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2 Long-lived volcanism expressed through mare infilling, domes and  
3 IMPs in the Arago region of the Moon

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16  
17 **Keywords**

18 Moon; volcanism; domes; IMPs; mare basalts; Apollo 11

19  
20 **Abstract**

21 Mare Tranquillitatis corresponds to the deposit of successive Early to Late Imbrian basaltic units  
22 filling the Tranquillitatis basin on the Moon. The present study focuses on the western half of the  
23 mare, in the vicinity of the Arago crater (6.16°N, 21.42°E). High resolution datasets from recent  
24 remote sensing missions were used to reconstruct the geologic history of the area, which includes a  
25 variety of geological features such as: 8 extrusive domes, numerous wrinkle ridges, a sinuous rille  
26 and 37 Irregular Mare Patches (IMPs). We performed crater counting to date the domes  
27 emplacement and estimated the domes lava rheologic properties (plastic viscosities, lava effusion  
28 rates, and durations of effusion) using their geometric characteristics. As a result we classify the

29 Arago domes into three groups: E1-type domes (Arago 1 and 8), H1-type domes (Arago 4 to 7), and  
30 B-type domes (Arago 2 and 3) respectively emplaced ~ 3.7 Ga, ~ 3.4 Ga, and ~ 2.8 Ga ago. IMPs  
31 are observed in the younger mare unit and on the top of the Arago 6 dome; they likely correspond to  
32 a late stage of waning mare volcanism in the area. Both IMPs and domes have a composition  
33 similar to the surrounding mare in the VNIR spectral domain, consistent with mafic materials. The  
34 exceptionally long-lived volcanism and its diversity recorded in the Arago region may be related to  
35 both a Th-rich anomaly reported nearby and to the large-scale magma center responsible for the  
36 Lamont positive Bouguer anomaly. In addition, volcanic features of the Arago region are  
37 superimposed on a Ti-rich mare unit visited by the Apollo 11 crew 175 km to the south at  
38 Tranquility Base. The geological and historical richness of this region makes it a compelling site for  
39 future science and/or In Situ Resources Utilization (ISRU) driven missions to the Moon.

40

41

## 42 **1. Introduction**

43 Recent studies show that the geologic and thermal evolution of the Moon is far more complex than  
44 previously thought (e.g., Wilson and Head, 2003, 2017; Braden et al., 2014; Zhao et al., 2017). This  
45 complexity is well illustrated by the diversity of volcanic landforms that are observed in the vicinity  
46 of the Arago crater, located in the western part of Mare Tranquillitatis. Mare Tranquillitatis is  
47 composed of Early to Late Imbrian geological units filling most of the ~800 km diameter impact  
48 basin of the same name with extensive basaltic flows, up to ~ 3.4 Ga (Pieters, 1978, Head and  
49 Wilson, 1992; Staid et al., 1996, 2011; Hiesinger et al., 2000, 2011). The study area encompasses  
50 the western part of Mare Tranquillitatis (18 to 30°E, 2 to 12 °N; Figure 1a), in the vicinity of Arago  
51 and Carrel craters, 175 km north of Tranquility Base, the Apollo 11 landing site (Figure 1c).  
52 Similarly to the Apollo 11 landing site area, the Arago region is dominated by relatively dark,  
53 ancient (> 3.6 Ga), high-Ti (> 9 wt% TiO<sub>2</sub>) mare basalt deposits (e.g., Pieters, 1978). The study area  
54 covers four of the geologic units previously mapped by Kodama and Yamaguchi (2003) and labeled  
55 Tr1 (dated at 3.85 Ga) through Tr4 (dated at 3.59 Ga), the later being the same than the Tranquility

56 Base unit. Estimated FeO and TiO<sub>2</sub> contents increase from Tr1 to Tr4 (Kodama and Yamaguchi,  
57 2003).

58 Eight volcanic domes and 37 Irregular Mare Patches (IMPs) have been reported in this area (Lena et  
59 al., 2013; Braden et al., 2014). The Arago domes were previously studied by Lena et al. (2013) and  
60 catalogued into two classes, based on their morphometric and spectral characteristics. Both classes  
61 of domes have low slope values and roughly circular outlines, and were therefore interpreted as  
62 likely emplaced by extrusive, effusive volcanism (Lena et al., 2013). IMPs were recently identified  
63 based on their high albedo and paucity of craters, and are tentatively interpreted as recent volcanic  
64 units (< 1 Ga, Braden et al., 2014) and/or the result of ancient eruptions of magmatic foams (> 3.8  
65 Ga, e.g., Wilson and Head, 2017; Qiao et al., 2018). Additional volcanic and tectonic features in the  
66 study area include a 200 km long sinuous rille (named Diamondback Rille), numerous north-south-  
67 trending wrinkle ridges, and extensional grabens bordering the highlands, indicating a complex  
68 geologic history. Adding to the complexity, the region shows: i) a positive gravity anomaly centered  
69 60 km southeast of Arago crater (tentatively interpreted as a buried impact structure; and referred to  
70 as the “Lamont” anomaly (Evans et al., 2016; Zhang et al., 2018) and ii) a high-Th content up to 6.1  
71 ppm, which represents an anomaly for a region located outside the Procellarum KREEP Terrane  
72 (PKT) (e.g., Jolliff et al., 2000; Lawrence et al., 2003; Figure 1b).

73 The present study describes the characteristics and relative timing of the emplaced volcanic features  
74 using a variety of new high resolution datasets. We show that the Arago region is not only a  
75 promising site for science because of its long and complex geologic history, but also a potential  
76 region of interest for future In Situ Resources Utilization (ISRU) missions.

77

## 78 **2. Datasets and methods**

### 79 2.1/ Remote sensing datasets

80 A number of datasets from the Planetary Data System and SELENE archive available between 18  
81 and 30°E, and between 3 and 12°N were processed and integrated into a Geographic Information

82 System (GIS). The data collection includes: Kaguya Terrain Camera (TC) panchromatic images and  
83 associated Digital Terrain Model (DTM, spatial resolution of 10 m/px), both assembled in mosaics  
84 (Haruyama et al., 2008); Lunar Reconnaissance Orbiter Camera Wide Angle Camera (LROC WAC,  
85 resolution of 100 m/px) and Narrow Angle Camera imagery (NAC, resolution < 1 m/px) (Robinson  
86 et al., 2010); Lunar Orbiter Laser Altimeter (LOLA) global Digital Elevation Model (DEM,  
87 resolution of 118 m/px) (Smith et al., 2017); Gravity Recovery And Interior Laboratory (GRAIL)  
88 gravity maps (Zuber et al., 2013); Lunar Prospector Gamma Ray Spectrometry maps (GRS,  
89 resolution from 15 to 150 km/px) (Lawrence et al., 1998); Diviner Christiansen Feature position  
90 map (Greenhagen et al., 2010) and Clementine UVVIS color ratio mineral map as well as  
91 Clementine-derived FeO and TiO<sub>2</sub> maps (McEwen et al., 1994; Lucey et al., 2000a, b; Heather and  
92 Duncan, 2002). Kaguya Multiband Imager data (MI, resolution from 10 to 62 m/px) were also used  
93 to build a false-color map mimicking the Clementine color ratio mineral map using following bands:  
94 R = 750/415 nm, G = 750/950 nm, B = 415/750 nm (e.g., Heather and Duncan, 2002). Moreover,  
95 the Moon Mineralogy Mapper (M<sup>3</sup>) VNIR hyperspectral data were processed with the method of  
96 Martinot et al. (2018) to provide mineralogical information for the study area. The M<sup>3</sup> spectroscopic  
97 data ranges from 430 to 3000 nm with 85 spectral channels and a spatial resolution from ~140 to  
98 280 m/px (Pieters et al., 2009). This study makes use of geometrically, photometrically,  
99 radiometrically and thermally corrected M<sup>3</sup> Level 2 data (Boardman et al., 2011; Clark et al., 2011;  
100 Green et al., 2011; Besse et al., 2013) from the OP1A and OP2C optical periods, which cover dome  
101 A7 and domes A3, A5 and A6 respectively. Because space weathering is known to weaken  
102 mineralogical absorption bands and to lower reflectance values at shorter wavelengths (inducing a  
103 red slope in the VNIR spectrum) (e.g., Adams and McCord, 1970; Pieters et al., 1993, 2000), the  
104 spectral continuum was removed following the method of Horgan et al. (2014) and Martinot et al.  
105 (2018). Both M<sup>3</sup> original and continuum-removed spectra were visually analyzed for definitive  
106 mineral identification, performed by comparing M<sup>3</sup> spectra with the Reflectance Experiment  
107 LABORatory (RELAB) reference library (<http://www.planetary.brown.edu/relab/>). Spectral

108 parameters such as band centers, band depths, band areas, and band asymmetries were calculated  
109 for the 1 and 2 micron absorption bands for each spectrum (Martinot et al., 2018). Colour composite  
110 maps generated using these parameters allow for visual detection of minerals and highlight potential  
111 spatial heterogeneities within the study area .

112 Previous detections of Irregular Mare Patches from Braden et al. (2014) and of the lunar domes  
113 from Wöhler et al. (2007) were added to the data collection. Both the USGS geological map L-1162  
114 (Fortezzo et al., 2013, renovation of the Wilhelms (1979) map) and the map of Kodama and  
115 Yamaguchi (2003) were used to map mare unit boundaries. All data are presented in equidistant  
116 cylindrical projection, with the North to the top.

117

## 118 2.2/ Modelling the dome rheological properties and ages

119 Kaguya TC images (Figure 2a) and their associated DTMs (Figure 2b) were used to determine the  
120 dimensions and geometry of the domes. Height and mean radius were measured to calculate slopes,  
121 areas, and volume in order to infer their rheologic properties. As domes do not always lie on a flat  
122 surface, but often straddle across topographic breaks, a minimum and a maximum height were  
123 measured and their average value was used for rheologic calculations. Crater count was performed  
124 on the domes to obtain age estimates by fitting the distribution of the largest craters, using  
125 *craterstats 2* software in ArcGIS (Michael and Neukum, 2010). Dome dimensions were entered into  
126 rheologic equations to assess the physical properties of the feeding lava flows (e.g., Wilson and  
127 Head, 2003; Wohler et al., 2007; Lena et al., 2007, 2013). First order mathematic relationships (Eqs.  
128 1 to 4) can be applied to link the geometry of volcanic landforms to the physical properties of their  
129 forming magmas (e.g., Hulme, 1974; Lyman et al., 2004). Dome eruption can be considered as the  
130 extrusion of a Bingham fluid (the cooling magma) characterized by a yield strength  $\tau$  (Eq. 1) and a  
131 plastic viscosity  $\eta$  (Eq. 2). Assuming that the magma spreads out onto a relatively flat surface in all  
132 directions from the vent, the dome effusion rate  $E$  (Eq. 3) and the duration of the lava effusion  $T_e$   
133 (Eq. 4) can be estimated.

134 The yield strength  $\tau$  (expressed in Pa) is given by:

135 
$$\tau = \frac{0.323h^2\rho g}{D/2} \quad (\text{Eq. 1})$$

136 Where  $\rho$  is the magma density with a mean value set at  $2000 \text{ kg.m}^{-3}$  as in previous studies (Wilson  
137 and Head, 2003; Wöhler et al., 2007; Lena et al., 2013),  $g$  is the acceleration due to gravity on the  
138 surface of the Moon with a value of  $1.63 \text{ m.s}^{-2}$ ,  $D$  is the diameter of the dome in meters) and  $h$  is the  
139 average height of the dome in meters.

140 The plastic viscosity  $\eta$  (expressed in Pa.s) can then be estimated using:

141 
$$\eta(\tau) = 6 \times 10^{-4} \tau^{2.4} \quad (\text{Eq. 2})$$

142 Although the density of terrestrial basaltic lavas is closer to  $2800 \text{ kg.m}^{-3}$  (e.g., Spera, 2000),  
143 previous authors have chosen a lower value as a model input for lunar lavas assuming a vesicular  
144 foam magma. Taking a density of  $2800 \text{ kg.m}^{-3}$  only increase the viscosity by a factor of  $\sim 2.2$ , and  
145 hence is not affecting the interpretation of the results discussed hereafter.

146 Assuming that the domes have a parabolic cross-section as the advance of the lava front cools  
147 (Wilson and Head, 2003), the lava eruption rate  $E$  (expressed in  $\text{m}^3.\text{s}^{-1}$ ) can be estimated by:

148 
$$E = \frac{0.323^{\frac{1}{2}} 300\kappa(D/2)^2}{0.65^{5/2} 0.72h} \quad (\text{Eq. 3})$$

149 Where  $\kappa$  is the thermal diffusivity of the lava with a value of  $10^{-6} \text{ m}^2.\text{s}^{-1}$  (Wilson and Head, 2003).

150 The duration of the lava effusion  $T_e$  (expressed in seconds) can then be estimated with:

151 
$$T_e = V / E \quad (\text{Eq. 4})$$

152 Where  $V$  is the dome average volume in  $\text{km}^3$ .

153 The domes of the Arago region were then classified as a function of their determined morphometric,  
154 spectral and rheologic properties.

155

### 156 **3. Results**

#### 157 3.1/ Mapping and distribution of the domes

158 Eight candidate volcanic domes, labelled Arago 1 to 8 (A1 to A8) were identified using the DTM  
159 derived from the TC images (Figures 2a, 2b and 3). Among them, Arago 8 (4,69°N; 22,72°E) was  
160 not reported before.

161 All the studied domes are located within the two youngest mare units mapped by Kodama and  
162 Yamaguchi (2003) (Figure 3). Domes Arago 2 and 3 are located in the Tr3 unit (previously  
163 described as medium-Ti unit, dated at 3.67-3.71 Ga (Kodama & Yamaguchi, 2003)), whereas  
164 domes Arago 1, 4, 5, 6, 7, and 8 are located in the Tr4 unit (the youngest regional unit having the  
165 higher-Ti content, dated at 3.59 Ga). With the exception of dome A1 (Figure 4a) and A7 (Figure 4e),  
166 the domes are located on a topographic step (Figures 4b, c, d, and f), where the local elevation  
167 decreases from west to east. Dome A1 is located in the vicinity of a 100 km long north-south-  
168 trending wrinkle ridge (Figures 4a and 5a). Besides this example, there is no obvious spatial  
169 relationship between domes, wrinkle ridges and sinuous rille (Figure 3).

170 Although the SE-NW alignment of domes Arago 1, 2, 4, 5, 6, and 8 does not directly crosscut any  
171 regional grabens, it suggests a regional tectonic control (see section 4).

172

### 173 3.2/Morphological characteristics

174 The domes radius, slope, area and volume that we have determined are reported in Table 1. The  
175 Arago domes range from 4.8 to 24 km in diameter, 40 to 400 m in height and 0.8 to 3 degrees in  
176 slope (Table 1, Figure 4). Four IMPs, characterized by hummocky and blocky floor terrains (Braden  
177 et al., 2014) are observed on the top of dome Arago 6 (Figures 4d and 5b). Pseudo-circular, shallow  
178 depressions of lower depth-to-diameter ratios than the standard values expected for fresh impact  
179 craters (between 0.11 and 0.21; e.g., Pike (1974); Stopar et al., (2017)) are present on the summits  
180 of Arago 1, 7 and 8 and may represent vents, although evidence for extrusive volcanism is not  
181 obvious (Figures 4a, 4e, and 5a). In addition, there is no obvious evidence supporting that these  
182 domes could be intrusive structures. Wöhler et al. (2007) previously classified Arago 1 to 7 as low  
183 slope, effusive domes.

184

### 185 3.3/ Ages

186 Crater counting was performed on the domes for estimating their ages (Figure 6 and 7), spanning  
187 over  $\sim 1$  Ga, from  $\sim 3.75$  to  $\sim 2.79$  Ga. Three groups of ages were derived. The older domes are  
188 Arago 1 and 8 ( $3.75 \pm 0.05/0.08$  Ga and  $3.73 \pm 0.10/0.34$  Ga, respectively), followed by Arago 4 to  
189 7 ( $3.19 \pm 0.19/0.62$  Ga,  $3.34 \pm 0.11/0.32$ ,  $3.68 \pm 0.08/0.18$  Ga and  $3.50 \pm 0.08/0.19$  Ga,  
190 respectively). The younger domes are Arago 2 and 3 ( $3.03 \pm 0.17/0.29$  Ga and  $2.79 \pm 0.28/0.36$  Ga,  
191 respectively). These age estimates rely on the assumption that the domes are monogenetic, i.e. they  
192 were formed during a single volcanic event.

193

### 194 3.4/ Rheology

195 The domes minimum or maximum height, diameter and volume were used as inputs for estimating  
196 the dome rheologic properties (see section 2.2). Results are shown in Table 2.

197 Plastic viscosities  $\eta$  range between  $1.57 \times 10^4$  and  $4.05 \times 10^6$  Pa.s, and lava effusion rate  $E$  estimates  
198 range from 43 to  $230 \text{ m}^3 \cdot \text{s}^{-1}$ , yielding a corresponding duration of lava effusion  $T_e$  between 0.27 and  
199 6.36 years.

200

### 201 3.5/ Spectroscopy

202 The spectral data from Clementine (Figure 1c), MI (Figure 2c), GRS (Figures 1b and 2d)), Diviner  
203 (Figure 2f) and  $M^3$  (Figure 8) do not reveal significant differences between the composition of the  
204 domes and the surrounding mare units. Dark blue tones on both the Clementine and Kaguya RGB  
205 composites are consistent with high Ti mature mare materials (Figures 1c and 2c). Using the  
206 Kaguya MI RGB composite (Figure 2c), we extracted a mean value of each ratio of bands, and  
207 compared the values with those of Clementine RGB used by Wöhler et al. (2007) in order to rank  
208 these domes into different categories (see section 4.1).

209 M<sup>3</sup> VNIR spectra of the different units are presented in Figure 8. The most common spectrum  
210 observed throughout the area is dominated by wide absorptions bands centered at 1.01 and 2.18 μm,  
211 consistent with the presence of high calcium pyroxenes (HCP) such as pigeonite or augite (e.g.,  
212 Adams, 1974; Cloutis and Gaffey, 1991; Figures 8c, 8d). Other common lunar minerals such as  
213 plagioclase, olivine or spinel (e.g., Martinot et al., 2018) could not be detected throughout the study  
214 area. M<sup>3</sup> data do not reveal major compositional differences between the domes covered by the  
215 dataset (Arago 3, 5, 6, and 7), neither between the IMPs (#1 and #7) or the surrounding mare units,  
216 all of them being also dominated by HCP signatures (Figure 8c). Spectral parameters maps (Figure  
217 8b) show that there is little variation in the position of the pyroxene 2 μm absorption center,  
218 suggesting that the composition of the area is relatively homogeneous at the M<sup>3</sup> scale (140 to 280  
219 m/px, depending on the optical period). Small craters exhibit stronger absorption features compared  
220 to the surrounding mare or dome material, as they excavate “fresher” material (meaning they were  
221 less exposed to space weathering at the lunar surface e.g., a fresh crater in Tr4 in figure 8c (blue  
222 spectrum) (e.g., McCord and Adams, 1973; Pieters et al., 2000)). Spectral analyses of the largest  
223 IMPs (e.g., Sosigenes, IMP#1, sea green spectrum in Figure 8c) show that they are also  
224 characterized by higher band depth values, which indicate that they are optically less mature than  
225 the mare and dome materials.

226

### 227 3.6/ Dome classification

228 Based on their geometry (slope value) and their spectral properties (R415/R750), the domes were  
229 ranked following the classification scheme by Lena et al. (2013):

230 -H1: small domes with low slopes (< 2°) and R415/R750 values between 0.62 and 0.68  
231 (Arago 4 to 7),

232 -B: large scale domes with higher slopes (1.3-5.4°) and R415/R750 between 0.55 and 0.64  
233 (Arago 2 and 3),

234 -E1: small domes with higher slopes (2-4°) and R415/R750 between 0.58 and 0.62 (Arago 1  
235 and 8).

236

## 237 **4. Discussion.**

### 238 4.1/Revisited dome classification

239 The use of higher resolution data from Kaguya and LRO in this study permitted to refine the domes'  
240 rank into three classes as defined by Lena et al. (2013):

- 241 - A2 and A3 fall in the dome category B (instead of class D: low flank slopes, high  
242 edifice volume, possibly polygenic in origin, with higher R415/R750 ratio);
- 243 - A4 to A7 fall as either H1 or C2 domes (instead of class A which have a higher  
244 R415/R750 ratio). Their dimensions are smaller than C2 domes, and thus match better  
245 those of the H1 category. However, it is to be noted that A4 to A7 are not considered  
246 polygenetic domes (as previously suggested for some domes of Marius Hills which  
247 defined the H class of Lena et al., 2013).
- 248 - A1 and the new Arago 8 are in class E1 (instead of class A: lowest slopes but higher  
249 R415/R750 ratio).

250 All the studied domes show relatively low slopes compared to lunar silicic domes reported  
251 elsewhere on the Moon (e.g., Wilson and Head, 2003; Wöhler et al., 2006; Glotch et al., 2010, 2011;  
252 Lena et al., 2013). In comparison, the silicic domes of Gruithuisen and Mairan (e.g., Wilson &  
253 Head, 2003; Glotch et al., 2011) show slopes between 5 and 15° for a similar size range such as  
254 Arago 2 and 3 (diameters around 20 km). The low slopes of the Arago domes are more similar to  
255 those of other mare domes, such as the shallow domes present on Mons Rümker (Zhao et al., 2017),  
256 or the Hortensius, Marius Hills and Milichius domes (Wöhler et al., 2006). The resolution of  
257 Diviner data is too low for a good determination of a possible silica composition. However, there is  
258 no evidence for low Christiansen Features values/high silica composition on the global map from  
259 Greenhagen et al. (2010) (Figure 2f). Both UV and VNIR spectral data indicate that the

260 composition of the domes is similar to the nearby mare unit, i.e. that they are basaltic in  
261 composition. Some domes present a rimless crater pit on their summit (interpreted as a volcanic  
262 vent); and most domes are roughly circular in shape. Together, these observations confirm the  
263 previous assumptions that the Arago domes are likely effusive in nature (e.g., Lena et al., 2013).  
264 The Arago domes might represent a volcanic stage later than the normal (or typical) mare  
265 Tranquillitatis volcanism. This is supported by their emplacement on the youngest regional units  
266 (Tr4), except for Arago 2 and 3 that are within Tr3 (Figure 3). Small volumes of remaining magmas  
267 could have been emitted at the surface, possibly along fractures, after the major mare flooding  
268 episodes. As there is no evidence of high silica contents for any of the domes, the more viscous  
269 character of the dome lavas compared to the surrounding mare materials could alternatively be  
270 explained by:

- 271 - A low magma temperature,
- 272 - The presence of more crystals due to progressive cooling in the magma chamber,
- 273 - Magmatic differentiation (more evolved compositions),
- 274 - Low rate and low volume eruptions,

275 Or a combination of the above (e.g., Francis and Oppenheimer, 2004, and references therein).

276

#### 277 4.2/Dome chronology

278 Based on previous observations and crater counting-derived chronology, the following chronology  
279 for the emplacement of the Arago domes is proposed.

280 Arago 1 and 8 are respectively dated at  $3.75 \pm 0.05/0.08$  Ga and  $3.73 \pm 0.10/0.34$  Ga. They would  
281 therefore be the first domes to be emplaced. A1 and A8 are emplaced over the Tr4 unit, which was  
282 dated at 3.59 Ga by Jerde et al (1994), and should therefore be younger than Tr4. We consider this  
283 discrepancy between estimated ages to be either due to errors in crater counts (the areas counted on  
284 the domes are restricted in size and may induce large errors) or in unit mapping. Alternatively, the  
285 domes could be more ancient than Tr4 and embayed by the latest regional mare unit. The two

286 domes have, in consideration with all domes of the area, the smaller radii, intermediate heights and  
287 volumes, the steepest slopes and are therefore both classified in the E1 category.

288 Arago 4, 5, 6 and 7 correspond to a later stage of dome activity at  $\sim 3.68$  to  $3.19$  Ga and are  
289 categorized as H1 class domes, characterized by low slopes and small volumes. Their apparent  
290 viscosities ( $< 2 \times 10^5$  Pa.s) yield values lower than Arago 1 and 8 ( $> 8 \times 10^5$  Pa.s) by an order of  
291 magnitude, indicative of less viscous magmas. Domes Arago 4, 5 and 6 are aligned along a SE-NW  
292 trend, possibly suggesting post- or syn-formation along tectonic features (e.g., fissure or fault).

293 Arago 2 and 3 were respectively emplaced at  $3.03 \pm 0.17/0.29$  Ga and  $2.79 \pm 0.28/0.43$  Ga and  
294 represent the latest dome emplacement stage in the region. Arago 2 and 3 have the largest  
295 dimensions and show intermediate slopes. Their higher apparent viscosities ( $4.05 \times 10^6$  and  $2.75 \times 10^6$   
296 Pa.s, respectively), compared to the earlier emplaced domes viscosities ( $< 8 \times 10^5$  Pa.s), might be  
297 related to either a silica enrichment of the feeding magmas, a lower temperature of the feeding  
298 magmas, or a larger amount of crystals in the magmas. Since there is no signature of high-Si  
299 contents in spectral data, the two latter hypotheses are favored.

300 Another possible explanation related to the magma rise speed and source dike dimensions is  
301 proposed by Lena et al. (2013). The previous classification scheme put the domes of category B  
302 (Arago 2 and 3) in a distinct rheologic group compared to categories H1 and E1. Domes of groups  
303 E1 and H1 would display high effusion rates but low edifice volumes consistent with a short  
304 duration of the effusion process. Category B domes would be emplaced by much larger and deeper  
305 feeder dikes, and would be characterized by lower lava effusion rates but larger erupted lava  
306 products, implying a longer duration of the effusion process (Lena et al., 2013).

307

308 The proposed chronology in this work, assuming the domes to be monogenetic, disagrees with  
309 previous work (Lena et al, 2013) which suggested that Arago 2 and 3 could belong to class D (i.e.,  
310 polygenetic domes). We did not find evidence of plural pulses of volcanism for domes Arago 2 and  
311 3, as reported for some of the Marius Hills domes (Whitford-Stark and Head, 1977) or the

312 Gruithuisen and Mairan domes (Wilson and Head, 2003; Glotch et al., 2011). Crater distributions  
313 on the Arago 1 to 5 and 7 domes (Figure 7) are rather uniform and do not show any slope break  
314 indicative of major resurfacing events. The lack of alignment over a single isochrone for dome  
315 Arago 6 can be explained by the superimposition of IMPs which induced partial resurfacing. Crater  
316 distributions for dome Arago 8 also do not align over an isochrone, suggesting a possible partial  
317 resurfacing, and possibly hints at a polygenetic origin (Figure 5c). Zhang et al. (2018) proposed that  
318 Arago 8 could correspond to a lava plateau rather than a dome, but the conclusions would remain  
319 similar in both cases, in terms of emplacement from a fissural eruption in more than a single  
320 episode.

321 The general lack of distinguishable units and the relatively small sizes of the other Arago domes are  
322 therefore consistent with an emplacement during a single episode. The relatively short duration of  
323 lava eruption ( $T_e < 7$  years) also make a single stage dome-forming eruptive event plausible.

324

#### 325 4.3/Implications for the region history

326 A previous geologic mapping work within Mare Tranquillitatis was performed by Kodama and  
327 Yamaguchi (2003). This study revealed that the Arago domes are located onto two specific geologic  
328 units: domes Arago 2 and 3 are located in the Tr3 unit (medium-Ti unit, dated at 3.67 Ga), whereas  
329 domes Arago 1, 4, 5, 6, 7 and 8 are located in the Tr4 unit (the youngest regional unit dated at  
330 3.59 Ga with also the higher-Ti contents of the mare) (Figure 3). The region contains wrinkle ridges,  
331 one sinuous rille, and numerous extensional grabens that surround, or are part of, the Tr4 unit  
332 (Figure 3). Almost all the IMPs present in Mare Tranquillitatis are located within the Tr4 unit and  
333 they partly overlap some domes, suggesting that they are among the youngest volcanic deposits in  
334 the area. Based on these observations, the following chronology is proposed.

335

336 The emplacement of Mare Tranquillitatis basalts started more than 3.85 Ga ago (during the Early  
337 Imbrian) with the emplacement of the Tr1 to Tr3 geologic units (Kodama and Yamaguchi, 2003).

338 The Tr4 unit was emplaced during the Late Imbrian (3.59 Ga ago) and the region was overlain by  
339 the small, effusive domes labelled Arago 1 and 8. Unit Tr4 represent the latest, large-scale effusive  
340 mare event visible in the Arago region. Domes Arago 4 to 7 are contemporary (3.59 Ga) or younger  
341 than Tr4 and might mark the end of the Tr4 mare emplacement with effusive eruptions along local  
342 fractures. Domes Arago 2 and 3, the largest domes with intermediate slopes, were emplaced at the  
343 beginning of the Erastosthenian (~ 2.9 Ga ago), possibly from more evolved, more crystal-rich, or  
344 cooler magmas. The late formation of these two domes suggests long-lived volcanism in the region,  
345 which is however located outside the PKT, but is still associated with a GRS Thorium anomaly  
346 (Lawrence et al., 2003) (Figure 2d).

347

348 Almost all IMPs are located on the Tr4 unit, likely representing a waning stage of dike  
349 emplacement in the region (e.g., Wilson and Head, 2017). IMPs were initially interpreted as young  
350 (< 1 Ga) volcanic features because of their optical immaturity and the low number of superimposed  
351 impact craters (e.g., Braden et al., 2014). Recent studies suggest that IMPs more likely formed  
352 concurrently or slightly later than the surrounding mare lava flows (e.g., Garry et al., 2012; Wilson  
353 and Head, 2017; Zhang et al., 2018). Similarly to the recently discovered Ring-Moat Dome  
354 Structures (RMDS) commonly observed in lunar mare regions, IMPs are indeed best explained as  
355 the result of basaltic lava flows inflation during their cooling phases(e.g., Garry et al., 2012; Zhang  
356 et al., 2017; Wilson and Head, 2017; Qiao et al., 2018; Wilson et al., 2019). IMPs formation  
357 mechanisms are controversial, but magma degassing below a solidified lava crust as observed in  
358 Hawaiian lava lakes (e.g., Wilson and Head, 2017) could induce cracking of the crust, resulting in  
359 the extrusion of gas-rich magmatic foams to form hummocky mounds. We favor this mechanism to  
360 explain the extrusion of IMPs onto the Tr4 unit, at the time of its emplacement or shortly after. At  
361 locations where the gas might have been able to escape from magmatic intrusions, domes could  
362 have been formed instead of IMPs. Four IMPs are, however, situated on the dome Arago 6 (Figure  
363 5b), implying that they should have formed after the dome emplacement. The small size of the

364 IMPs (tenth of meters) observed in this unit could be due to the important thickness of the Tr4 unit,  
365 minimizing the quantity of extruding foam and resulting in small IMPs. We infer the domes Arago  
366 4 to 7 to be contemporaneous or younger than unit Tr4, similarly to the IMPs. Because of the gaps  
367 in age between the three groups of domes in the Arago region, it is however possible that the IMPs  
368 and dome formation periods overlapped, and that some of the IMPs predate the youngest domes  
369 Arago 2 and 3, which might have been fed by a different, deeper magma source (see section 4.2).

370 The emplacement of the Diamondback sinuous rille, Arago domes and regional IMPs can therefore  
371 be interpreted as the result of intrusive dikes reaching different depths within the cooling lunar crust  
372 (e.g., Zhang et al., 2018, Wilson and Head, 2017). Dikes breaching the surface and erupting may  
373 create high flux effusive eruptions such as sinuous rilles, whereas dikes just reaching the near  
374 surface may extrude small amounts of lava, producing small domes. As the lunar crust cools and  
375 thickens over time, dikes may have remained trapped at shallow depths and have undergone gas  
376 exsolution. Their accumulation, and the local foam extrusion, would eventually form the IMPs.  
377 Dikes remaining trapped at depth may result in grabens and pit chains instead. This interpretation  
378 however implies the existence of a magma storage beneath the mare to support outgassing lava  
379 eruption. Although Mare Tranquillitatis is not associated with any lunar mascon, positive Bouguer  
380 anomalies observable from the GRAIL dataset are located ~90 km southeast of dome Arago 2, just  
381 below dome Arago 8 (the “Lamont” anomaly) and another 40 km south of dome Arago 7 (the  
382 northern extension of the Lamont anomaly) (Figure 2e). This may indicate the presence of large-  
383 scale magmatic intrusions at depth (Zuber et al., 2013). The Lamont gravity anomaly was  
384 previously interpreted as a buried impact structure associated with both intrusive and extrusive  
385 volcanism (e.g., Evans et al., 2016; Zhang et al., 2018). These previous studies show that ancient  
386 buried impact structures such as Lamont, may be accompanied by dense dike intrusions, crater-  
387 concentric and crater-radial patterns of alignment of volcanic features such as cones, domes, rilles,  
388 linear or arc-shaped ridges and grabens (e.g. Zhang et al., 2018). Figure 3 shows that most wrinkle  
389 ridges and extensional grabens in the Arago region are indeed concentric to the Lamont anomaly,

390 whereas domes Arago 1, 2, 4, 5, 6 and 8 are aligned radially to the Lamont structure. As it is the  
391 case for several domes, some of the IMPs are aligned radially, and might represent the surface  
392 manifestation of large-scale, intrusive dikes likely connected to the Lamont structure.

393

#### 394 4.4/The Arago region, a suitable landing site for future science and ISRU missions?

395 The Arago region exhibits a diversity of volcanic features and deposits, suggesting a long-lived  
396 magmatic history, possibly spanning over one billion years. These volcanic features were formed by  
397 a range of volcanic eruption styles, including flooding volcanism (rille and mare units), small shield  
398 volcanoes (domes) and outgassing process related depressions (vents and IMPs). The long duration  
399 of volcanism ( $> 1$  Ga) is rather unusual for such locations outside of PKT. As lunar volcanism  
400 provides a window into the thermal and compositional evolution of the Moon, such regions contain  
401 a diverse and long geological record that is key to future scientific advances (e.g., NRC, 2007;  
402 Crawford et al., 2012; Jaumann et al., 2012). The Arago region therefore represents a high scientific  
403 interest site for future missions of exploration (e.g., Flahaut et al., 2012). In addition, the Arago  
404 region offers an interesting target for future ISRU activities. The Arago region corresponds to a  
405 Thorium positive anomaly (Figure 2d) which might be of interest for nuclear power, although  
406 thorium still lacks applications compared to uranium (e.g., Crawford, 2015). But most significantly,  
407 the region is dominated by Ti-rich units, with estimates of  $13.7 \pm 0.7$  wt%  $\text{TiO}_2$  for the mare unit  
408 Tr4 (where most of the domes are located) and  $12.6 \pm 0.8$  wt%  $\text{TiO}_2$  for unit Tr3 (where Arago 2 and  
409 3 are located) (Kodama and Yamaguchi, 2003). Unit Tr4 extends further south to the Tranquility  
410 Base where Apollo 11 astronauts collected soils with 7.5 to 12 wt%  $\text{TiO}_2$  (e.g., Beatty, 1979; Lucey  
411 et al., 2006) which is mainly accommodated in the mineral ilmenite ( $\text{FeTiO}_3$ ). Together with  
412 Oceanus Procellarum and the western part of Mare Imbrium, Mare Tranquillitatis is one of the few  
413 vast regions of high ilmenite concentrations on the Moon. Ilmenite has long been recognized as a  
414 key resource for oxygen production through mineral reduction (e.g., Cutler and Krag, 1985; Gibson  
415 and Knudsen, 1985; Taylor and Carrier, 1992; Anand et al., 2012). A number of reductants is

416 possible (e.g., Gibson and Knudsen, 1985), although hydrogen seems to be favored. Ilmenite  
417 reduction ranks high among ISRU processes to be tested and demonstrated with upcoming missions,  
418 owing to its relative simplicity and technological readiness (e.g., Anand et al., 2012; Crawford,  
419 2015). As noted by Anand et al. (2012), this process also yields a metal product (titanium) which  
420 may be of additional economic importance. The deposit of interest for mining appears rather wide  
421 and locally homogeneous from orbit, and the predicted content has been confirmed with ground  
422 truth.

423 Given its combined scientific interest and potential for resource utilization, we argue that the Arago  
424 region is a key candidate site for a future exploration mission. It would also offer the unique  
425 opportunity to fly over Tranquility Base 50 years after the first human walked on the Moon.

426

## 427 **5. Conclusion**

428 Eight volcanic domes in the Arago region, western Mare Tranquillitatis, were reported and  
429 characterized in this paper. Despite various morphometric characteristics, most domes are  
430 interpreted as single stage eruptive events, effusive in nature. High resolution observations,  
431 combined with the results of this study, suggest the following geological history of Mare  
432 Tranquillitatis. The emplacement of mare basalts older than 3.85 Ga (regional unit Tr1) was  
433 followed by the emplacement of additional lava flows (Tr2 to Tr5), volcanic domes and  
434 superimposed IMPs, a period which lasted for more than 1 Ga. Of the eight Arago mare domes, the  
435 youngest ones (Arago 2 and 3) display distinct rheological parameters and may originate from a  
436 distinct, deeper source. The Arago region is located outside of the PKT, but it is associated with a  
437 positive Thorium anomaly, which could explain its exceptional volcanic history and complexity.  
438 The Arago region unique geologic record holds clues to the Moon's thermal and magmatic  
439 evolution. In addition, the Arago region corresponds to one of the few ilmenite-rich lunar mare  
440 deposits presenting a strong potential for future ISRU activities.

441

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451

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609 **8. Figures Captions**

610 Figure 1

- 611 A. Location of the study area (white box) on the nearside of the Moon. Previously referenced  
612 lunar domes and IMPs are shown as red triangles and green squares respectively. The LROC  
613 WAC global mosaic is used as a background.
- 614 B. Location of the study area (white box) on the Lunar Prospector Thorium abundance map.  
615 The outline of the Procellarum KREEP Terrane (PKT) is represented as a thick black line.
- 616 C. Location of the study area (white box) on Clementine RGB mineral composite (R = 750/415  
617 nm, G = 750/950 nm, B = 415/750 nm, see text for more details). Apollo and Luna landing  
618 sites are labeled.

619 Figure 2

- 620 A. Mosaic of Kaguya Terrain Camera (TC) panchromatic images of the study area. The studied  
621 domes are represented as white outlines.
- 622 B. Digital Terrain Model derived from the Kaguya TC map of the area superimposed on the  
623 corresponding TC images.
- 624 C. False-colour mosaic of Kaguya Multiband Imager using the following band ratios R =  
625 750/415 nm; G = 750/950 nm; B = 415/750 nm. This color composite uses similar bands as  
626 the Clementine color ratio mineral map, but offers a higher spatial resolution.
- 627 D. Lunar Prospector Thorium abundance map of the study area.
- 628 E. GRAIL Bouguer anomaly of the study area. The location of the Lamont anomaly is  
629 indicated with an arrow.
- 630 F. Diviner Christiansen Feature map of the study area.

631

632 Figure 3

- 633 Interpretative sketch map of the study area: red lines represent extensional grabens; orange  
634 lines represent wrinkle ridges; green numbers represent IMPs ; units Tr2 to Tr4 from

635 Kodama and Yamaguchi (2003) are also indicated. Domes are represented in different  
636 colors according to the classes defined in this paper: green for Arago 2 and 3 of category B;  
637 blue for Arago 1 and 8 of category E1; red for Arago 4 to 7 of category H1. The sinuous  
638 rille (Diamondback Rille) is represented by a purple line, visible in the southeast of the  
639 study area.

640

641 Figure 4

642 A to F: Topographic profiles of the Arago 1 to 8 domes. The basemaps are Kaguya TC  
643 DTMs (rainbow scale) overlain in transparency on corresponding TC images. Black lines  
644 indicate the location of the W-E profiles, except for the new candidate dome Arago 8 where  
645 a N-S profile has been added. Local topography seems to control the final shape of the  
646 domes.

647 Figure 5

648 A. LRO NAC images M181023296LE and RE of Arago 1 (outlined in blue). A wrinkle ridge  
649 (brown) appears to reach the base of the dome.

650 B. LRO NAC images M181030493LE and M1159970410LE shows 4 IMPs (outlined in green)  
651 on the top of Arago 6 (outlined in red), implying that the IMPs formed after the dome's  
652 emplacement.

653 C. LRO NAC images M1182324465RE and M1136406467RE reveal the presence of a  
654 previously unmapped dome (outlined in blue), named Arago 8 in this study.

655 Figure 6

656 A to F : Crater counts on the NAC images of domes (A1, A2 ,A3, A4-6, A7 and A8 respectively).  
657 Craters (in magenta) were counted on the entire dome area with the exception of dome A8 as the  
658 western portion of the dome is not covered by NAC imagery (counted area is indicated by a yellow  
659 outline).

660 Figure 7

661 A to H : Corresponding isochrones of figure 6 and fitted ages.

662 Figure 8

663  $M^3$  spectral analysis of the Arago domes and surroundings ( $M^3$  stripe M3G20090607T025544 from  
664 OP2C1).

665 A. –  $M^3$  2900-nm mosaic (stretched values: 0.119-0.147). Outlines of the domes are shown in white,  
666 the limit between mare unit Tr4 and Tr3 (to the south, bottom part of the image) is indicated by a  
667 thick red line. The locations of the spectra shown in figure C) are shown by orange dots.

668 B. –  $M^3$  RGB composite of spectral parameters from Martinot et al., (2018) (R = 2 micron band  
669 center, stretched values: 1.900–2,400 nm; G = 2 micron band depth, stretched values: 0.04– 0.09; B  
670 = reflectance at 1,580 nm, stretched values: 0.07–0.10).

671 C. –  $M^3$  continuum-removed spectra of domes A3, A5 and A6, of nearby mare units Tr3, Tr4  
672 (including a spectra taken over a fresh, small crater, labeled Tr4fresh) and of IMPs #1 (Sosigenes)  
673 and #7.  $M^3$  spectra are  $3 \times 3$  pixel averages with the exception of the spectrum taken over IMP#7  
674 which is a single pixel spectrum (as the IMP is smaller in size than a 3x3 pixel average). Data were  
675 processed using the algorithm developed by Martinot et al., (2018) (see section 2). Reflectance  
676 values were offset and vertical bars were placed at 1000 and 2000 nm for clarity.

677 D. – Continuum –removed pyroxene spectra from the RELAB spectral library, processed with the  
678 same routine (method of Martinot et al., 2018), are shown for comparison. RELAB respective  
679 samples ID are: AG-TJM-010/C1AG10, DL-CMP-008/BKR1DL008, and DH-MBW-  
680 005/BKR1DH005 for augite, pigeonite, and enstatite. Reflectance values were offset and vertical  
681 bars were placed at 1000 and 2000 nm for clarity.

682

683 **9. Tables**

684 Table 1: Morphometric properties of the eight Arago domes. Given the irregular shape of the domes, both a minimum and maximum height and radius  
 685 were measured.

Dome	Coordinates		Height (m)		Mean radius (m)		Slope (°)		Area (km <sup>2</sup> )		Volume (km <sup>3</sup> )	
	Latitude (°)	Longitude (°)	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Arago 1	7.70	22.07	103	159	2550.25	3146.25	2.46	2.98	17.81	24.90	0.70	1.65
Arago 2	7.57	21.55	320	398	9767.25	12021.50	1.96	1.92	240.02	395.85	31.97	60.23
Arago 3	6.16	19.94	245	397	8411.25	12048.00	1.69	1.90	212.90	425.41	18.15	60.35
Arago 4	8.52	21.21	38	114	2748.50	7113.25	0.82	0.93	18.36	129.19	0.30	6.04
Arago 5	8.95	20.94	46	94	3276.50	4805.50	0.81	1.15	31.87	77.38	0.52	2.28
Arago 6	9.27	20.76	84	129	3666.00	4068.25	1.41	1.84	35.45	43.11	1.18	2.24
Arago 7	11.29	24.11	85	105	2427.75	2859.25	2.01	2.12	18.42	22.53	0.52	0.90
Arago 8	4.70	22.72	116	213	3435.50	5240.00	2.54	2.62	26.96	57.97	1.43	6.12

686

688 Table 2 : Modelled rheologic properties of the eight Arago domes. Mean heights shown in row 4 were used to perform calculations.

Dome	Slope (°)	Diameter (km)	Height (m)	$\tau$ (yield strength, Pa)	$\eta$ (plastic viscosity, Pa.s)	E (lava effusion rate, m <sup>3</sup> /s)	Te (eruption duration, years)
Arago 1	2.72	5.70	131	$6.34 \times 10^3$	$8.01 \times 10^5$	43.05	0.87
Arago 2	1.94	21.79	359	$1.25 \times 10^4$	$4.05 \times 10^6$	229.84	6.36
Arago 3	1.79	20.46	321	$1.06 \times 10^4$	$2.75 \times 10^6$	226.63	5.49
Arago 4	0.88	9.86	76	$1.23 \times 10^3$	$1.57 \times 10^4$	222.40	0.45
Arago 5	0.98	8.08	70	$1.28 \times 10^3$	$1.71 \times 10^4$	162.18	0.27
Arago 6	1.63	7.73	106.50	$3.09 \times 10^3$	$1.42 \times 10^5$	97.62	0.56
Arago 7	2.07	5.29	95	$3.59 \times 10^3$	$2.05 \times 10^5$	51.14	0.44
Arago 8	2.58	8.68	164.50	$6.57 \times 10^3$	$8.71 \times 10^5$	79.52	1.51

