) to collect backscatter electron (BSE) images and X-ray
147 element maps as shown in Figure 1 (Supplementary note S-2.1). Normalised phase modal
148 proportions (Table S-2) were estimated by combining these element maps and using Adobe
149 Photoshop to count the number of pixels in each assigned phase type. Further BSE imaging

150 was carried out using a FEI Quanta 650 FEG-SEM at the University of Manchester, and
151 mineral compositions were acquired using a Cameca SX 100 electron microprobe at the
152 University of Manchester (Table S-3).

153

154 Finally, we measured the oxygen isotopic compositions of silicates, magnetite and carbonate
155 *in situ* in the Bench Crater meteorite thin section using a CAMECA IMS 1270 E7 at CRPG-
156 CNRS (Nancy, France). Details are provided in Supplementary note S-2.3 and the data are
157 listed in Table 2. After the analyses, all the SIMS spots were carefully checked by BSE-SEM
158 to estimate potential contribution by adjacent minerals (Figs. S-7 and S-8).

159

160 **5. Results and interpretation**

161 **5.1. Petrography**

162 The Bench Crater meteorite is 3.00×1.75 mm in size (Fig. 1 and Fig. S-1). Transmitted light
163 optical microscope observations show that the meteorite appears very well preserved with a
164 low-level petrofabric (preferred matrix cross-cutting fracture orientation, see Fig. 1), sub-
165 rounded magnetite grains, see Fig. 2) and fractured sulphides. It is composed of brown-
166 coloured aggregates of ferromagnesian minerals that are possibly aqueously altered
167 chondrules (olivine + pyroxene, ~10% by area of the meteorite; Fig. 3) embedded within a
168 fine-grained matrix (~68% by area; Fig. 3). Many ferromagnesian phases in the matrix have
169 been replaced by the hydrated mineral saponite (with a chemical composition of
170 $\text{Ca}_{0.01}\text{Mg}_{0.06}(\text{Mg}_{2.73}\text{Fe}_{0.33}\text{Cr}_{0.03})(\text{Si}_{3.63}\text{Al}_{0.37})\text{O}_{10}(\text{OH})_2 \cdot 4(\text{H}_2\text{O})$ as reported by Zolensky, 1997)
171 that retained structural water even after delivery to the lunar surface (Figs. S-4, S-5 and S-6)
172 (Zolensky, 1997). This is consistent with low EPMA analytical totals of 91-93 wt% obtained
173 on matrix areas (Table S-3), since water/OH is not measured by EPMA. Lath shaped
174 sulphides (~5.3% by area; Fig. 3) comprise pyrrhotite, pentlandite, and rare chalcopyrite –

175 including the large rectangular sulphide crystal in the middle of the sample (Fig. 1).
176 Manganese-rich ilmenite occurs at trace levels (~0.3% by area). Low-temperature aqueous
177 alteration minerals include framboidal and plaquet magnetite (~12.4% by area; Fig. 3). The
178 Bench Crater meteorite also contains Ca-rich minerals including calcite and dolomite (~2.4%
179 by area) and apatite (~2.3% by area). Apatite is typically found within the aqueously altered
180 chondrules, is Cl-poor, and is characterised by low F abundance (0.8-1.1 wt%; Table S-3)
181 compared to apatite in indigenous lunar samples, which typically contains at least 3 wt% F
182 (e.g., McCubbin *et al.*, 2015).

183

184 **5.2. Agglutinitic rim**

185 The meteorite fragment has a patchy thin (<100 μm) vesicular crust (Figs. 1 and 4), coating
186 about 10 % of its exterior. This crust is more feldspathic (12.8 ± 0.2 wt.% Al_2O_3) and
187 enriched in TiO_2 (2.2 ± 0.2 wt% TiO_2) compared to carbonaceous chondrite meteorites (<5
188 wt% Al_2O_3 , <0.3 wt% TiO_2 ; Nittler *et al.*, 2014), and instead is more similar to Apollo 12
189 bulk regolith compositions (13.9 ± 2.3 wt% Al_2O_3 , 3.1 ± 1.1 wt% TiO_2 ; Graf, 1993) (Table S-
190 3). As the Moon has no atmosphere, this crust is not a fusion crust (formed on Earth during
191 breakup of bolides as they are frictionally heated during atmospheric entry), but is more akin
192 to agglutinitic or splash coat crusts found on rocks in the lunar regolith formed from flash
193 impact melting. The lunar-like composition of the vesicular rim (Table S-3) suggests
194 interaction between the impactor and melted local basaltic lunar regolith either during or after
195 its delivery. Temperatures of ~1100 °C are required to melt lunar regolith (Colozza, 1991).
196 Therefore, some areas of the outer 10-30 μm of Bench Crater have likely been affected by
197 flash heating, provoking dehydration of the matrix to form fibrous material (Fig. 4).
198 However, the occurrence of hydrated saponite-bearing matrix (Fig. 4) just >50 μm away from

199 the glassy coat suggests that heat was quickly dissipated, and that the internal part of the
200 sample was not baked and extensively degassed during the agglutination process.

201

202 **5.3. Oxygen isotopes**

203 To try to classify Bench Crater's parent meteorite group, we measured *in situ* the oxygen
204 isotope composition of magnetite, carbonate and the groundmass of the aqueously altered
205 chondrules (within both intermediate phase and amorphous material). In matrix areas, the
206 $\delta^{18}\text{O}$ and $\delta^{17}\text{O}$ values range from ~ 9.9 to 16.8‰ and 5.2 to 8.3‰ (Table 2), respectively,
207 generally falling along the terrestrial fractionation line (TFL), between the O isotope
208 compositions of the matrices of CM and CI carbonaceous chondrite falls (Fig. 5). The
209 magnetite $\delta^{18}\text{O}$ and $\delta^{17}\text{O}$ values range from ~ 5.7 to 8.5‰ and 4.8 to 6.1‰ (Table 2),
210 respectively, and fall above the TFL, on the same mass dependent fractionation line than the
211 one defined by O isotope compositions of magnetite in CI and CM carbonaceous chondrite
212 falls (Fig. 5). The two carbonate analyses yielded O isotope compositions roughly similar to
213 those measured in the aqueously altered chondrules, plotting at the ^{16}O -rich end of the trend
214 defined by carbonate analysis in CM chondrite falls (Fig. 5).

215

216 **5.4. Hydrogen, carbon and nitrogen isotopes**

217 We removed a small portion of the matrix of the Bench Crater meteorite and analysed its H,
218 C and N isotope compositions *in situ* in two different $15 \times 15 \mu\text{m}$ areas (see Fig. 1 for
219 location of sampled material) (Fig. 6, Fig. S-10). These two areas yielded bulk δD values of -
220 36 ± 40 and $+200 \pm 40 \text{‰}$ (all uncertainties on isotopic ratios given at 2σ), $\delta^{13}\text{C}$ values of $-2 \pm$
221 20 and $-23 \pm 20 \text{‰}$, and $\delta^{15}\text{N}$ values of -27 ± 20 and $-52 \pm 20 \text{‰}$ (Figs. 7 and 8; Table 1).
222 Two additional $10 \times 10 \mu\text{m}$ areas analysed only for their H isotope compositions yielded bulk
223 δD values of -13 ± 18 and $+35 \pm 18 \text{‰}$. The variability in δD values measured in the four

224 analysed areas likely relates to variable proportions of H-bearing silicates to insoluble organic
225 matter, since these two hosts of hydrogen in carbonaceous chondrites have generally very
226 different δD values (e.g., Alexander *et al.*, 2007, 2012). Overall, the Bench Crater meteorite
227 is characterised by δD values ranging between -36 ± 40 and 200 ± 40 ‰, and bulk
228 average $\delta^{13}\text{C}$ of -13 ± 30 ‰ (2 SD, n = 2) and $\delta^{15}\text{N}$ of -40 ± 36 ‰ (2 SD, n = 2) (Table 1).

229

230 NanoSIMS imaging did not show any micron-size H-, C- or N-isotopically anomalous
231 regions (Fig. 6 and Figs. S-9 and S-10), contrary to what is observed in interplanetary dust
232 particles (IDPs), ultracarbonaceous Antarctic micrometeorites, and the most primitive
233 chondrites like Murchison, in which hotspots with elevated isotope ratios are common (Figs.
234 S-9 and S-10) (e.g., Messenger, 2000; Nakumura-Messenger *et al.*, 2006; Duprat *et al.*,
235 2010 ; Remusat *et al.* 2016). There was also no isotopic distinction between C-rich and C-
236 poor areas of the Bench Crater samples (Fig. 6).

237

238 **6. Discussion**

239 The Bench Crater meteorite provides the first direct evidence of surviving hydrated
240 carbonaceous chondrite material delivered to the lunar regolith (Zolensky, 1997). It is, thus,
241 currently the only direct ground-truth of the planetary end-member for all H, N and C light-
242 element isotopic analysis of lunar soils. These findings provide important benchmarks for
243 models of volatile processing and transport across the lunar surface (Benna *et al.* 2019).

244

245 **6.1. Bench Crater meteorite classification**

246 The Bench Crater meteorite is mineralogically and compositionally unusual compared with
247 other carbonaceous chondrite groups. It is mineralogically distinct from CV types, which are
248 lacking in calcite and dolomite and have comparatively lower abundances of phyllosilicates

249 (1.9–4.2%) and magnetite (6 %) (Howard *et al.*, 2010) than Bench Crater (Figure 3).
250 Affinities have previously been made with C-ungrouped types (McSween, 1976; Fitzgerald
251 and Jones 1977) and CM2 carbonaceous chondrites (Zolensky *et al.*, 1996). For instance, the
252 high abundance of acicular sulphides and the presence of aqueously altered chondrules are
253 similar to the CM1/2 Boriskino meteorite (Vacher *et al.*, 2018; Verdier-Paoletti *et al.*, 2019)
254 and thermally metamorphosed CI, CM and CY chondrites (e.g., Ikeda, 1992; Tonui *et al.*,
255 2014; King *et al.*, 2019a). However, the high modal abundance of magnetite bears more
256 resemblance to CI chondrites and matrix-rich (altered) CR chondrites such as Al Rais and
257 Grove Mountains (GRO) 95577 (Fig. 3). Notably the meteorite matrix is magnesian and is
258 compositionally more similar to CI-meteorite groups than CM or CR types (Fig. S-6) (van
259 Kooten *et al.*, 2018), suggesting a higher state of parent body aqueous alteration. It should be
260 noted that minor dehydration due thermal processing is unlikely to have changed the
261 MgO/FeO ratio; this ratio being constant in CM chondrites having experienced dehydration
262 (Lipschutz *et al.*, 1999). Bench Crater also share similarities with the Lonewolf Nunataks
263 (LON) 94101 meteorite, which has been described as a CM chondrite with coarse acicular
264 sulphides and a wide variety of CM- and magnetite-rich CI-like clasts (Lindgren *et al.*, 2013).
265 Bench Crater might be akin a clast-rich CM chondrite, but its limited size and hence
266 representativeness precludes definitive assessment of this possibility. All these observations
267 indicate that the Bench Crater meteorite cannot be directly related to any known
268 carbonaceous chondrite groups present in our current meteorite collections.

269

270 Bench Crater meteorite also shows oxygen isotope characteristics that connect it to the
271 hydrated CI and CM carbonaceous chondrites. For example, the Bench Crater magnetite
272 grains have O isotope compositions that are on the same mass fractionation line as magnetite
273 in CI and CM chondrite groups (Fig. 5). Furthermore, Bench Crater carbonates are

274 characterised by O isotope compositions plotting at the ^{16}O -rich end of the trend defined by
275 carbonates from CM2 chondrite falls (Fig. 5) (Verdier-Paoletti *et al.*, 2017; Vacher *et al.*,
276 2018) and some CM1 chondrites from the Antarctic meteorite collection (Allan Hills 83100,
277 Allan Hills 84034 and Meteorite Hills 01070; Telus *et al.*, 2019). The O isotope composition
278 of silicates in Bench Crater aqueously altered chondrules plots along the TFL, similarly to the
279 O isotope compositions measured in bulk CI chondrites and in their matrix and most olivine
280 grains (Fig. 5) (e.g., Leshin *et al.*, 1997; Piralla *et al.*, 2020). The O isotope compositions of
281 silicates in aqueously altered chondrules yield an average $\Delta^{17}\text{O}$ of -0.12 ± 0.45 ‰. Such a
282 $\Delta^{17}\text{O}$ value is, within errors, intermediate between the $\Delta^{17}\text{O}$ of CI chondrite matrix ($0.37 \pm$
283 0.42 ‰) and to that of CM chondrite matrix ($\Delta^{17}\text{O} = -1.76 \pm 0.63$ ‰) (e.g., Clayton and
284 Mayeda, 1984, 1999). Finally, the $\delta^{17}\text{O}$ and $\delta^{18}\text{O}$ isotope ratios in Bench Crater component
285 are significantly lower than $\delta^{17,18}\text{O}$ values of bulk CY chondrites (Tonui *et al.*, 2014; King *et*
286 *al.*, 2019a).

287

288 The evolution of the $\Delta^{17}\text{O}$ values in Bench Crater meteorite components implies that the
289 oxygen isotope compositions of secondary phases (magnetite, carbonates) did not result from
290 fluid circulation along a temperature gradient, which would produce a trend with a slope of
291 0.52. Instead, variations of $\Delta^{17}\text{O}$ values imply that the main process controlling the O isotope
292 compositions of the Bench Crater secondary phases is related to isotopic equilibrium between
293 ^{16}O -rich anhydrous silicates and ^{17}O - and ^{18}O -rich fluids as commonly reported in CM
294 chondrites (e.g., Verdier-Paoletti *et al.*, 2017; Marrocchi *et al.*, 2018). In this scenario,
295 magnetite would correspond to early precipitates whereas carbonates formed after significant
296 hydrothermal alteration. Furthermore, the carbonate O isotope compositions show similarity
297 with those reported in CM chondrites whose precipitation temperatures were estimated to be
298 $< 200^\circ\text{C}$ (Vacher *et al.*, 2019a). This suggests that Bench Crater did not experience

299 significant heating and dehydration processes, although the lack of tochilinite would suggest
300 a temperature higher than 320°C (Pignatelli *et al.*, 2017). However, we note that the stability
301 field of tochilinite is strongly affected by Mg-Fe substitutions (Kozerenko *et al.*, 1996, 2001)
302 and is not well constrained (Vacher *et al.*, 2019b).

303

304 Taken together, the oxygen isotope composition of Bench Crater mineral phases (Fig. 5),
305 along with its modal mineralogy (Fig. 3) and matrix composition (Fig. S-6), do not exactly
306 match that of a known carbonaceous chondrite group. It might represent a rare type of
307 carbonaceous asteroid parent body that is currently unsampled in the Earth's meteorite
308 collection. However, Bench Crater has important similarities with carbon-rich hydrated CI
309 and CM chondrites; the differences could be related to greater amounts of water ice grains
310 originally accreted by the Bench Crater parent body. Such a hypothesis could be tested thanks
311 to several assumptions, and following the methodology applied to CM, CO, CR and CV
312 carbonaceous chondrites (Marrocchi *et al.*, 2018). Bench Crater carbonates show $\delta^{17,18}\text{O}$
313 values plotting on the CM Ca-carbonate trend (Vacher *et al.*, 2016, 2018; Verdier-Paoletti *et*
314 *al.*, 2017), suggesting they precipitated from water with a similar O isotope evolution than
315 that of CM chondrites. Assuming that the bulk oxygen isotope composition of Bench Crater
316 is similar to the most altered CM chondrites (i.e., $\delta^{18}\text{O} = 10 \text{ ‰}$; Clayton and Mayeda, 1984,
317 1999) and considering the O isotope composition of anhydrous CM silicates as plausible
318 Bench Crater protolith (i.e., $\delta^{18}\text{O} = -4.2 \text{ ‰}$; Clayton and Mayeda, 1984, 1999), we calculated
319 the water/rock ratio at different temperature ranging from 25 to 150°C. This gives a
320 water/rock ratio for Bench Crater in the range 0.35 to 0.55, which is slightly higher than for
321 most CM chondrites that are characterised by a narrow range of water/rock ratio of 0.3-0.4
322 irrespective of their petrological type (e.g., Zolensky *et al.*, 1997; Marrocchi *et al.*, 2018).
323 Although speculative, these results suggest than the Bench Crater asteroidal parent-body was

324 more water-rich than the source location(s) of other CM chondrites. In addition, the physio-
325 chemical conditions of hydrothermal alteration in the Bench Crater parent-body (e.g., Palguta
326 et al., 2010; Travis and Schubert, 2005) might have been different than in other CM chondrite
327 original parent body(ies), as indicated by the higher abundance of magnetite in Bench Crater
328 compared to most CM chondrites (i.e., 12.4 % by area vs. 1.1-2.4 vol.%, see Fig. 3), and the
329 lack of tochilinite.

330

331 **6.2. Thermal and shock history of the Bench Crater meteorite**

332 The agglutinitic rim of Bench Crater indicates that it has been affected by flash heating on the
333 lunar surface, but that such effects only affected the outer ~10-30 μm of the fragment. Matrix
334 mineralogy and chemical composition also allows assessing the thermal history of the Bench
335 Crater fragment as a whole. Low analytical totals obtained through EPMA analyses in the
336 matrix of Bench Crater (91-93 wt%; Table S-3) may be related to the presence of
337 microporosity, and/or species not accounted for during EPMA analysis such as water/OH
338 and/or carbon. TEM observation of saponite in the matrix suggests that the missing 7-9 wt%
339 are likely related to the presence of water and/or OH. However, low EPMA totals obtained in
340 Bench Crater matrix are higher than those typically recorded in unmodified CI and CM
341 meteorite matrix (Lee *et al.* 2016), and more similar to carbonaceous chondrite types that
342 have undergone a small degree of dehydration from thermal processing at around 500-600°C
343 (Nakamura 2006, Lee *et al.*, 2016).

344

345 Peak temperatures experienced by the bulk Bench Crater meteorite can be constrained by
346 petrographic observations. The preservation of saponite indicates that the bulk meteorite did
347 not experience heating over ~700-900°C, as saponite has been shown to fully decompose
348 above these temperatures (e.g., Akai, 1997; Nozaki et al., 2006). Moreover, temperatures

349 cannot have exceeded *ca.* 600-700 °C as carbonates are not decomposed and no vesicles can
350 be seen in calcite phases (from CO₂ loss) (Fig. S-8), (e.g, Nakamura, 2006; Nozaki *et al.*,
351 2006). As no serpentine is observed in the Bench Crater sample matrix, heating may have
352 occurred at temperatures between ~400 and 800°C as serpentine breaks down by ~400°C
353 (Tomioka *et al.*, 2007). Boundaries of the aqueously altered chondrules are generally well
354 preserved (Figs. 1 and 2), analogous to those observed in carbonaceous chondrite heating
355 experiments <600 °C (Tonui *et al.*, 2014). Interestingly, *ca.* 600 °C also corresponds to the
356 temperature where hydrogen isotope anomaly hotspots have been shown to disappear in
357 Murchison organics (Remusat *et al.*, 2016), which may account for the absence of hydrogen
358 hotspots in Bench Crater. Therefore, we estimate that the bulk Bench Crater meteorite
359 underwent heating between ~400-600 °C, which was enough to partially, but not totally,
360 dehydrate the fine-grained matrix.

361

362 It is challenging to determine if heating of Bench Crater was caused by asteroidal parent body
363 processes (for example, internal heating from ²⁶Al decay, impact metamorphism, flash
364 heating from solar irradiation during an orbital transfer close to the Sun; Nakamura 2006;
365 Nakato *et al.*, 2008), during the impact event that delivered Bench Crater to the Moon, or
366 during lunar surface residence (*e.g.*, repeated diurnal thermal cycling, flash heating from
367 other impact events). It is generally thought that thermal metamorphism that has affected the
368 dozens of heated CM chondrites was short lived and took place billions of years after the
369 formation of the Solar System, ruling out internal heating from ²⁶Al decay as a possible cause
370 (*e.g.*, King *et al.*, 2019b; Amsellem *et al.*, 2020). If heating of Bench Crater took place on its
371 parent body the remaining options then include short-lived impact-related metamorphism or
372 solar irradiation. The Bench Crater meteorite does not have a strong petrofabric (Fig. 1),
373 unlike some of the shocked CM chondrite types studied by Lindgren *et al.* (2015) and Vacher

374 *et al.* (2018), suggesting that it has not been highly shocked. However, intermediate phase
375 (i.e., decomposed phyllosilicates) similar to that observed in Bench Crater was observed
376 during <21-30 GPa peak pressure impact experiments on the Murchison (CM2) meteorite
377 (Tomioka *et al.*, 2007). Thus, it is difficult to further discriminate whether shock
378 metamorphism or solar irradiation were responsible for heating of Bench Crater if
379 metamorphism took place on its parent body.

380

381 **6.3. Isotopic fractionation effects**

382 Hydrogen in carbonaceous chondrites is hosted within both phyllosilicate and organic phases,
383 whereas carbon and nitrogen are mostly hosted within organic components, and to a lesser
384 extent within carbonates for carbon (e.g., Pearson *et al.*, 2006; Alexander *et al.*, 2007, 2012;
385 Füri and Marty, 2015; van Kooten *et al.*, 2017; Piani and Marrocchi, 2018; Piani *et al.*, 2018).
386 The H and C isotope compositions obtained on two areas of Bench Crater are similar to those
387 obtained on bulk CI and CM chondrite meteorites (Fig. 7). The H isotope compositions
388 measured in Bench Crater is also consistent with the H isotope compositions measured in CI-
389 and CM-like clasts found in Howardite-Eucrite-Diogenite meteorites (Patzek *et al.*, 2020). On
390 the other hand, the N isotope composition of Bench Crater is intermediate between the bulk
391 $\delta^{15}\text{N}$ values of CI-CM chondrites and the bulk $\delta^{15}\text{N}$ value of the 12037 soil (Figs. 7 and 8,
392 Table S-2). Figure 7 indicates that there may be some slight δD , $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ variability
393 between the two area analysed that may relate to sample heterogeneity on the scale of a few
394 microns. Alternatively, the observed δD , $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ variations may be related to localised
395 impact shock-induced volatile element isotopic fractionation (Tomioka *et al.*, 2007). It is
396 easier to ‘lose’ the isotopes ^{13}C , ^{15}N and H mostly bound in inorganic phyllosilicate
397 components in CI-CM type chondrites than ^{12}C , ^{14}N and D that are mostly bound in insoluble
398 organic matter, as has been shown for CM chondrites during 30-40 GPa peak shock pressure

399 impact events (*i.e.* <1.5 km/s velocities) (Tyburczy *et al.*, 2001). Starting from CM chondrite-
400 like H, C and N isotope characteristics, such a process could qualitatively explain the
401 concomitant δD increase and $\delta^{13}\text{C}$ - $\delta^{15}\text{N}$ decrease observed for the two areas analysed in the
402 Bench Crater meteorite.

403

404 **6.4. Implications for the survivability of hydrated asteroids and their volatile budgets** 405 **delivered to the lunar surface**

406 *Nitrogen isotopes:* The wide range of isotope signatures observed for N trapped in the lunar
407 regolith is consistent with varying mixing proportions between isotopically light solar wind N
408 ($\delta^{15}\text{N}$ around -400 ‰) and a more ^{15}N -rich ‘planetary’ component (Hashizume *et al.*, 2000;
409 Füri and Marty, 2015; Füri *et al.*, 2015; Mortimer *et al.*, 2016) (Fig. 8). The Bench Crater
410 $\delta^{15}\text{N}$ value of -40 ± 18 ‰ is lower than bulk N isotope compositions of CI-CM carbonaceous
411 chondrite meteorites (Fig. 7). This may indicate that Bench Crater sampled an asteroidal
412 parent-body not represented in the meteorite collection. However, the original N isotope
413 composition of Bench Crater may have also been modified on the lunar surface. Its $\delta^{15}\text{N}$
414 value is intermediate between that of the bulk 12037 soil and bulk CI-CM chondrite $\delta^{15}\text{N}$
415 values (Fig. 7), which may indicate that the original N isotope composition of Bench Crater
416 has been lowered due to isotopic exchange with N in the target mare basaltic Apollo 12 soil,
417 possibly during the flash-heating event that formed the meteorite’s agglutinitic rim (Fig. 4).
418 However, this latter scenario seems unlikely since CM-like chondrites contain more than one
419 order of magnitude more N (~600 to 1000 ppm; Pearson *et al.*, 2006; Alexander *et al.*, 2012)
420 compared to the 12037 bulk soil (~40 ppm; Becker and Clayton, 1978; Kerridge *et al.*, 1978).

421

422 *Hydrogen isotopes:* *In situ* analyses of Apollo soil and agglutinate particles have yielded a
423 large range of D/H ratios, suggesting mixing between nearly D-free implanted solar wind (δD

424 ~ -1000 ‰) and H-bearing sources with higher D/H ratios that may include reworked
425 (melted) material from vaporisation of impacting D-rich organics or water-bearing asteroids,
426 interplanetary dust particles (IDPs) and comets, volcanic gases, or caused by a spallogenic
427 component (Liu *et al.*, 2012; Stephant and Robert, 2014). Bench Crater has δD values
428 ranging between -36 ± 40 and 200 ± 40 ‰ (Figs. 7 and 8). It is unlikely that the D/H ratio of
429 Bench Crater hydrogen-bearing species could have been significantly altered by interacting
430 with low D/H hydrogen derived from the lunar target soil since CM-like chondrites contain
431 more than two orders of magnitude more H (*ca.* 1-1.5 wt%; e.g., Alexander *et al.*, 2012) than
432 Apollo 12 bulk soils (*ca.* 10-100 ppm; e.g., Carter, 1985). Instead we interpret that this range
433 of δD values of 0-200 ‰ likely corresponds to the bulk original H isotope composition of the
434 Bench Crater parent body, which is consistent with bulk H isotope compositions measured in
435 CI and CM chondrites (Figs. 7 and 8).

436

437 **7. Conclusions**

438 The survivability of hydrated asteroidal material in Apollo 12 soil 12037 indicates that (i)
439 delivered volatiles are stable against small meteoritic impact events at the Moon's surface,
440 and (ii) agglutination of impactor particles either during the impact event, or subsequently
441 during lunar regolith gardening, does not necessarily cause complete degassing and
442 dehydration or light stable isotope fractionation of delivered hydrated material. These
443 findings provide important constraints to ground-truth future lunar prospecting missions that
444 will investigate the volatile concentration and isotopic composition of the lunar regolith at,
445 and below, the surface (e.g., Carpenter *et al.*, 2014; Colaprete *et al.*, 2016; Barber *et al.*,
446 2017). Bench Crater provides critical constraints for these exploration activities that aim to
447 identify the sources of different volatile species with depth and time.

448

449 Bench Crater bears some resemblance with highly aqueously altered and/or brecciated CM
450 chondrites such as Boriskino (Vacher *et al.*, 2018; Verdier-Paoletti *et al.*, 2019) and LON
451 94101 (Lindgren *et al.*, 2013). However, fully evaluating the possibility that Bench Crater is a
452 CI-like clast-rich brecciated CM chondrite is hindered by its limited size and thus
453 representativeness. With this caveat in mind, detailed mineralogical, geochemical, and
454 isotopic data obtained on Bench Crater might also suggest that it is unique compared with
455 known carbonaceous meteorite groups present in our meteorite collection, providing evidence
456 for delivery of a sample from a previously unknown type of mildly thermally processed
457 carbonaceous asteroid parent body. Other types of potentially unique partially thermally
458 heated carbonaceous chondrite clasts have also been observed in other planetary regolith
459 samples, including those from the howardite and ureilite parent bodies (Zolensky *et al.*, 2019
460 and references therein). These thermally processed carbonaceous meteorites can provide
461 important constraints for interpreting spectral observations of the surface of carbonaceous
462 asteroids that likely host a mixture of hydrated and dehydrated phases (e.g., King *et al.*,
463 2019). In addition, they may provide a close match to samples that will be brought back from
464 asteroid 162173 Ryugu by the Hayabusa2 spacecraft in 2020, since spectral characteristics of
465 its surface are consistent with those of thermally metamorphosed CI-CM-CY carbonaceous
466 chondrites (e.g., King *et al.*, 2019a; Kitazato *et al.*, 2019).

467

468 Altogether, Bench Crater mineralogical, geochemical and isotopic characteristics do not
469 match any other types of carbonaceous chondrite present in our collections. Given that Bench
470 Crater may have been delivered to the Moon anytime in the last 100 Myr, this may indicate a
471 recent change in sources of materials impacting the Earth-Moon system. Identifying such
472 changes would help to better understand the sources and causes of impact bombardment,
473 providing better constraints to refine theoretical Solar System models (e.g., Wetherill, 1975)

474 and track the migration of volatile-rich planetary bodies into the inner Solar System through
475 time (Joy *et al.*, 2016).

476

477

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767

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777 meteorite and for that serendipitous discovery we are grateful.

778

779

780 **Figure Captions**

781 **Figure 1.** The Bench Crater meteorite. **(a)** Transmitted light optical image of Bench Crater
782 meteorite showing a dark matrix and brown-coloured ferromagnesian silicate aggregates. **(b)**
783 BSE image; the white arrow indicates the location where some matrix was extracted for
784 NanoSIMS analysis; and see Figure S-4 for close up images. **(c)** False colour X-ray element
785 composite map showing the mineralogical composition of the meteorite. Colour scheme
786 indicated on the figure, where ferromagnesian silicate aggregates are cyan; matrix material is
787 blue; apatite, calcite and dolomite are yellow; pyrrhotite, pentlandite and magnetite are red;
788 ilmenite is pink; and the feldspathic agglutinate rim is white. **(d)** False colour X-ray element
789 composite map. Colour scheme indicated on the figure, where apatite is cyan; calcite and
790 dolomite are blue; pyrrhotite and pentlandite (S-bearing phases) are yellow; and magnetite is
791 red.

792

793 **Figure 2.** BSE images of Bench Crater meteorite fabric showing a representative matrix
794 region of the meteorite (a), and close up views of different ferro-magnesian aggregates (F-M
795 Agg) (aqueously altered chondrule) comprised of intermediate phases (I-M phase),
796 amorphous phases, ilmenite, apatite and pyrrhotite (Pyrr). Black linear features are fractures.
797

798 **Figure 3.** Mineralogy of the Bench Crater meteorite (area %) compared to that of CI, CM,
799 CR, ungrouped C2 (C2-ung) and Adelaide carbonaceous chondrites. For Bench Crater, the
800 normalised modal mineral proportions have been established from pixel analysis of X-ray
801 composite phase maps of the whole section (see Supplementary Table S-2). Literature modal
802 mineralogy (vol. %) data have been acquired using X-ray diffraction and are from Howard et
803 al. (2010, 2011, 2015) and King et al. (2015, 2017) for CV, CI, CM, CR and C2-ung
804 carbonaceous chondrites, and from Davy et al. (1978) for Adelaide meteorite.
805

806 **Figure 4.** BSE images of Bench Crater meteorite. (a) – (d) Close up of the thin (<100 µm)
807 irregular vesicular glassy agglutinitic rim that partially coats about 10 % of the exterior of
808 Bench Crater meteorite. Chemical analysis of the coat shows it to be feldspathic (Table S-3).
809 Abbreviations are Ap for apatite, Mag for magnetite, F-M Agg for ferro-magnesian
810 aggregate, and Pyrr for pyrrhotite.
811

812 **Figure 5.** Oxygen isotope composition of Bench Crater matrix, magnetite and carbonate,
813 represented together with the bulk, matrix, magnetite and carbonate O isotope composition of
814 CI and CM carbonaceous chondrite falls (data from Clayton and Mayeda, 1984, 1999; Rowe
815 *et al.*, 1994; Leshin *et al.*, 1997; Verdier-Paoletti *et al.*, 2017; Vacher *et al.*, 2018; Piralla *et*
816 *al.*, 2020). CCAM and TFL stand for Carbonaceous Chondrite Anhydrous Mineral line and
817 Terrestrial Fractionation Line, respectively. Note that the lunar oxygen isotope fractionation

818 line is identical to the TFL (e.g., Wiechert *et al.*, 2001). Carbonate T1 and T2 for Boriskino
819 refers to carbonates formed before and after phyllosilicates, respectively (see Vacher *et al.*,
820 2018).

821

822 **Figure 6.** NanoSIMS maps of H, D, $^{12}\text{C}^{1}\text{H}$, ^{18}O and δD variations for Bench Crater Area 1.
823 Intensities for H, D, $^{12}\text{C}^{1}\text{H}$, and ^{18}O correspond to counts per second, while δD values are
824 given in permil normalised to VSMOW. Images have been smoothed by a moving $n \times n$
825 average where $n = 3$ and 9 pixels for intensity and δD maps, respectively, corresponding to
826 ~ 235 and 705 nm spatial resolution.

827

828 **Figure 7.** Light isotope chemistry of the Bench Crater meteorite compared with the H, C and
829 N isotope composition of a range of carbonaceous chondrites (data from Pearson *et al.*, 2006
830 and Alexander *et al.*, 2012) and the insoluble organic matter they host (data from Alexander
831 *et al.*, 2007), and of Apollo soil 12037 (Becker and Clayton, 1978; Kerridge *et al.*, 1978).
832 Data for the two regions of Bench Crater measured in this study are linked by a dashed line,
833 and uncertainties are at one sigma (Table 1). Organic rich nanoglobules from Tagish Lake
834 meteorite (Nakumura-Messenger *et al.* 2006) typically plot off-scale as is the unusual organic
835 rich CM chondrite Bells is indicated as having high $\delta^{15}\text{N}$ and δD compared with other CM
836 group stones and ordinary chondrites. For comparison to comets we refer the reader to Figure
837 8.

838

839 **Figure 8. (a)** Hydrogen and **(b)** nitrogen isotope composition of the Bench Crater meteorite
840 compared with different planetary materials (see Supplementary Information note S3 for
841 literature sources). The δD value measured *in situ* for Murchison is shown in (a).

842

844 **Table 1.** Light isotope (H, C and N) compositions determined for fragments of the Bench
 845 Crater and Murchison meteorites in this study and related literature measurements.

	δD (‰)	$\pm 2\sigma$	$\delta^{13}C$ (‰)	$\pm 2\sigma$	$\delta^{15}N$ (‰)	$\pm 2\sigma$
Murchison ^a	-117	± 98				
Murchison ^b			-1.61	± 0.19	52.7	± 0.31
Murchison ^c	-61.7	± 6.2	-2.87		45.57	
Bench Crater Area 1 ^a	-36	± 40	-2	± 20	-27	± 20
Bench Crater Area 2 ^a	200	± 40	-23	± 20	-52	± 20
Bench Crater Area 3 ^a	-13	± 18				
Bench Crater Area 4 ^a	35	± 18				
Bench Crater C and N average (n. 2)			-13	± 30	-40	± 36
Soil 12037 (bulk)			-11.91 ^d		-80.2 ^e	
Soil 12037 (bulk)					-86 ^f	
Soil 12037 (High T steps)					-125 ^f	

846

847 ^a This study, determined by NanoSIMS analysis.

848 ^b Pearson *et al.* (2006)

849 ^c Alexander *et al.* (2012)

850 ^d Average of two reported values in Kerridge *et al.* (1978)

851 ^e Kerridge *et al.* (1978)

852 ^f Becker and Clayton (1978)

853 **Table 2.** Oxygen isotope results in phases within Bench Crater meteorite.

Phase	Analysis	$\delta^{18}\text{O}$ (‰)	2 σ (‰)	$\delta^{17}\text{O}$ (‰)	2 σ (‰)	$\Delta^{17}\text{O}$ (‰)	2 σ (‰)
Silicates in aqueously altered chondrule	#1	14.58	1.28	6.51	0.54	-1.07	0.86
	#2	11.42	1.19	6.44	0.55	0.50	0.82
	#3	9.91	1.21	5.21	0.52	0.06	0.82
	#4	12.40	1.22	6.37	0.51	-0.08	0.82
	#5	11.63	1.19	6.36	0.51	0.32	0.80
	#6	12.79	1.19	6.42	0.51	-0.23	0.80
	#7	15.98	1.21	8.13	0.53	-0.18	0.82
	#8	16.79	1.16	8.30	0.52	-0.43	0.80
	#9	11.06	1.20	5.73	0.51	-0.02	0.80
Magnetite	#1	7.98	0.68	5.59	0.39	1.44	0.52
	#2	8.50	0.67	6.05	0.32	1.63	0.48
	#3	5.77	0.60	4.77	0.35	1.77	0.47
	#4	5.72	0.55	4.78	0.32	1.81	0.43
Carbonates	Dolomite#1	19.95	0.46	9.26	0.40	-1.12	0.47
	Calcite#1	12.76	0.54	6.39	0.38	-0.25	0.47

854

855

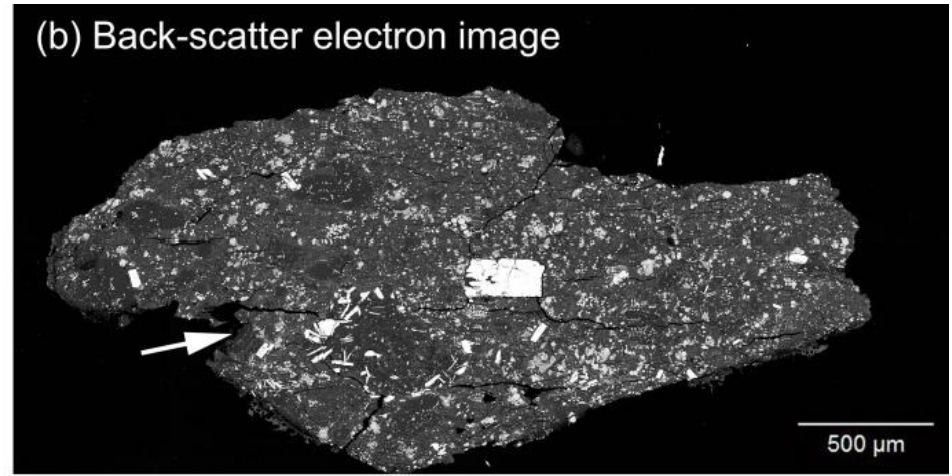
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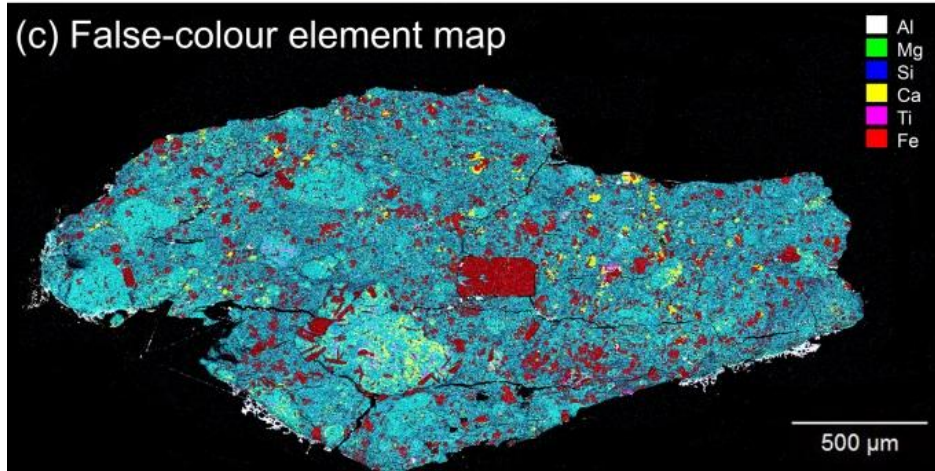
(a) Optical image



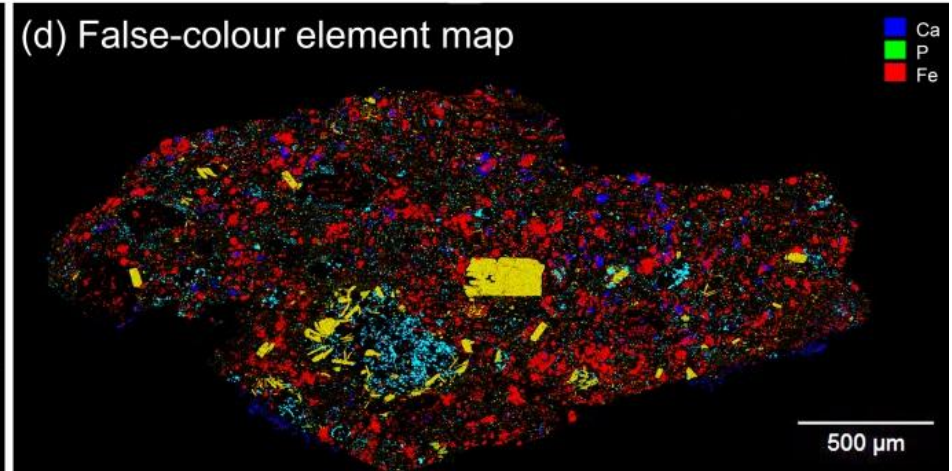
(b) Back-scatter electron image



(c) False-colour element map



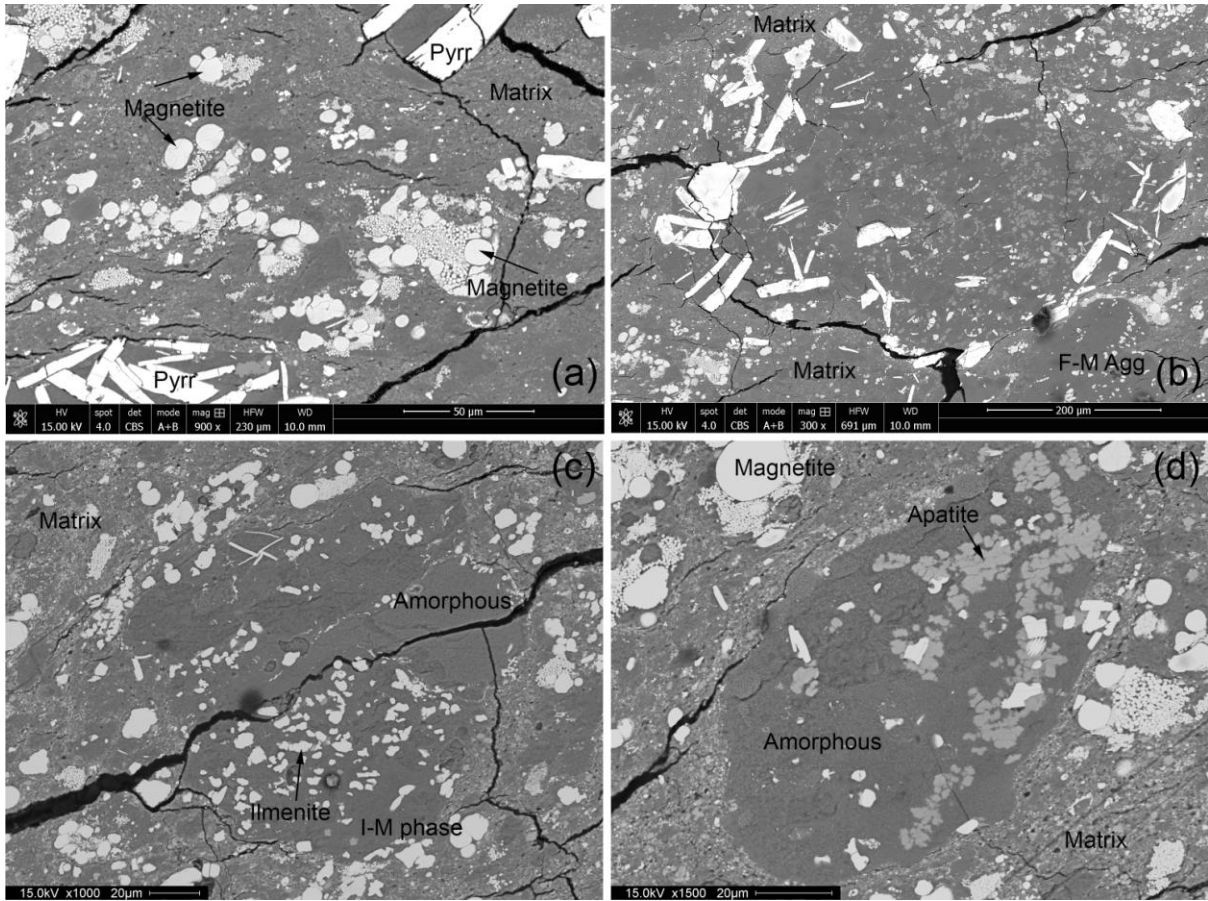
(d) False-colour element map



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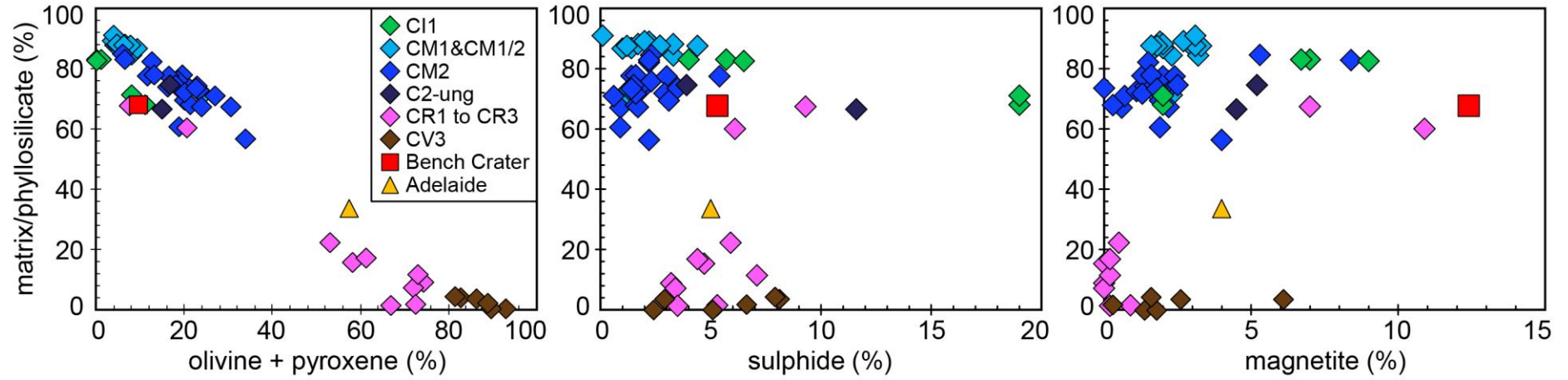
859 **Figure 1.**

860



861

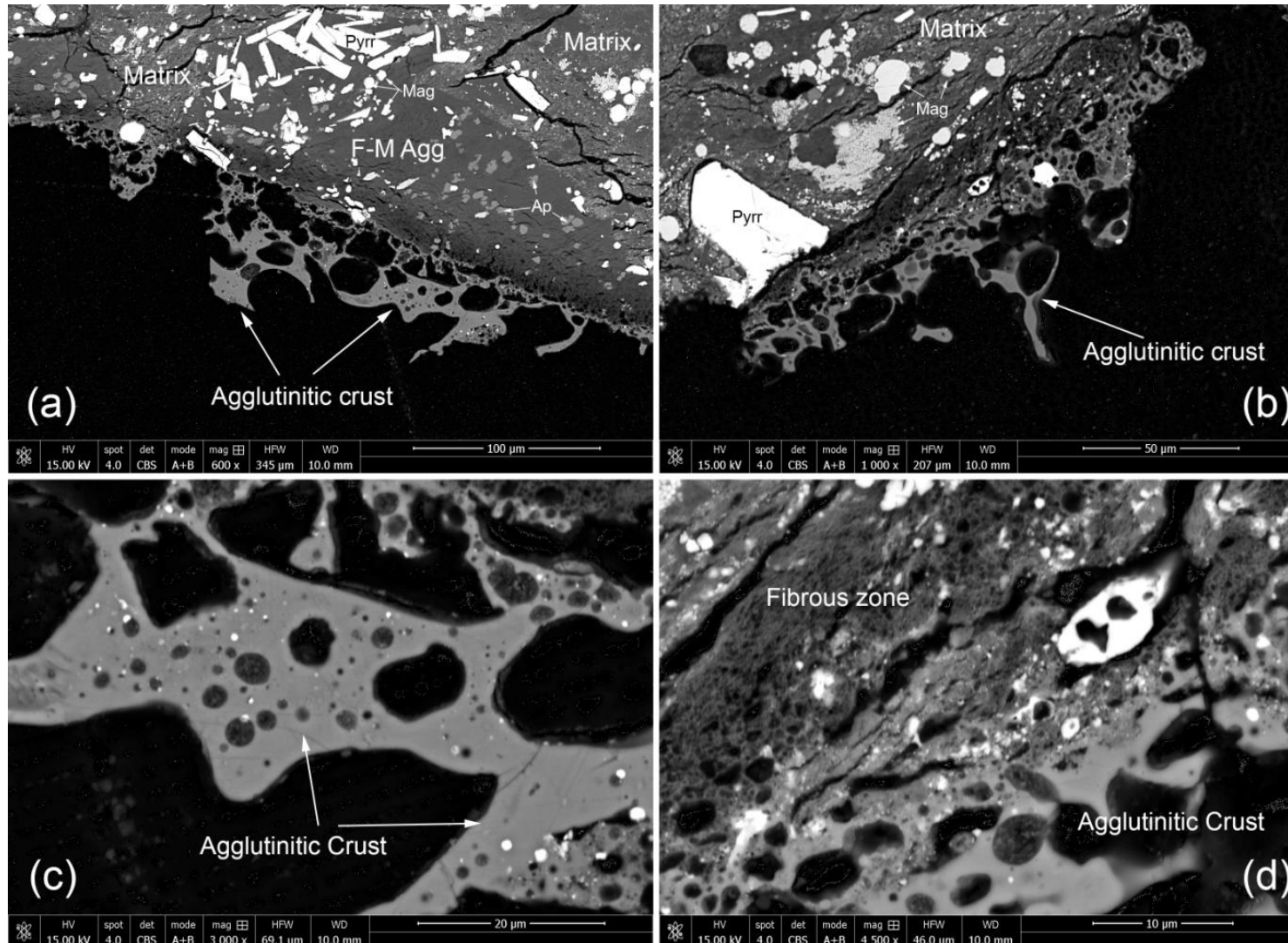
862 **Figure 2.**



863

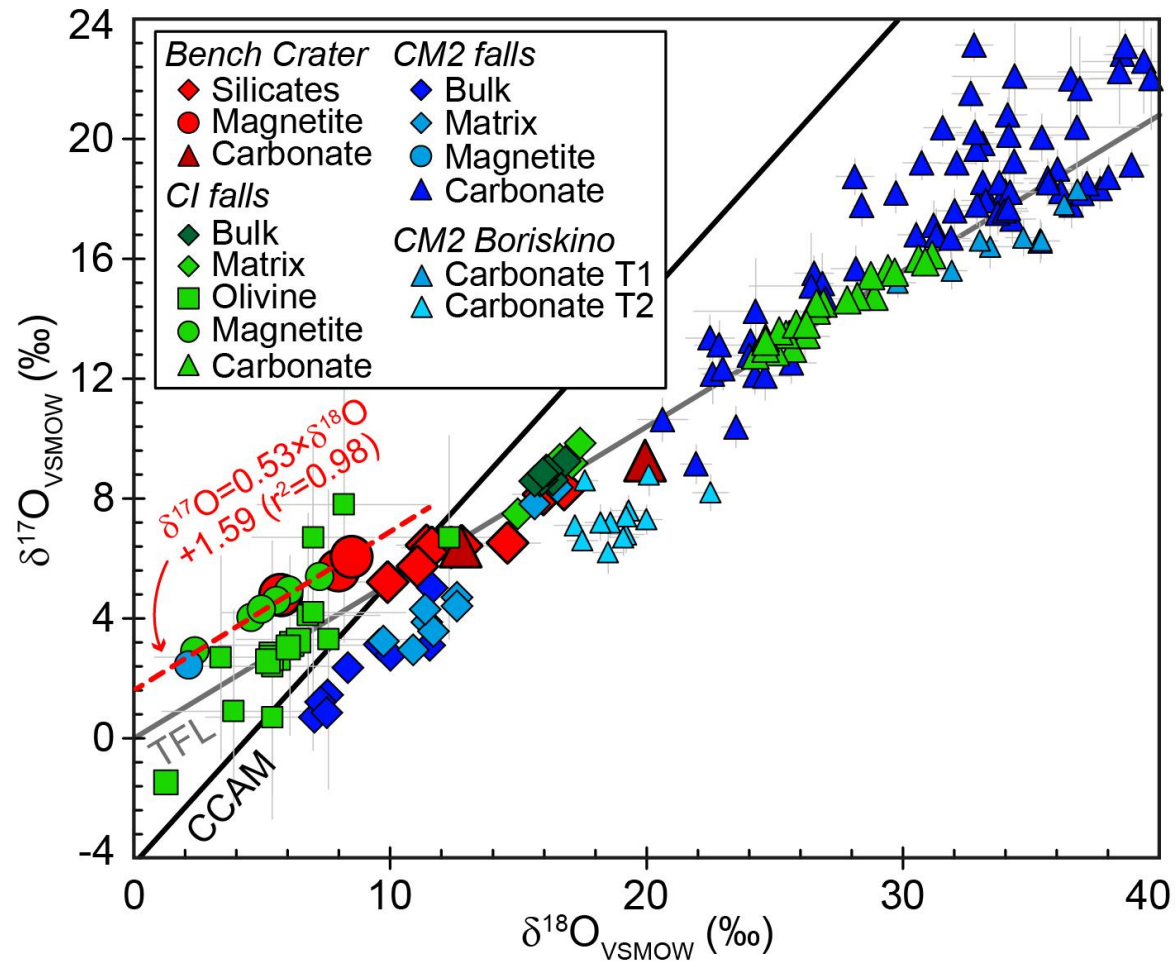
864 **Figure 3.**

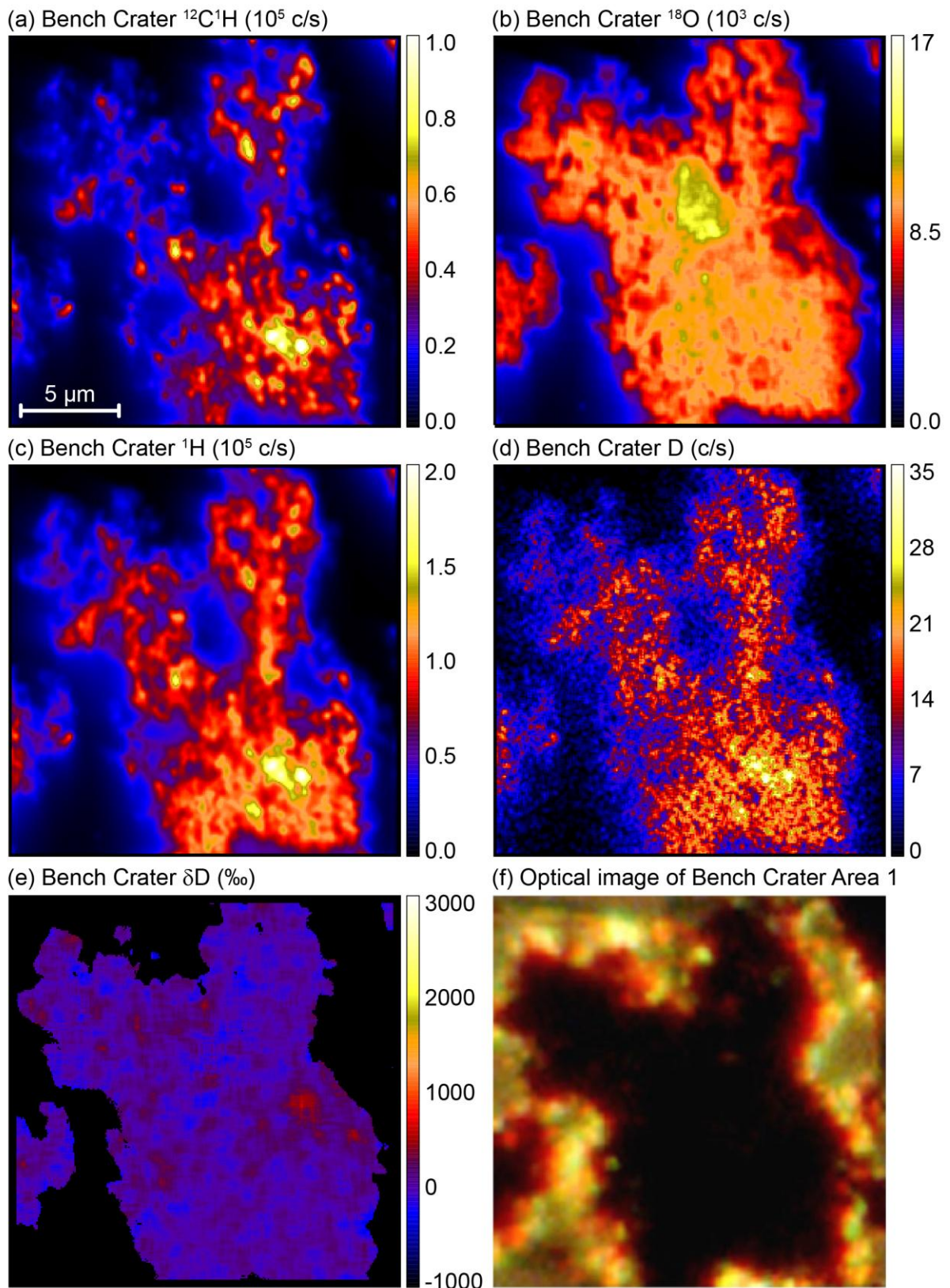
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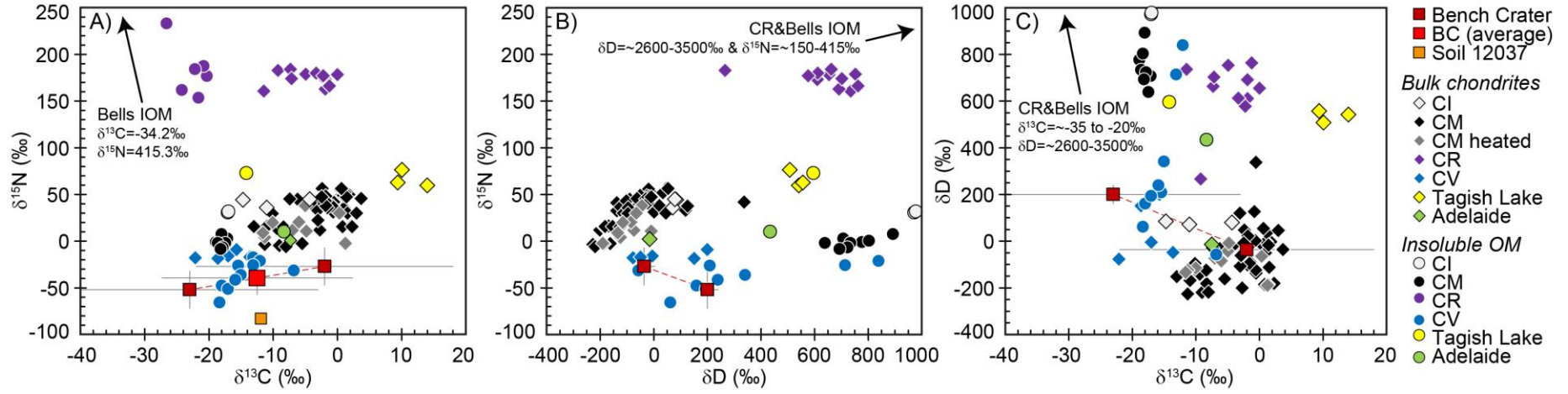
867 **Figure 4.**





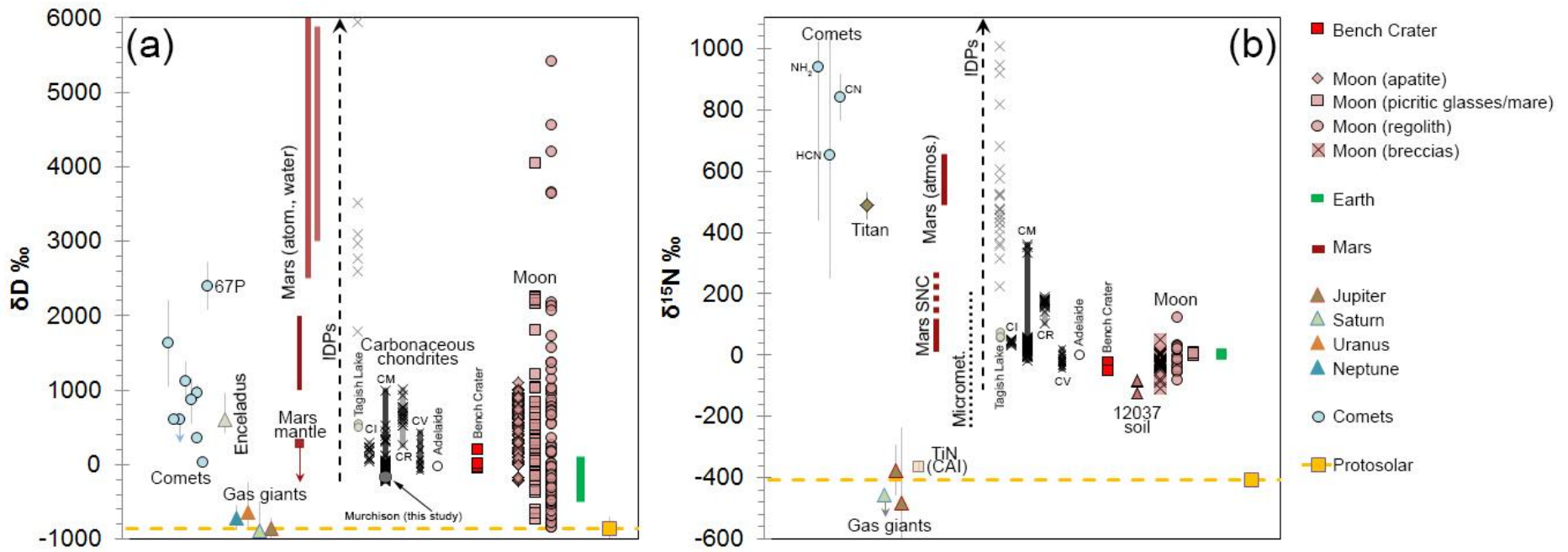
871

872 **Figure 6.**



873

874 **Figure 7.**



875

876 **Figure 8.**