

1 **Detection of organic compounds in impact glasses formed by the collision of an**  
2 **extraterrestrial material with the Libyan Desert (Africa) and Tasmania (Australia)**

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10  
11 **ABSTRACT**

12 Impact glasses are rich silica melted formed at high temperature and pressure by the  
13 impact of an extraterrestrial body on Earth. Here, Libyan Desert Glasses (LDGs) and  
14 Darwin Glasses (DGs) were studied. Two non-destructive analytical techniques were  
15 used to detect and characterize organic compounds present in their inclusions: Raman  
16 spectroscopy and Scanning Electron Microscopy coupled to energy dispersive X-ray  
17 spectroscopy (SEM-EDS). Phytoliths, humboldtine, palmitic acid, myristic acid, oleic  
18 acid, 4-methyl phthalic acid and S-H stretching vibrations of amino acids were  
19 identified. The presence of these particular organic compounds in such materials has not  
20 been reported so far, providing information about (a) the ancient matter of the area  
21 where the impact glasses were formed, (b) organic matter belonging to the  
22 extraterrestrial body which impacted on the Earth, or (c) even to current plant or  
23 bacterial life, which could indicate an active interaction of the LDG and DG with the  
24 surrounding environment. Moreover, the identification of fullerene allowed us to know

25 a pressure (15 GPa) and temperatures (670 K or 1800-1900 K) at which samples could  
26 be subjected.

27

28 **Keywords:** impact glass; Libyan Desert Glass; Darwin Glass; organic compounds;  
29 Raman spectroscopy

30

### 31 **1. Introduction**

32 The presence of organic matter has been already mentioned in meteorites, comet and  
33 asteroidal dust [1, 2]. This is an important fact to the search of life in the Solar System,  
34 because these molecules are used as biomarkers (i.e. chemicals that indicate life) on  
35 Earth. However, there is always a dilemma with the origin of organic compounds in  
36 extraterrestrial or impact materials. Their survival is difficult to understand after certain  
37 conditions, such as the impact on Earth with high temperature and/or pressure. Thus,  
38 they could be considered like a terrestrial contamination according to some literature [1,  
39 3]. Normally, the identified terrestrial organic contaminants in meteorites are low  
40 molecular weight or solvent-soluble hydrocarbons [3].

41 The same situation could happen with the organic matter in impact glasses. They are  
42 natural rich silica-melts produced by hypervelocity impact events of a meteorite,  
43 asteroid or comet on any geographic area on Earth, probably at pressures higher than 20  
44 GPa [4]. They can be ejected away from the impact site to short or large distances and  
45 are usually named with the location of their origin. In this work, organic content in  
46 Libyan Desert Glasses (LDGs) and Darwin Glasses (DGs) was analyzed by non-  
47 destructive analytical techniques.

48 LDGs fragments are scattered in the Western Desert of Egypt (near the Libyan border)  
49 in the soils' surfaces lying in interdune channels over an area of 6500 km [1, 5]. They

50 are commonly small irregular pieces with yellow to whitish translucent colour together  
51 with dark inclusions [5], and they are estimated to be 28.5 million years old [6].  
52 Chemically, LDGs are nearly pure silica (95.5-99% wt SiO<sub>2</sub>) [7]. Nonetheless, they are  
53 also composed by other compounds, which are sometimes forming bubbles, black or  
54 brownish inclusions (possibly derived by melting or decomposition of iron oxides), dark  
55 or brown streaks and white cristobalite spherulites. The concentration of impurities is  
56 highly variable [5, 8, 9].

57 In the case of DGs, they are located in the Western Tasmania (Australia) in a densely  
58 forested valley [10, 11]. Glass fragments were recovered 20 km from the source crater  
59 and within a 400 km<sup>2</sup> strewn field [10]. They are estimated to be 796-815 million years  
60 old [11]. Chemically, DGs contain different percentages of SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>, FeO,  
61 MgO and K<sub>2</sub>O [10].

62 Both impact glasses were found in two terrestrial areas with diversity of climates: a  
63 desert, arid and dry, and a forest, wet and with numerous vegetation. The different  
64 terrestrial weathering processes of both climates could influence the composition of the  
65 samples.

66 Most of investigations about LDG and DG are focused on the identification of inorganic  
67 mineral phases [4-10, 12-15]. In contrast, the study of organic compounds trapped in  
68 them is hardly mentioned. Despite this fact, it is a remarkable point that can provide  
69 information about the ancient life in the area where they were formed, or even about  
70 organic compounds belonging to the extraterrestrial body, since some elements found in  
71 LDGs and DGs have been assigned to meteoritic matter [8, 14, 15]. The impact, with its  
72 corresponding high pressures and temperatures, could mean the removal or  
73 transformation of the organic remains. However, some authors mention that there is

74 always a gradient of temperature and pressure during the impact. Hence, there could be  
75 a chance of survival at relatively low temperatures and pressures [16].

76 Among the techniques employed in the analysis of organic compounds in impact  
77 glasses are those in charge of the elemental characterization: two-step Laser  
78 desorption/Laser ionization Mass Spectrometry (L2MS), Field Emission Scanning  
79 Electron Microscopy (FE-SEM) and Scanning Electron microscopy (SEM) or  
80 Transmission Electron Microscopy (TEM) [17,18] with Energy Dispersive X-ray  
81 spectroscopy (EDS), and Scanning Transmission X-ray Microscopy (STXM) near edge  
82 X-ray Absorption Fine structure Spectroscopy (NEXAFS) [19]. Besides, those  
83 techniques are employed for the molecular analysis: Fourier Transform infrared (FT-IR)  
84 spectroscopy [19] and Pyrolysis–gas chromatography–mass spectrometry [16].

85 In our work, SEM-EDS was firstly employed to detect inclusions where carbon (an  
86 indication of possible organic matter) was present. Then, micro-Raman spectroscopy  
87 was used to obtain the molecular information about the compounds in the inclusions.  
88 Raman spectroscopy has been already employed in the identification of organic matter  
89 in meteorites [20]. Besides, it will be used onboard ExoMars2020 and Mars2020  
90 missions, in order to identify organic compounds as indication of life in the  
91 extraterrestrial environment of Mars [21]. Therefore, despite no works about using  
92 Raman spectroscopy to detect organic compounds in LDGs and DGs were found in  
93 literature, we thought that this technique would be appropriate because of its experience  
94 in the study of terrestrial and extraterrestrial materials. Moreover, the capabilities shown  
95 by micro-Raman spectroscopy to analyze the nature of inclusions give benefit to our  
96 approach. In addition, Raman analysis was carried out without sample destruction and  
97 any kind of pre-treatment, maintaining the integrity of the samples to new analysis in  
98 the future.

## 100 2. Material and methods

### 101 2.1 Material

102 Eighteen impact glasses from the Meteorites Collection of the Basque Country  
103 University (UPV/EHU) were analyzed, of which 8 are LDGs and 10 are DGs. They  
104 were collected during an expedition to the Western Desert of Egypt and to the Western  
105 Tasmania respectively. The LDGs have a translucent glassy matrix, with whitish  
106 spherical, brownish and dark inclusions in some cases (see Fig.S1). Their dimensions  
107 range between 1-5 x 2-4 cm and 5-23 g weight. On the contrary, DG samples are mainly  
108 spheroid, and with different shades: a green brownish dark colour, black or very light  
109 and translucent and most of them have some bubbles inside the bulk (see Fig. S1). Most  
110 of the specimens are mainly not higher than 1×1 cm, but some of them have dimensions  
111 of 4.5×3.7 cm, 3×1 cm and 2.8×1 cm.

112 In general, the silica glass matrix of the LDGs exhibits a holohyaline texture with some  
113 mineral occurrence such as aluminum-rich tiny crystallites, cristobalites ( $\text{SiO}_2$ ) and  
114 zircons ( $\text{ZrSiO}_4$ ). Moreover, there are other minerals trapped within the LDG matrix,  
115 such as silicon oxides (quartz ( $\alpha\text{-SiO}_2$ ), coesite ( $\text{SiO}_2$ )), silicates (microcline feldspar  
116 ( $\text{KAlSi}_3\text{O}_8$ ), forsterite ( $\text{Mg}_2\text{SiO}_4$ ), enstatite ( $\text{MgSiO}_3$ ), tephroite ( $\text{Mn}_2\text{SiO}_4$ )), sulphates  
117 (gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ), anhydrite ( $\text{CaSO}_4$ ), carbonates (calcite ( $\text{CaCO}_3$ ), magnesite  
118 ( $\text{MgCO}_3$ )), etc. [22]. In the case of the DGs, they are vesicular with a glassy  
119 groundmass. The glassy groundmass is holohyaline defining Schlieren structures. These  
120 structures are characterised by the presence of abundant elliptical vesicles. Among the  
121 mineral compounds found in our DGs are cristobalite ( $\text{SiO}_2$ ), malachite ( $\text{Cu}_2\text{CO}_3(\text{OH})_2$ )  
122 and ponsjankite ( $\text{Cu}_4\text{SO}_4(\text{OH})_6\text{H}_2\text{O}$ ) [13].

### 123 2.2 Methods

124 **2.2.1 Thick and thin section preparations.**

125 Some LDGs and DGs were sliced in order to facilitate the analysis of the inner  
126 inclusions. Thick and thin sections were prepared to get samples of small thickness.  
127 Sections were obtained by slicing the samples using a cutting (Buehler-PetroThin) with  
128 a diamond saw. In order to acquire a perfectly flat surface without deformations, the  
129 fragments were polished using silicon carbide powder of different grain size on frosted  
130 glasses. The thick of the fragments was approximately 800  $\mu\text{m}$ . Once obtained the flat  
131 surface, in the case of the thin sections, the samples were mounted on glass slides  
132 (dimensions of 27 x 46 x 1.5 mm) with epoxy resin (a fixer compound composed of  
133 polyurethane, acrylic and cyanoacrylate) and then, the samples were smoothed using  
134 progressively finer abrasive grit until they were only 30  $\mu\text{m}$  thick.

135 **2.2.2 Scanning Electron Microscopy coupled to Energy Dispersive X-ray**  
136 **spectroscopy (SEM-EDS).**

137 It was used an EVO 40 Scanning Electron Microscope (Carl Zeiss NTS GmbH,  
138 Germany) coupled to an X-Max Energy-Dispersive X-Ray spectroscopy (EDX) system  
139 (Oxford Instruments, UK) for the elemental mapping. The equipment is also installed  
140 on an antivibratory table inside a temperature-controlled room. SEM images were  
141 acquired at high vacuum employing an acceleration voltage of 20 KV. Magnifications  
142 up to 10 000 $\times$  were reached using a Secondary Electron (SE) detector for image  
143 acquisitions. Moreover, elemental mappings were performed using an 8.5 mm working  
144 distance, a 35 $^\circ$  take-off angle and an acceleration voltage of 20 kV.

145 **2.2.3 Raman spectroscopy.**

146 Two Raman spectrometers were employed in order to use three lasers (785 nm, 514 nm  
147 and 532 nm). Firstly, it was used a Renishaw RA 100 Raman Spectrometer, coupled to  
148 a fibre optic micro-probe (Oxford, UK), equipped with 785 nm excitation laser and a

149 Peltier cooled CCD detector. At 100% laser power, the nominal power of the excitation  
150 source is 150 mW and in the sample 30 mW. Neutral filters allow working at 1% (5  
151 mW at the source and 1 mW at the sample) and 10% (50 mW at the source and 10 mW  
152 at the sample) as well. This parameter was varied if thermodescomposition was  
153 observed.

154 The micro-probe was joined to different long range lenses (4×, 20× and 50×) that  
155 allowed us to focus the laser beam around 5-100  $\mu\text{m}$  at the sample. The spectral  
156 resolution is around  $2\text{ cm}^{-1}$ . The instrument is also coupled to a micro-camera whose  
157 positioning is controlled by a micrometric stage, which permits a perfect focusing on  
158 the areas of interest.

159 The second spectrometer was an InVia confocal micro Raman instrument (Renishaw,  
160 UK) provided by 514 nm and 532 nm excitation lasers (at highest powers, the nominal  
161 laser power at the source is 50 mW, and at the samples 20 mW) and Peltier cooled CCD  
162 detector ( $-70^{\circ}\text{C}$ ). The instrument is coupled to a Leica DMLM microscope (Bradford,  
163 UK). For visualization and focusing 5x N PLAN (0.12 aperture) and 20x N PLAN EPI  
164 (0.40 aperture) lenses were used. The spectra were acquired using 50x N PLAN (0.75  
165 aperture, lateral resolution of  $2\text{ }\mu\text{m}$ ) long-range objectives. At high magnifications, the  
166 laser spot was reduced to  $1\text{ }\mu\text{m}$  diameter. The microscope implements a Prior Scientific  
167 motorized XYZ positioning stage with a joystick, and has a micro-camera for searching  
168 points of interest. In order to obtain Raman chemical images, the StreamLine  
169 technology (Renishaw) was employed. The inVia's motorized microscope stage moves  
170 the sample beneath the lens so that the line is rasterized across the region of interest.  
171 Data are swept synchronously across the detector as the line moves across the sample,  
172 and are read out continuously. Moreover, the equipment is installed on an antivibratory  
173 table inside a temperature-controlled chamber. The spectral resolution is of  $1\text{ cm}^{-1}$ .

174 In order to achieve the best signal-to-noise ratio the number of accumulations and  
175 integration time were varied in both spectrometers. WIRE 3.2 software (Renishaw, UK)  
176 was used for data collection and initial pre-treatment, while the data treatment was  
177 carried out with the Omnic software (Thermo Fisher-Nicolet, Madison, Wisconsin,  
178 USA). Furthermore, the results were compared with standard Raman spectra from the e-  
179 VISARCH and e-VISART Raman spectra databases [23] and spectra obtained from the  
180 on-line database RRUFF [24].

181

### 182 **3. Results and discussion**

#### 183 **3.1 Darwin glasses (DGs)**

184 According to SEM images and elemental mappings performed over sections of DGs  
185 (Fig. 1), carbon was identified in some of inner inclusions. The spatial distribution of  
186 elements such as C, O, Al, Si, etc. (see elemental mappings of Fig. 1) allowed us to  
187 distinguish that the carbon elemental mapping did not coincide with any element  
188 detected in the sample, indicating the possible presence of organic carbon. Therefore,  
189 Raman spectroscopy was centered on such inclusions to detect organic compounds.

190 In our previous work about DGs, a group of Raman bands around  $3000\text{-}2800\text{ cm}^{-1}$  was  
191 observed, and they were attributed to C-H stretching vibrations [13]. In the present  
192 work, other Raman bands appeared at 3009sh, 2930vs, 2892vs, 2851vs, 1653m, 1606m,  
193 1460sh, 1439m, 1301m, 1265sh and  $1060\text{vw cm}^{-1}$  as well (see Fig. 2). According to  
194 bibliography [25, 26], they correspond to a mixture of oleic acid ((Z)-9-octadecenoic  
195 acid,  $\text{CH}_3(\text{CH}_2)_7\text{CH}=\text{CH}(\text{CH}_2)_7\text{COOH}$ ) and 4-methyl phthalic acid (Benzene-1,2-dioic  
196 acid,  $\text{CH}_3\text{C}_6\text{H}_3\text{-1,2-(CO}_2\text{H)}_2$ ). Oleic acid is a common fatty acid that plays a key role in  
197 plants [27], and the methyl derivative of the phthalic acid is a constituent of combustion  
198 products and could be released from plants into the air [28]. Therefore, the presence of



199 both compounds would be an indication of the interaction of the DGs with the  
200 surrounding environment, characterized by being densely forested and wet. Moreover,  
201 degradations products of those compounds have not been identified in the DGs.  
202 According to literature [16], organic components inside DGs could be trapped into the  
203 impact melt in a low-oxygen environment and preserved when the melt quenched to  
204 glass, avoiding the organic breakdown by oxidation since the impact [16].

205 The oleic acid and the methyl derivative of the phthalic acid have been identified in the  
206 inner inclusions of our samples, so their initial trapping during the impact is highly  
207 probable. Moreover, those inclusions could have acted as closed low-oxygen  
208 environment avoiding the oxidation of the organic matter.

209 In addition, the presence of halite, sulphates, carbonates, phyllosilicates, silica, hematite  
210 and phosphates can isolate and biosignatures [29]. Sulphates, carbonates and silica are  
211 present in our DGs [13], so they could have conserved the organic compounds. Also,  
212 silica-rich water derived from hydrothermal systems is another well-established  
213 medium that promotes faithful preservation [29].

214 Notwithstanding, it cannot be ruled out the presence of partially soluble organic  
215 compounds due to terrestrial weathering processes.

216 Fatty acids and polycyclic aromatic hydrocarbons (PAHs), such as 4-methyl phthalic  
217 acid, have been previously found in meteorites [30], but not so often in these impact  
218 glasses.

### 219 **3.2 Libyan Desert Glass (LDGs)**

220 In this case, we also found carbon in the inner bubbles of LDG specimens by means of  
221 Raman image analysis, again suggesting the presence of organic compounds in such  
222 inclusions. However, not only inclusions were detected inside our LDGs, but also in  
223 their outermost part.

224 Among superficial inclusions distributed through the translucent glassy matrix of the  
225 LDG specimens, Raman spectra with bands at 3074m, 2963sh, 2938vs, 2905sh, 1716m,  
226 1607s, 1450w, 1367vw, 1273w, 1189w, 1101w, 1020vw, 930vw, 860vw, 833vw, 724w,  
227 635w and 462vw  $\text{cm}^{-1}$  were found (see Fig. 3). Except for the feature at 462  $\text{cm}^{-1}$ , which  
228 corresponds to quartz from the glassy matrix of the LDGs [12], no similar spectrum has  
229 been previously described in any of the LDG studies. According to bibliography, the  
230 Raman spectrum could be assigned to phytoliths [31]. Phytoliths are silica particles  
231 stemming from living plants that provide support and protection to the plant. During the  
232 silicification process, small amounts of organic matter are trapped [31]. In our spectrum  
233 (see Fig. 3), such organic matter has been observed with peaks in the range about 3100-  
234 3000  $\text{cm}^{-1}$ , characteristics of aromatic C-H stretching modes, and Raman bands between  
235 3000-2800  $\text{cm}^{-1}$  attributed to C-H stretching vibrations. The range from 1650-1300  $\text{cm}^{-1}$   
236 includes various aromatic C-C stretching vibrations, and the range from approximately  
237 1250 to 1000  $\text{cm}^{-1}$  contains bands commonly attributed to C-H bending modes [32, 33].  
238 Normally, when the plant dies, phytoliths are released into the soil, where they can be  
239 accumulated for thousands of years [31]. In this way, those terrestrial materials could  
240 have been adhered to the LDGs after or during the impact of the extraterrestrial body on  
241 the Libyan Desert. Moreover, phytoliths have been already found in cracks of  
242 meteorites and in impact glasses as well, with high probability of containing terrestrial  
243 organic materials [18, 34].

244 In other superficial dark inclusions, Raman spectra showing only a band centred at  
245 1572m  $\text{cm}^{-1}$  was found, suggesting the presence of a high ordered fullerene-type  
246 compound. According to literature, that band could correspond to the crystalline 3D-  
247 polymeric  $\text{C}_{60}$  structure after high-pressure/high-temperature treatment at 15 GPa and  
248 670 K [35]. Moreover, some Raman spectroscopic studies on the so-called onion-like

249 fullerene spherical nanostructures have also identified a Raman band at  $1572\text{ cm}^{-1}$  when  
250 a high degree of structural perfection of the graphitic network is attained (subjecting  
251 nanodiamonds to temperatures in the range 1800-1900 K) [36, 37]. Therefore, the LDG  
252 specimen could have been subjected to pressure of 15 GPa and temperatures of 670 K  
253 or 1800-1900 K. These conditions are in accordance with previous ones, obtained in the  
254 identification of other mineral phases in a precedent work [22]. Apart from synthetic  
255 origin, fullerenes can be of natural origin from energetic events such as volcanic  
256 eruptions, flame generation or from biological algal remains [38-40]. In LDGs its  
257 presence was previously described [9].

258 The origin of the carbon in the LDG might be in the extraterrestrial body or in the  
259 terrestrial target rocks [41]. Kramers et al. (2013) [14] identified carbon phases in a  
260 stone found in the southwestern part of the LDG field. They considered the stone as a  
261 remnant of a cometary nucleus fragment of the bolide that formed the LDG. Moreover,  
262 it is noteworthy that traces of carbon have not been found in the target rocks of the LDG  
263 area [42].

264 In inner inclusions of the LDG, apart from carbon, Raman bands at 1586m, 1555vw,  
265 1460sh, 1450vw, 1432m, 1391vw, 1331s and  $913\text{ m cm}^{-1}$  were distinguished in a thick  
266 section, as is shown in Fig. 4. The 1586 and  $1331\text{ cm}^{-1}$  bands are the G and D Raman  
267 bands of amorphous carbon respectively [43] while the  $914\text{ cm}^{-1}$  Raman band  
268 corresponds to  $\nu(\text{C-C})$  stretching mode [44], and those bands at 1460 and  $1432\text{ cm}^{-1}$   
269 could be assigned to the  $\nu(\text{C-O})$  stretching mode of oxalate anions [44]. Oxalates are  
270 widespread in nature and are formed by reaction of metals and oxalic acid excreted from  
271 fungi, lichens and plants [44]. It is possibly an iron oxalate called humboldtine  
272 ( $\text{FeC}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$ ), since no other metal oxalate matches this spectrum [45]. Nonetheless,  
273 the intensity of our spectrum Raman bands does not exactly coincide with those of the

274 humboldtine Raman spectra found in bibliography at ambient conditions [45]. In  
275 accordance with some studies of oxalates, these changes of intensities are due to high  
276 pressures suffered by the samples [46], as those suffered in the LDG formation.  
277 Therefore, the oxalate would be present in the Libyan Desert before the impact and  
278 could have been trapped and preserved within the matrix of the LDG during its  
279 formation. Its degradation with time and high temperatures, typical of Libyan Desert,  
280 could have resulted in FeO and CO<sub>2</sub> [44], however, they have not been detected but  
281 hematite (Fe<sub>2</sub>O<sub>3</sub>) or limonite (FeO(OH)) [22], which could be degradation products of  
282 FeO or could have been incorporated subsequently from the environment.

283 The identification of carbon and the oxalate within the glass, and therefore their  
284 preservation, indicates that melting does not destroy all organic matter. As has been  
285 mentioned before, the conservation of organic compounds would be aided by the  
286 presence of sulfates, carbonates, silica and hematite [29], previously identified in these  
287 samples [22].

288 Furthermore, in some other inner inclusions of other LDG, Raman bands at 2963sh,  
289 2925sh, 2880vs, 2846vs, 2723br, 2439m, 1462s, 1441s, 1426sh, 1295s, 1178vw,  
290 1128m, 1095w, 1062m, 960w, 890w, 810br, 602vw and 482br cm<sup>-1</sup> were found (see  
291 Fig. 5). In accordance with bibliography [47], they correspond to a mixture of palmitic  
292 acid (hexadecanoic acid, CH<sub>3</sub>(CH<sub>2</sub>)<sub>14</sub>COOH) and myristic acid (tetradecanoic acid,  
293 CH<sub>3</sub>(CH<sub>2</sub>)<sub>12</sub>COOH). The Raman signal of the LDG matrix was observed together with  
294 them as well (see Fig. 5). Palmitic acid is the most common fatty acid found in plants  
295 (including palm oil, palm kernel oil and coconut oil), animals and many  
296 microorganisms [47]. Myristic acid is a widely spread saturated fatty acid too, present in  
297 palm and coconut oil, cow's milk fat and some fish oils [47]. Moreover, Raman bands  
298 in the 2600–2400 cm<sup>-1</sup> region were present. They correspond to S-H stretching

299 vibrations of amino acids residues containing sulfhydryl groups [48]. The presence of  
300 those compounds could be an indication of an active interaction of the LDG with the  
301 surrounding environment (terrestrial weathering). Palmitic and myristic acid are by-  
302 products of oleic acid when is subjected to certain anaerobic conditions [49]. Therefore,  
303 they would be degradation products and the oleic acid would have been completely  
304 degraded on Earth since no Raman spectra have been identified in the LDGs. Oleic acid  
305 could not be conserved within the LDG. However, they were located in inner inclusions  
306 of the LDG, so they could have been also trapped during the impact.  
307 Other authors have also identified those compounds in Darwin glasses but using gas  
308 chromatography after destroying the samples [16].

309

#### 310 **4. Conclusions**

311 SEM/EDS allowed us to identify the candidate inclusions to be analyzed by Raman  
312 spectroscopy in the search of organic compounds due to the identification of carbon, not  
313 correlated with any other element.

314 Despite Raman spectroscopy has not been employed till now to detect organic  
315 compounds in DG and LDG, this work has demonstrated its ability to provide a huge  
316 amount of information about organic compounds as well as the pressures and  
317 temperatures at which samples were subjected. Moreover, this technique preserves the  
318 samples unlike other ones, which destroy the specimens. Organic compounds such as  
319 phytoliths, oxalates, palmitic acid, myristic acid, oleic acid, 4-methyl phthalic acid and  
320 S-H stretching vibrations of amino acids residues containing sulfhydryl groups were  
321 identified in some inclusions of the LDGs and DGs. Moreover, quartz, fullerene,  
322 amorphous carbon, calcite and amorphous calcite were also found.

323 Nowadays the lack of knowledge lies within the origin of the organic compounds in the  
324 LDGs and DGs. The only work describing the presence of organic compounds in DGs  
325 suggests that such organic components inside DGs were trapped into the impact melt,  
326 avoiding its decomposition since the impact [16]. In addition, the presence of phytoliths,  
327 palmitic acid, myristic acid, oleic acid, 4-methyl phthalic acid and S-H stretching  
328 vibrations of amino acids residues found in this work can be related to plant or bacterial  
329 life, suggesting an active interaction of the LDG and DG with the surrounding  
330 environment. They would be in the impact glasses due to terrestrial weathering  
331 processes.

332 The identification of oxalates in the exterior of the specimens could indicate the  
333 colonization of the LDGs by microorganisms, novel information in this type of  
334 materials. However, the identification of shocked oxalate in the inner inclusions could  
335 suggest that terrestrial oxalates were trapped during the LDG formation. The  
336 identification of palmitic acid and myristic acid, oleic acid and 4-methyl phthalic acid in  
337 the inner inclusions of the impact glasses could also suggest an initial trapping process  
338 into the impact melt and its preservation when the melt quenched to glass. However, the  
339 conservation of some compounds in the LDGs, such as the oleic acid, could have been  
340 altered, since some by-products were detected (palmitic acid and myristic acid). That  
341 situation was not observed in the DGs, where it was only identified oleic acid, not their  
342 degradation products. Thereby, it is remarkable that there are differences between the  
343 presence of organic compounds in the LDGs and DGs, probably due to they were  
344 formed by different extraterrestrial bodies and in different locations (Libyan Desert and  
345 Tasmania respectively).

346 In addition, the identification of a special fullerene indicated that LDG could have  
347 reached temperatures in the range of 670 -1900 K and pressures of 15 GPa. These facts

348 display that samples could reach different temperatures during their formation, in  
349 agreement with the temperature data from other inorganic compounds found in the same  
350 specimens by us [13, 22]. Thus, we mainly consider such compounds were trapped  
351 during the impact melt formation, remaining unaltered for millions of years in the inner  
352 inclusions of the impact glasses. Moreover, some partially-polar organic compounds  
353 found in the outer inclusions could have been also added to the samples subsequently by  
354 terrestrial weathering.

355

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363

364 **Conflict of Interest:** none

365

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