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**The role of substrate characteristics in producing anomalously young crater retention ages in volcanic deposits on the Moon: Morphology, topography, sub-resolution roughness and mode of emplacement of the Sosigenes Lunar Irregular Mare Patch (IMP)**

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26 **Abstract:** Lunar Irregular Mare Patches (IMPs) are comprised of dozens of small,  
27 distinctive and enigmatic lunar mare features. Characterized by their irregular shapes,  
28 well-preserved state of relief, apparent optical immaturity and few superposed impact  
29 craters, IMPs are interpreted to have been formed or modified geologically very  
30 recently ( $< \sim 100$  Ma; Braden et al. 2014). However, their apparent relatively recent  
31 formation/modification dates and emplacement mechanisms are debated. We focus in  
32 detail on one of the major IMPs, Sosigenes, located in western Mare Tranquillitatis,  
33 and dated by Braden et al. (2014) at  $\sim 18$  Ma. The Sosigenes IMP occurs on the floor  
34 of an elongate pit crater interpreted to represent the surface manifestation of magmatic  
35 dike propagation from the lunar mantle during the mare basalt emplacement era  
36 billions of years ago. The floor of the pit crater is characterized by three  
37 morphological units typical of several other IMPs: 1) bulbous mounds 5–10 m higher  
38 than the adjacent floor units, with unusually young crater retention ages, meters thick  
39 regolith and slightly smaller sub-resolution roughness than typical mature lunar  
40 regolith, 2) a lower hummocky unit mantled by a very thin regolith and significantly  
41 smaller sub-resolution roughness, and 3) a lower blocky unit composed of fresh  
42 boulder fields with individual meters-scale boulders and rough sub-resolution surface  
43 texture. Using new volcanological interpretations for the ascent and eruption of  
44 magma in dikes, and dike degassing and extrusion behavior in the final stages of dike  
45 closure, we interpret the three units to be related to the late-stage behavior of an  
46 ancient dike emplacement event. Following the initial dike emplacement and collapse  
47 of the pit crater, the floor of the pit crater was flooded by the latest-stage magma. The  
48 low rise rate of the magma in the terminal stages of the dike emplacement event  
49 favored flooding of the pit crater floor to form a lava lake, and CO gas bubble  
50 coalescence initiated a strombolian phase disrupting the cooling lava lake surface.  
51 This phase produced a very rough and highly porous (with both vesicularity and  
52 macro-porosity) lava lake surface as the lake surface cooled. In the terminal stage of  
53 the eruption, dike closure with no addition of magma from depth caused the last  
54 magma reaching shallow levels to produce viscous magmatic foam due to H<sub>2</sub>O gas  
55 exsolution. This magmatic foam was extruded through cracks in the lava lake crust to  
56 produce the bulbous mounds. We interpret all of this activity to have taken place in  
57 the terminal stages of the dike emplacement event billions of years ago. We attribute  
58 the unusual physical properties of the mounds and floor units (anomalously young  
59 ages, unusual morphology, relative immaturity, and blockiness) to be due to the  
60 unusual physical properties of the substrate produced during the waning stages of a  
61 dike emplacement event in a pit crater. The unique physical properties of the mounds  
62 (magmatic foams) and hummocky units (small vesicles and large void space) altered  
63 the nature of subsequent impact cratering, regolith development and landscape  
64 evolution, inhibiting the typical formation and evolution of superposed impact craters,  
65 and maintaining the morphological crispness and optical immaturity. Accounting for  
66 the effects of the reduced diameter of craters formed in magmatic foams results in a  
67 shift of the crater size-frequency distribution age from less than 100 million years to  
68 billions of years, contemporaneous with the surrounding ancient mare basalts. We  
69 conclude that extremely young mare basalt eruptions, and resulting modification of  
70 lunar thermal evolution models to account for the apparent young ages of the IMPs,  
71 are not required. We suggest that other IMP occurrences, both those associated with  
72 pit craters atop dikes and those linked to fissure eruptions in the lunar maria, may  
73 have had similar ancient origins.

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## 76 1. Introduction

77 Lunar Irregular Mare Patches (IMPs) (Braden et al. 2014) are a group of unusual  
78 mare features on the Moon, notable for their “blistered” appearance (meniscus-like  
79 bulbous shaped mounds with surrounding rough and optically immature materials).  
80 Since the discovery of the most notable endogenic IMP feature, Ina, in Lacus  
81 Felicitatis (18.65°N, 5.30°E) on Apollo 15 orbiter photographs (Whitaker 1972;  
82 El-Baz 1973), lunar IMPs have intrigued lunar scientists for decades. Other major  
83 IMP occurrences include Sosigenes in the western margin of Mare Tranquillitatis  
84 (Stooke 2012). Sosigenes is also the largest, and most areally extensive among the  
85 dozens of IMPs identified on the central nearside (Braden et al. 2014).

86 The Sosigenes IMP (8.34°N, 19.07°E) was discovered on Lunar Reconnaissance  
87 Orbiter Narrow Angle Cameras (LROC NAC) images (Stooke 2012). It is located on  
88 the floor of a 7×3 km, approximately elliptical-shaped depression, and is composed of  
89 irregularly shaped mounds with surrounding topographically lower, hummocky and  
90 blocky units that are typical for other lunar IMP occurrences (Braden et al. 2014). In  
91 optical images, the mounds appear to be smoother than the lower units. However, the  
92 hummocky and blocky units are more optically immature (e.g., Grice et al. 2016) and  
93 have fewer superposed impact craters than the mounds. The wide range of  
94 characteristics of the suite of units associated with the Sosigenes IMP floor indicates  
95 complex, and potentially different, formation/modification processes for the origin of  
96 the multiple interior terrains.

97 Distinguished by their irregular shapes, well-preserved state of relief, apparent  
98 optical immaturity and few superposed impact craters, lunar IMPs are generally  
99 regarded to have been formed or modified by geologically recent processes. Crater  
100 counts revealed <100 Ma or even younger model ages for Sosigenes and several other  
101 lunar IMPs (Braden et al. 2014; Schultz et al. 2006). A topographic diffusional model  
102 reported maximum ages of 5–400 Ma for some of the Ina scarps, and suggested that  
103 some sub-meter troughs were formed very recently (<1–2 Ma) or are even currently  
104 active (Fassett and Thompson 2015).

105 However, the specific formation mechanism of lunar IMPs has been long debated.  
106 Earlier geomorphologic investigations integrated with regional geologic context  
107 characterization based on Apollo orbiter photographs suggested that Ina is a collapsed  
108 summit caldera of an extrusive volcanic dome, and that the bulbous mounds might  
109 represent some of the youngest lava extrusions on the Moon (El-Baz 1973; Strain and  
110 El-Baz 1980). Braden et al. (2014) documented 70 small topographic anomalies, with  
111 morphologies and textures resembling Sosigenes and other IMPs, on the nearside  
112 mare regions, and interpreted the mounds as small lava extrusions that occurred  
113 within the last 100 Ma (specifically, ~18 Ma for the Sosigenes mounds), significantly  
114 later than the established cessation time of mare basaltic volcanism of ~2.9 Byr ago  
115 from isotopic measurements (e.g., Borg et al. 2004), or ~1–1.2 Byr ago from crater  
116 size-frequency distribution (CSFD) investigations (Hiesinger et al. 2011; Schultz and  
117 Spudis 1983; Head and Wilson 2017).

118 Recent insights from new orbiter data and terrestrial analogues have provided  
119 substantial information on the nature of lunar IMPs with the potential of resolving  
120 various issues related to their origin. Observations from LROC NAC data (imagery  
121 and topography) and comparative planetology studies of terrestrial lava flow inflation  
122 fields (in particular, the McCarty’s flow in New Mexico) have led to the proposal that  
123 Ina was formed through lava flow inflation processes, in which the mounds were  
124 inflated lava flows, the hummocky units were lava breakouts from the margins of the  
125 mounds, and the blocky units were boulders exposed through mass wasting processes

126 (Garry et al. 2012). Radar observations (Carter et al. 2013) revealed that lunar IMPs  
127 exhibited a variety of different radar backscatter properties, and that one of the three  
128 studied IMPs (Cauchy-5) was mantled by fine-grained, block-free materials,  
129 consistent with pyroclastic deposits. Inspired by the same mineralogy between  
130 different units within Ina and the background mare deposits (Schultz et al. 2006;  
131 Bennett et al. 2015), Bennett et al. (2015) suggested that the mounds and lower units  
132 of Ina were probably emplaced contemporaneously and that the significant optical  
133 freshness of the lower units was possibly due to their blockiness; however, the  
134 specific emplacement mechanism was not indicated and other observed characteristics  
135 (e.g., impact crater density) were also not explained. Schultz et al. (2006) examined  
136 the optical maturity and superposed impact crater density of the floor rubble terrain at  
137 Ina, and proposed that Ina, along with several other IMPs (e.g., Hyginus) were  
138 probably volcanic remnants which were at least 3.5 Byr old, but that episodic  
139 out-gassing of juvenile volatiles (CO, H<sub>2</sub>O) from the deep lunar interior within the  
140 past 10 Ma removed the surface regolith materials, causing the rough texture and  
141 optical immaturity, and erasing superposed small craters. Thermophysical mapping by  
142 the LRO Diviner thermal radiometer revealed that Sosigenes and several other IMPs  
143 had much lower rock abundances than the ejecta of some late-Copernican-aged craters  
144 (e.g., ~170 Ma Aristarchus and ~85 Ma Tycho, actually only slightly higher than  
145 typical lunar surfaces, Ghent et al. 2014) and an interpreted surface regolith layer  
146 thicker than 10 cm, suggesting that either lunar IMPs were older than the crater-count  
147 dating results, or there was an unusually rapid development of regolith materials on  
148 IMPs compared with blocky ejecta blankets (Elder et al. 2016).

149 Recently, Wilson and Head (2016, 2017b) and Qiao et al. (2016a, 2016b, 2017)  
150 proposed that the lunar IMPs are actually ancient in age, contemporaneous with the  
151 adjacent mare deposits, and formed through very late stage CO-driven strombolian  
152 activity in a lava lake that produced the rough texture of the lower unit and a final  
153 H<sub>2</sub>O gas exsolution phase that occurred during the final closure of the magmatic dike  
154 and produced magmatic foam (very vesicular lava, e.g., Wilson and Head 2017b). The  
155 mounds were interpreted by Wilson and Head (2016, 2017b) to have formed from the  
156 final stage extrusion of these viscous magmatic foams through fractures in the cooling  
157 lake floor. The apparent immaturity of the floor and the meniscus-like shape of the  
158 mounds were attributed to very poor crater formation and retention in the mounds and  
159 the vesicularity and blockiness of the floor material.

160 In the present work, in order to explore the formation mechanism of lunar IMPs,  
161 we report on an analysis of one of the major IMPs, Sosigenes, based on the latest  
162 orbiter data sets. We characterize its regional geologic setting, the morphology and  
163 topography of the suite of interior units and the superposed impact craters, and we  
164 determine its sub-resolution roughness (with a baseline of centimeters to decimeters)  
165 using phase ratio imagery. We then evaluate the several previously proposed  
166 formation hypotheses to see if they can account for the observed morphological,  
167 topographic, photometric, spectral, and stratigraphic properties observed at Sosigenes  
168 and other IMPs. Finally we analyze the applicability to the Sosigenes IMP of the new  
169 formation mechanism that was suggested recently based on observations at Ina  
170 (Wilson and Head 2016, 2017b; Qiao et al. 2016b, 2017).

171

## 172 **2. Data and Methods**

173 We first undertake an analysis of the geomorphological and topographic  
174 characteristics of the Sosigenes IMP feature and surrounding region, based on the  
175 latest high-resolution orbiter image and altimetric data sets (Figs. 1–11). We use high

176 resolution images (up to 0.47 m pixel size) from LROC NAC to characterize the  
 177 morphological details of the suite of units associated with Sosigenes. Kaguya Terrain  
 178 Camera (TC) 10 m/pixel low-sun image mosaics (evening map products, Haruyama et  
 179 al. 2008) are employed in regional mapping. Topographic and slope analyses are  
 180 conducted on a 2 m grid Digital Terrain Model (DTM) produced from LROC NAC  
 181 image pairs (Henriksen et al. 2017). SELENE-TC+LRO-LOLA merged DEM  
 182 products (SLDEM2015, Barker et al. 2015) are used to characterize regional  
 183 topographic trends. The SLDEM2015 topography inherits the high spatial sampling  
 184 resolution of Kaguya TC data (512 pixels/degree (ppd), much higher than raw LOLA  
 185 data points for non-polar regions), and preserves the excellent altimetric accuracy of  
 186 the LOLA data (~3–4 m). We also count craters superposed on the Sosigenes mounds  
 187 using CraterTools in ArcGIS (Kneissl et al. 2011) on LROC NAC images with a range  
 188 of illumination conditions, and we analyze the crater counting results using the  
 189 software package CraterStats (Michael and Neukum 2010).

190 We then use the phase-ratio technique to characterize the surface roughness at  
 191 sub-resolution scale (Figs. 12, 13 and 15). The brightness (e.g., reflectance, radiance,  
 192 apparent albedo) of each point on the lunar surface is a function of the phase angle  $\alpha$   
 193 (e.g., Hapke 2012; Shkuratov et al. 2011). The brightness generally decreases with  
 194 increasing  $\alpha$ , and the rate of this decrease is directly related to the complexity of the  
 195 surface structure (e.g., roughness and porosity) at the sub-resolution scale. The rate of  
 196 phase function decrease can be characterized by the phase-ratio technique, which  
 197 employs two individual images covering the same lunar surface region, but with  
 198 different phase angles, to generate ratio images. For LROC NAC images with a  
 199 typical pixel size of ~1 m (Robinson et al. 2010), the derived phase ratio images are  
 200 sensitive to surface texture with a baseline of centimeters to decimeters. The  
 201 phase-ratio technique usually can identify many new details, some of which are not  
 202 well resolved in typical albedo images, e.g., the detection of weak swirls in the  
 203 southern portion of Oceanus Procellarum (Shkuratov et al. 2010), and has successfully  
 204 been employed to resolve the origin of some interesting features on the Moon, e.g.,  
 205 dark-halo craters (Kaydash et al. 2014).

206 To obtain phase ratio images for the Sosigenes IMP, we select LROC NAC  
 207 frames covering the Sosigenes floor acquired at different phase angles, but with close  
 208 spatial sampling size and illumination geometry, i.e., similar incidence and sub-solar  
 209 azimuth angles, thus minimizing the differences in extent and orientation of shadows  
 210 caused by resolved topographic relief, and aiding the alignment of the image pairs.  
 211 Imaging conditions of the selected image pair are listed in Table 1.

212 The raw NAC EDR (Experiment Data Record) images are photometrically  
 213 corrected and map-projected using the USGS's Integrated Software for Imagers and  
 214 Spectrometers (ISIS3, e.g., Anderson et al. 2004). The ISIS3 *ironacal* routine is used  
 215 to correct the raw NAC image digital number (DN) to radiance factor ( $f$ ). The NAC  
 216 radiance factor image pairs are then placed in the same projection, and co-registered  
 217 with the ISIS3 *coreg* sub-pixel registration routine. The co-registration procedure  
 218 improves the alignment of the image pairs. The aligned image pairs are finally used to  
 219 calculate the phase ratio images. In this work, we put the NAC image with smaller- $\alpha$   
 220 in the numerator and larger- $\alpha$  in the denominator, which is similar to previous  
 221 approaches (e.g., Shkuratov et al. 2011; Blewett et al. 2014; Clegg et al. 2014).

222

### 223 3. Results

#### 224 3.1. Nomenclature

225 There are multiple features with nomenclatures containing the term *Sosigenes*.



226 For clarification, we here make a brief reference to the features described in this work  
 227 (Figs. 1 and 2). *Sosigenes* is the IAU official name for a ~17 km diameter crater  
 228 centered at 8.7°N, 17.6°E, including three satellite craters, termed *Sosigenes A*,  
 229 *Sosigenes B*, and *Sosigenes C*. We use the term *Crater Sosigenes* for this ~17 km  
 230 crater. *Rimae Sosigenes* is the IAU approved term for a lunar rille system, centered at  
 231 8.08°N, 18.72°E and near the *Crater Sosigenes*, and we adopt this nomenclature. We  
 232 here refer to: 1) *Sosigenes depression* or *Sosigenes pit (crater)* as the ~7 km long,  
 233 elongate depression centered at 8.34°N, 19.06°E; 2) *Sosigenes IMP* as the ~5 km long,  
 234 irregular mare patch feature on the floor of *Sosigenes pit crater*, centered at 8.34°N,  
 235 19.05°E, which consists of the enigmatic Ina-like materials; 3) *Sosigenes linear*  
 236 *feature/structure* as a set of co-aligned linear structures, including pit craters, pit  
 237 chains and linear ridges, centered at 8.25°N, 19.31°E, with a total length of ~33 km.

238

### 239 3.2. Regional geologic setting

240 The Sosigenes IMP structure is located within an elliptical rimless depression at  
 241 the western margin of Mare Tranquillitatis, only ~15 km from an adjacent surface of  
 242 exposures of the ejecta deposit of the Imbrium basin (Fig. 1a-c). This depression is  
 243 part of a series of three main types of structures (*Sosigene linear feature*), which  
 244 co-align in an orientation normal to the strike of the *Rimae Sosigenes* (Fig. 2), and are  
 245 radial to the center of Mare Tranquillitatis (Fig. 1). The *Sosigenes linear feature*  
 246 clearly cross-cuts one of the *Rimae Sosigenes graben*, and is thus relatively younger.  
 247 Nested topographic profiles show that the cross-cut Rima *Sosigenes* is clearly a  
 248 graben, with two inward-facing normal faults bounding a down-dropped block (Figs.  
 249 2b and 3e). The cross-cut Rima *Sosigenes graben* is narrowest in the area adjacent to  
 250 the superposed *Sosigenes depression* (~0.9 km wide, compared with up to ~1.6 km  
 251 elsewhere). *Rimae Sosigenes* are parts of a series of linear and arcuate rilles oriented  
 252 concentrically to the edge of Mare Tranquillitatis, a common setting around the  
 253 margins of ancient impact basins. These are attributed to extensional deformation  
 254 associated with the loading of the impact basins with mare basalts, and associated  
 255 lithospheric flexure and deformation; the general geometry of loading influences  
 256 stress orientation and can favor emplacement of dikes, related graben formation above  
 257 the dikes, and often effusive and explosive eruptions along the strikes of the dike and  
 258 graben (Solomon and Head 1979, 1980; Head and Wilson 1993). The often  
 259 discontinuous nature of several of the Rima *Sosigenes graben* is likely to signal the  
 260 locations of eruptions and flooded regions from these eruptions; spectral and  
 261 detrended topographic data showed evidence for numerous lava flows streaming from  
 262 *Rimae Sosigenes* down into Mare Tranquillitatis (Tye and Head 2013). Wilson and  
 263 Head (2017a) and Head and Wilson (1993; 2017) have examined the relationship  
 264 between dike emplacement and graben formation and have shown that for dikes that  
 265 stall near the surface, graben formation is a predicted consequence, with variations in  
 266 dike width along the strike being related to the depth of the top of the dike below the  
 267 surface; the narrowest part of the graben typically represents the part of the dike  
 268 closest to the surface, and the graben widens with increasing dike top depth (Head and  
 269 Wilson 2017). Analysis of the Rima *Sosigenes graben* shows that it is narrowest in the  
 270 region of the cross-cutting *Sosigenes feature* (Figs. 2 and 3e), suggesting that this area  
 271 represents the top of the dike (Fig. 4).

272 The younger *Sosigenes linear structure* itself, about 33 km long, cross-cuts Rima  
 273 *Sosigenes* normal to its strike, and has very different features from the graben  
 274 structure, consisting of co-aligned pit craters, craters aligned in a chain, and a narrow  
 275 ridge. Two elongate rimless pit craters characterize the western ~12 km of the feature

276 (Fig. 2). The western-most pit crater is tear-drop shaped, 4.5×2.2 km in dimensions,  
 277 elongate along strike, and is U-shaped in cross section (Fig. 3a) with a typical floor  
 278 depth below the rim of ~350 m. It has a volume of ~1.8 km<sup>3</sup>. The main feature is an  
 279 elongate, generally rimless pit crater 7.2×2.8×0.35 km with a relatively flat floor of  
 280 ~5.1×1.4 km. This pit crater is the deepest part of the series of co-aligned features  
 281 (315 to 410 m deep; see nested profiles in Fig. 3b), cross-cuts the Rima Sosigenes  
 282 graben, and has a volume of ~3.8 km<sup>3</sup>. The relatively flat floor of this feature is  
 283 characterized by irregular mare patches (IMPs). The Sosigenes IMP is the most  
 284 extensive one among the ~70 documented lunar IMP formations (Braden et al. 2014).  
 285 Extending to the east of this main pit crater is a linear beaded chain of poorly  
 286 developed coalescing pits, about 6 km long and about 1.5 km wide. The first pit in the  
 287 chain is the most well-developed and deepest (Fig. 2 and profile #7 in Fig. 3c). These  
 288 pit chains are very similar to those seen above dikes that reach the shallow subsurface  
 289 with significant volumes of gas in the dike tip (Fig. 4c) and then partially vent the gas  
 290 to cause collapse, resulting in subsidence and drainage of material overlying the dike  
 291 (Head and Wilson 2017; see the case of the Hyginus crater chain, Wilson et al. 2011).  
 292 The third portion of the feature is a narrow (~0.5 km) discontinuous linear ridge  
 293 extending about 14–15 km from the eastern end of the pit chain, with a typical height  
 294 of ~15–20 m (Fig. 3d). This narrow ridge occurs directly along the strike of the center  
 295 of the feature, and is thus interpreted to be related to the genesis of the collapse pits  
 296 and crater chain segments. Head and Wilson (2017; their Figs. 14 and 24e) have  
 297 interpreted similar features elsewhere in the maria to be due to minor lava extrusion  
 298 during the waning stages of eruptions and the closing of the dike, causing residual  
 299 magma to be extruded into a narrow ridge.

300 Taken together, the characteristics of the co-aligned pit craters, pit chains and  
 301 linear ridge all support the interpretation that these features are related to the intrusion  
 302 of a dike from the mantle to the shallow subsurface and surface (Fig. 5). The dike  
 303 intruded normal to Rimae Sosigenes during the basalt filling of Mare Tranquillitatis.  
 304 We interpret the pit craters and crater chains to be related to the collapse of the gas  
 305 cavity at the top of the dike, and the ridge to be related to extrusion downslope in the  
 306 Tranquillitatis basin, formed in the waning stages of dike emplacement and dike  
 307 closure, as the relatively cooled residual magma in the dike was extruded to the  
 308 surface (Head and Wilson 2017; their Fig. 16). The extensive void space expected in  
 309 the subsurface at the top of the dike in this environment provides ample room to  
 310 accommodate the missing volume from the pit craters and chains due to collapse and  
 311 drainage. In addition, the pre-existing Rima Sosigenes graben may well have provided  
 312 additional subsurface void space and have been partly responsible for the relatively  
 313 larger size and volume of the central flat-floored pit crater. As is common in some  
 314 lunar collapse pits (e.g., Hyginus; Wilson et al. 2011), the floor of the larger pit may  
 315 have been resurfaced in the context of the post-collapse closing of the dike and  
 316 extrusion of basaltic magma onto the pit floor in the same manner that produced the  
 317 extrusive ridge (Wilson and Head 2017a). This sequence of events is illustrated in Fig.  
 318 5.

### 319 320 3.3. Morphology and topography

321 The enigmatic Ina-like IMP materials occur on the floor of the Sosigenes  
 322 depression, and are surrounded by depression walls (Fig. 6). The topographic slopes  
 323 of the depression walls generally range from 15° to 35°, and may achieve a maximum  
 324 of nearly 50° along some portions of the northern wall (Fig. 7b). The rim of the  
 325 depression is relatively flat; most areas have a slope less than 2° (baseline is 6 m, Fig.

326 7b). Unlike Ina, which possesses a low raised “collar” bordering the whole depression  
 327 (Garry et al. 2012; Strain and El-Baz 1980), the Sosigenes depression only displays a  
 328 raised rim along a small region on the southern rim, with a maximum height of ~30 m  
 329 (Figs. 6a, 7a and 7c). Relative to the surrounding mare regions, the Sosigenes  
 330 depression is ~320 m deep for most of the area of the depression floor, and reaches a  
 331 maximum depth of ~350 m at the north central margins (Fig. 7a). Within the  
 332 depression, the regional terrain elevation (Fig. 7) gradually increases by ~50 m from  
 333 the northern part to southern part over a distance of ~1.3 km, corresponding to a  
 334 kilometer-scale slope of ~2.2°.

335 The Sosigenes IMP floor can be categorized in terms of three morphologic units,  
 336 similar to other lunar IMPs (Garry et al. 2012; Strain and El-Baz 1980; Braden et al.  
 337 2014): (1) topographically higher, bulbous-shaped mound units, (2) topographically  
 338 lower, hummocky units, and (3) topographically lower, blocky units (Fig. 6).  
 339

### 340 3.3.1. Mound units

341 The Sosigenes depression floor is dominated by one very extensive and  
 342 geographically continuous mound unit, with another five smaller mounds (with  
 343 maximum length <300 m) scattered along the marginal areas of the depression floor (a  
 344 total of ~82% of the interior floor area, Fig. 6). This association is different from that  
 345 of Ina, where the mounds are comparable in size with the exposures of the lower  
 346 terrains, and are composed of over fifty small patches (Garry et al. 2012; Qiao et al.  
 347 2016b, 2017). These mound units are typically up to ~10 m higher than the adjacent  
 348 terrains (Figs. 9 and 10). The margins of the mound units generally have rounded  
 349 outlines and sharp, scarp-like contacts with the lower hummocky and blocky units  
 350 (Figs. 9 and 10). Topographic moats, typically ~5 m wide and ~1 m deep, are often  
 351 observed at the mound-floor contacts (Figs. 10d, e).

352 Though the mounds appear flat in optical images, their surfaces show a regional  
 353 topographic trend at longer baselines. The elevation of the mounds is generally higher  
 354 in the southern and eastern part, lower in the northern regions, and reaches the lowest  
 355 in the central northern area (Fig. 7a), where the pre-existing Rimae Sosigenes graben  
 356 intersects (Fig. 6). The total elevation change across the large mound is up to 65 m  
 357 over 1.2 km distance (Figs. 7 and 8). The topographic pattern of the Sosigenes  
 358 mounds is significantly different from those of the Ina feature, where the summits of  
 359 Ina mounds broadly have comparable elevations, and become lower towards the  
 360 interior; the topographic relief across the Ina mound summits is generally less than 10  
 361 m (Garry et al. 2012). The topographic difference between the mounds of Ina and  
 362 Sosigenes is probably mainly attributed to their geologic settings: the topography  
 363 surrounding Sosigenes shows a gradual decrease of elevation from western Imbrium  
 364 ejecta deposits to eastern mare deposits, and the Sosigenes feature intersects some  
 365 pre-existing linear rilles and wrinkle ridges (Fig. 6), whereas Ina is at the summit of a  
 366 small shield volcano, with relatively gentle regional topographic relief (Strain and  
 367 El-Baz 1980; Qiao et al. 2016b, 2017).

368 Although showing a regional tilt, the surface of the Sosigenes IMP mounds is  
 369 locally relatively flat: the NAC DTM-derived slope map (with a baseline of 6 m, Fig.  
 370 7b) shows that nearly 85% of the mound area has slopes less than 5°. Slopes along the  
 371 mound margins, however, are typically greater than ~10°, and can reach as high as  
 372 ~30°. On the relatively steep portions of the mounds, elephant-hide-like texture is  
 373 observed on the surface regolith (Fig. 11b), which is usually regarded as a result of  
 374 regolith creep processes (e.g., Melosh 2011).

375 Some small isolated mounds are present along the peripheral part of the giant



376 mound, though many still show very narrow bridge-like connections with the latter.  
 377 These marginal mounds are generally more extensive than the other five individual  
 378 mounds, with a typical dimension of 400×230 m (Fig. 10). These mound units at  
 379 Sosigenes are typically 5–10 m higher than the adjacent floor units (Figs. 9 and 10),  
 380 which is systematically less than the Ina mounds (10–20 m, Garry et al. 2012).

381 The largest impact crater (Fig. 11c) on the Sosigenes mounds has a diameter of  
 382 ~130 m. The morphological characteristics of this crater, e.g., degraded rim, gentle  
 383 wall slopes, absence of boulders in the crater interior and surrounding bright rays and  
 384 halos, suggest this crater is heavily eroded, and massive boulders, if they were  
 385 initially excavated by the crater-forming impact, have not survived the long period of  
 386 degradation (boulders breakdown time is estimated at ~300 million years; Basilevsky  
 387 et al. 2013). Alternatively, the crater may represent an impact into a layer of  
 388 unconsolidated materials, for instance solidified magmatic foam, in which case it  
 389 would penetrate deeper and make a smaller crater (Wilson and Head 2016, 2017b).  
 390 Depth measurements of the freshest craters  $\geq$ ~20 m in diameter (n=5) on the mounds  
 391 (Fig. 11a) show that these craters have relatively higher depth/diameter ratios ( $0.1611$   
 392  $\pm 0.0225$ , 0.1306–0.1828 range) than fresh craters on typical mare basalts ( $0.096 \pm$   
 393  $0.0012$ , Daubar et al. 2014), suggesting that some regolith materials within these  
 394 craters may have been crushed as a foam, with maximum impactor penetration.

395 Some interesting boulder trails are observed to originate from the Sosigenes  
 396 depression wall and then extend to the depression floor (Figs. 11d, e). Depending on  
 397 the floor materials, the rolling boulders may have different surface morphological  
 398 manifestations on the depression floor. A boulder rolling onto the mound units will  
 399 generally continue to plow through the surface regolith and produce boulder trails  
 400 until it come to a standstill (Fig. 11d), similar to its behavior observed at the wall. In  
 401 contrast, a boulder rolling onto the hummocky units will either terminate at the  
 402 bottom of the wall, or continue to travel on the hummocky unit, but it does not  
 403 produce any boulder trails detectable on high-resolution LROC NAC images (Fig.  
 404 11e). These superposed craters and boulder trail features can provide key information  
 405 on the regolith properties of different geomorphologic units within the Sosigenes IMP,  
 406 suggesting relatively thicker regolith (meters thick) on the mound units and much  
 407 thinner regolith (nearly absent) on the hummocky units (Hovland and Mitchell 1971).

408 Taken together, the morphologies and dimensions of the Sosigenes mounds and  
 409 related features all support the interpretation that the mounds have been exposed at the  
 410 surface for a long period (probably billions of years), and have been modified by  
 411 subsequent erosion processes.

412

### 413 3.3.2. Hummocky units

414 The hummocky units generally occur at the margins of the Sosigenes depression  
 415 floor, although some can extend to the central floor (Fig. 6). The hummocky units  
 416 along the margins typically have narrow elongate shapes in map view, while those  
 417 extending to the center regions have irregular and patchy shapes. Compared with the  
 418 mounds, the total area covered by the hummocky units at Sosigenes is relatively small  
 419 (~15% by area); this is different from Ina (mounds ~50% and hummocky units ~44%)  
 420 (Qiao et al. 2016b, 2017). In LROC NAC high resolution images, the hummocky  
 421 units show ridged and pitted textures (Fig. 11f). The NAC DTM-derived topographic  
 422 slopes of the hummocky units typically range from 1.5° to 9° (5–95 percentile values);  
 423 small portions of the hummocky units have surface slopes comparable to those of the  
 424 mounds (Fig. 7b). The hummocky units generally have scarp-like contacts with the  
 425 mounds (Fig. 9), and topographic moats are often present along the contacts (Figs.

426 10d, e). The hummocky units appear rough and angular on high-resolution NAC  
427 images; however, very few boulders are observed over most of the hummocky units  
428 (Fig. 11g) except for areas surrounding some fresh impact craters.

429 Some small impact craters are also observed on the hummocky units (Fig. 11g),  
430 which can be regarded as natural probes into the shallow subsurface. The diameter of  
431 these craters can be as small as ~20 m. However, these small craters still penetrate the  
432 surface regolith layers, as massive boulders are excavated and deposited on the crater  
433 wall, floor and rim (Fig. 11g). These observations indicate that the surface regolith  
434 materials of the hummocky units are very thin, significantly thinner than the  
435 excavation depth of these craters (~1.7 m; Melosh 1989). Some irregular depression  
436 structures with dimensions up to ~50 m are observed on the hummocky units (Fig.  
437 11f). These depressions are characterized by very complicated geomorphologies,  
438 including variable outlines (circular, elliptical, irregular, etc.), concentric interior  
439 structures, fractures and mounds on the depression floors. We interpret these  
440 depressions to represent poorly developed impact craters, indicating impacts into  
441 unusual target materials, e.g., highly-porous solidified lava lake crust.

442

### 443 3.3.3. Blocky units

444 Blocky units have the smallest areal occurrence among all the three units on the  
445 depression floor (3%, compared with 4% for Ina (Qiao et al. 2016b, 2017)) (Fig. 6).  
446 These units are mostly observed within the hummocky units or along the edges of  
447 hummocky units (Fig. 6). In earlier, relative lower resolution Apollo orbiter  
448 photographs, the blocky units at Ina were characterized as “bright” materials (Strain  
449 and El-Baz 1980). Images from the LROC NAC with much higher resolution show  
450 unambiguously that these units are extensive fresh (thus bright on optical images)  
451 boulder fields with individual boulders approaching ~12 m in dimension (Fig. 11h).  
452 The surface of these blocky materials is also the most rugged among the three interior  
453 units, with slopes ranging from 2° to 13° (5–95 percentile values, Fig. 7b). A large  
454 portion of these blocky materials occurs at the contacts between the mounds and  
455 hummocky materials, which are characterized by a topographic depression of ~2 m  
456 depth (Figs. 9c, d).

457

### 458 3.4. Sub-resolution roughness

459 Although the LROC NAC images are of very high resolution (~0.47–1.2  
460 m/pixel), additional information on surface morphology and roughness at even higher  
461 resolution can be obtained by employing the phase-ratio technique (Kaydash and  
462 Shkuratov 2011). Sub-resolution roughness derived from phase-ratio imagery appears  
463 to be a very effective tool to study the micro-topography and structure properties of  
464 the surface of the Moon and other airless bodies, which is useful for characterizing the  
465 nature of surface modification processes, e.g., mass wasting (Kaydash et al. 2012),  
466 regolith creep (Kaydash and Shkuratov 2011), pyroclastic deposition (Blewett et al.  
467 2014), and impact melt flows (Shkuratov et al. 2012; Blewett et al. 2014). We here  
468 apply the phase-ratio technique to the Sosigenes IMP feature, to see whether it shows  
469 any photometric anomalies. The several previously proposed hypotheses for the origin  
470 of lunar IMPs make different predictions about the sub-resolution roughness of the  
471 IMPs interior materials. The phase-ratio imagery may provide some critical evidence  
472 for evaluating these hypotheses.

473

474 We calculate phase ratio images of eastern Sosigenes from images acquired at  
475 30° and 67° phase angles (Fig. 12, Table 1). Several image regions of interest (ROIs)  
are outlined on the mound, hummocky and blocky units, and the surrounding

476 background mature mare regions (Fig. 12c and its raw resolution version in  
 477 supporting information), to evaluate quantitatively the reflectance and photometric  
 478 properties of these units. Table 2 presents the average radiance factor and phase ratio  
 479 values of these ROIs. For all the surfaces of different morphologic units, their  
 480 radiance factor values in the larger- $\alpha$  image are systematically lower than those in the  
 481 smaller- $\alpha$  image, which is consistent with the ubiquitous trend of decreasing  
 482 brightness with increasing phase angle (e.g., Hapke 2012; Jin et al. 2015).

483 Examination of Fig. 12 and Table 2 reveals both brightness and photometric  
 484 anomalies for all three morphological units of the Sosigenes IMP. In the smaller- $\alpha$   
 485 image ( $\alpha = 30^\circ$ ), the mound units have slightly higher radiance factor values (104%)  
 486 than the background maria; the hummocky units are significantly brighter (133%)  
 487 than the background; the blocky units are even brighter than the background mare  
 488 materials (165%). In larger- $\alpha$  images ( $\alpha = 67^\circ$ ), the mounds have an even higher  
 489 radiance factor (106%) when compared with the background; the hummocky units are  
 490 also brighter (158%) than the background; however, the blocky units show a slight  
 491 decrease in brightness when normalized to the background (159%), though they are  
 492 still much brighter than background.

493 Therefore, both the mounds and hummocky units of the Sosigenes IMP exhibit a  
 494 slower decrease of the radiance factor than the background as the phase angle  
 495 increases, while the hummocky units show a much slower decreasing trend. However,  
 496 the blocky units show a contrary photometric trend: a more rapid decreasing of  
 497 radiance factor than the background with increasing phase angles. These interesting  
 498 brightness trends with increasing phase angles are clearly demonstrated in the phase  
 499 ratio ( $f(30^\circ)/f(67^\circ)$ ) images (Fig. 12b and Table 2). The mounds have slightly smaller  
 500 phase ratio values ( $\sim 98\%$ ), the hummocky units have significantly smaller phase ratio  
 501 values ( $\sim 84\%$ ), while the blocky units have higher phase ratio values ( $\sim 107\%$ ), than  
 502 background mature mare regions.

503 Negative phase ratio anomalies generally correspond to gentler phase function  
 504 curve slopes largely due to a weakening of the shadow-hiding effect, indicating a  
 505 smoother sub-resolution surface texture than typical lunar surface regolith materials.  
 506 Conversely, positive phase ratio anomalies indicate a rougher sub-resolution surface  
 507 texture. There is a potential correlation between brightness and phase ratio value,  
 508 which may mislead the evaluation of sub-resolution roughness from phase ratio  
 509 images. Some previous analyses have observed a positive correlation between the  
 510 brightness and larger- $\alpha$ /smaller- $\alpha$  phase ratio (Shkuratov et al. 2012). This observed  
 511 correlation is due to the illumination of the shadows by multiple light scattering from  
 512 the bright lunar surface. However, no obvious correlation has been observed between  
 513 the phase-ratio and the radiance factor for the Sosigenes IMP features in this work.  
 514 The correlation coefficient between  $f(67^\circ)/f(30^\circ)$  and  $f(30^\circ)$  for eastern Sosigenes (the  
 515 same extent as Fig. 12) is only 0.2624. The weak correlation is also verified by the  
 516 two-dimensional scatter plot of phase ratio and radiance factor for the background  
 517 mare regions and individual terrains of Sosigenes interior (Fig. 13), which clearly  
 518 shows the very weak correlation of the whole set of plot points, and that the Sosigenes  
 519 interior terrain units do not generally lie along the trend of the background materials.  
 520 In addition, a visual check of the brightness and phase ratio images (Fig. 12) can also  
 521 prove the very weak phase ratio-radiance factor correlation, as we can readily find  
 522 some areas with close radiance factor values, but significantly different phase ratios.  
 523 Therefore, the phase ratio image of Sosigenes IMP is a direct and robust indicator of  
 524 its sub-resolution roughness.

525 While the hummocky units are often characterized as ‘uneven’ regions, this

526 description is based on meter-scale LROC NAC images (Garry et al. 2012). At  
527 sub-resolution length-scales (centimeters or decimeters), the hummocky units are  
528 smoother than the mature mare background. We suggest that this is reasonable using  
529 evidence from high resolution images. Though the hummocky units appear rugged in  
530 meter-scale LROC NAC images, almost no exposed boulders are observed in most  
531 portions of the hummocky units (Fig. 11f). The smaller sub-resolution roughness  
532 revealed by the phase ratio images is also consistent with the Diviner-derived rock  
533 abundance data (Fig. 14, Bandfield et al. 2011). The rock abundance of the  
534 hummocky units is not as high as that of the walls of some fresh small craters and the  
535 Sosigenes depression wall, where freshly exposed boulders are clearly observed in  
536 LROC NAC images. Moreover, the blocky units of the Sosigenes IMP floor indeed  
537 have a high concentration of exposed boulders (e.g., central north of Sosigenes, Fig.  
538 11h), which, correspondingly, have greater phase ratio values (Fig. 12b), indicating a  
539 rougher sub-resolution surface texture. The consistency among the phase ratio values,  
540 LROC NAC images of these blocky materials, and Diviner-derived rock abundance  
541 data further validates our sub-resolution roughness interpretations.

542 The phase ratio images also reveal the confined (i.e., not diffuse) extent of the  
543 Sosigenes floor materials, especially for the hummocky units (Fig. 12b). This  
544 observation is substantially verified by the phase ratio value profile derived across  
545 some of the mounds, hummocky units, and the depression wall at Sosigenes (Fig. 15).  
546 The phase ratio profile exhibits a sharp decrease at the margins of the hummocky  
547 units (points 2 and 3 in Figs. 12b and 15). One should be aware that the extremely  
548 high phase ratio values at the steep scarps of the hummocky unit margins could be  
549 artifacts due to resolvable surface topography at the margins. The steep scarps cause  
550 significantly different imaging results from different observing angles, which inhibit  
551 the alignment of the image pairs (Kaydash et al. 2011), even with similar incidence  
552 and sub-solar azimuth angles.

553 In summary, the LROC NAC phase ratio technique reveals very important  
554 characteristics of the Sosigenes IMP interior units: (1) the surface materials of the  
555 mound units have slightly smoother sub-resolution surface texture than typical mature  
556 lunar mare regolith; (2) the hummocky units are characterized by a significantly lower  
557 sub-resolution roughness with confined spatial extent; (3) the blocky units are  
558 composed of fresh boulders, with rougher sub-resolution surface texture. These  
559 photometric observations will provide key information for analyzing the origin of  
560 lunar IMPs.

561

### 562 3.5. Impact crater counts

563 One of the most unusual characteristics of lunar IMPs is their apparently small  
564 number of superposed impact craters, suggesting to Braden et al. (2014) a model age  
565 of <100 Ma (specifically, 18.1 Ma for Sosigenes). To explore the potential causes for  
566 the extremely low impact crater density, we compile impact crater-size frequency  
567 distribution (CSFD) measurements for the Sosigenes IMP. We count all impact craters  
568  $\geq 10$  m in diameter on the Sosigenes mounds using LROC NAC images with a range  
569 of illuminations geometries (Fig. 16, Table 3). We have taken particular care to  
570 eliminate the contamination by secondary impact craters and endogenous pits  
571 according to their morphologic characteristics (e.g., Shoemaker 1962; Oberbeck and  
572 Morrison 1974; Head and Wilson 2017). To investigate the potential effects of  
573 topographic slopes on the density of craters of variable size ranges, we select several  
574 typical areas with variable NAC DTM-derived slopes ( $<3^\circ$ ,  $3\text{--}6^\circ$  and  $>6^\circ$ , see Fig. 17),  
575 count craters with several diameter ranges (10–15 m, 15–20 m, and 20–30 m) and



576 present CSFD (R-values) plots for these areas (Fig. 18 and Table 4). For comparison,  
 577 we also conducted CSFD and slope analyses on a mare region with similar surface  
 578 areas (a 2×2 km<sup>2</sup> crater-counting area, and an 840×840 m<sup>2</sup> sub-area for slope analysis)  
 579 surrounding Sosigenes IMP (Figs. 18-20). The cumulative size frequency distributions  
 580 of these identified impact craters are plotted in Fig. 21.

581 Compared with Braden et al. (2014), we identify significantly more impact  
 582 craters on the Sosigenes mounds, e.g., 683 craters ≥10 m in diameter (compared with  
 583 286 of Braden et al. (2014)). The size-frequency distribution of these craters shows  
 584 partly saturated equilibrium for craters <~35 m in diameter (Fig. 21). Fitting of impact  
 585 craters ≥35 m yields an absolute model age of  $51 \pm 10$  Ma using the lunar chronology  
 586 function (CF) and production function (PF) of Neukum et al. (2001), compared with  
 587  $18.1 \pm 1$  Ma of Braden et al. (2014).

588 In addition, the crater density (R-values) at the Sosigenes mounds shows  
 589 interesting trends with topographic slopes. The R-value CSFD plot clearly shows that  
 590 the crater density generally decreases with increasing slope (Fig. 18 and Table 4),  
 591 indicating that craters on steeper sloped surfaces are more easily destroyed/erased,  
 592 probably by regolith creep process (Xiao et al. 2013) (although we cannot rule out a  
 593 statistical error caused by the small size of the count areas (van der Bogert et al.  
 594 2015)).

595 For the 2×2 km<sup>2</sup> mare area south of Sosigenes IMP, we identify 1870 craters ≥10  
 596 m in diameter. The production function fit for craters ≥170 m in diameter gives an  
 597 absolute model age of  $2.1 \pm 0.9$  Ga (Fig. 21), which is younger than the 3.68  
 598 (+0.03/-0.04) Ga age reported by Hiesinger et al. (2011) for the surrounding mare  
 599 regions. We attribute the variability to statistical errors mainly caused by the small  
 600 count area size (4 km<sup>2</sup>), which has been frequently observed in previous studies (e.g.,  
 601 van der Bogert et al. 2015), and the spatially and temporally heterogeneous nature of  
 602 secondary impacts (e.g., Chapman 2004; McEwen and Bierhaus 2006). Compared  
 603 with the Sosigenes mounds, typical mare areas are generally very flat (Fig. 20), and  
 604 show much higher crater densities than the Sosigenes mound areas with comparable  
 605 slopes (<3°) (Fig. 18).

606

#### 607 **4. The Origin of Sosigenes IMP Feature**

##### 608 4.1. Evaluation of several previous formation hypotheses

609 We compile key observations of lunar IMPs from the regional geologic setting  
 610 (El-Baz 1973; Strain and El-Baz 1980; Garry et al. 2012; and this work), topography  
 611 (Strain and El-Baz 1980; Garry et al. 2012; Fassett and Thomson 2015; and this work),  
 612 morphology (Strain and El-Baz 1980; Garry et al. 2012; and this work),  
 613 sub-resolution roughness (this work), optical maturity (Schultz et al. 2006; Staid et al.  
 614 2011; Garry et al. 2013; Bennett et al. 2015), reflectance (Strain and El-Baz 1980;  
 615 Garry et al. 2013; Staid et al. 2011; and this work), composition/spectroscopy  
 616 (Bennett et al. 2015; Staid et al. 2011; Schultz et al. 2006), and impact crater density  
 617 (Schultz et al. 2006; Braden et al. 2014; and this work) to test the several previously  
 618 proposed formation hypotheses.

619

##### 620 4.1.1. Recent individual lava extrusions

621 Earlier morphologic investigations of Apollo orbiter photographs suggested that  
 622 the Ina IMP was a collapsed summit caldera of a volcanic dome and, specifically, that  
 623 the mounds might represent the youngest lava extrusions on the Moon (El-Baz 1973;  
 624 Strain and El-Baz 1980). Recently, benefiting from the newly-obtained high  
 625 resolution LROC NAC images, Braden et al. (2014) derived absolute model ages



626 younger than 100 Ma for three IMP occurrences (specifically, ~18.1 Ma for  
 627 Sosigenes), based on observations from CSFDs, absence of clear crater equilibrium  
 628 diameters, steep slopes of the mounds' margins (e.g., 8–32° range with average of 16°  
 629 at Sosigenes), LROC WAC multi-band spectroscopy and NAC morphologies.  
 630 Specifically, Braden et al. (2014) suggested that the mounds were lava flows  
 631 emplaced several billion years after the surrounding mare basalts, and that the  
 632 hummocky units were collapsed eruptive vents (thus fragmenting pre-existing mare  
 633 deposits within the vents), contemporaneous with the very recent mounds (Fig. 22).

634 The geologically recent lava extrusion hypothesis, if true, would require a major  
 635 rethinking of the current and past interior thermal regimes of the Moon as pointed out  
 636 by Braden et al. (2014). However, a recent volcanic event interpretation cannot  
 637 explain a range of key observed characteristics. (1) If these mounds are volcanic  
 638 extrusions emplaced within the last 100 Ma, it is predicted that only a very thin layer  
 639 of surface regolith would have developed since the very young lava extrusions.  
 640 Assuming an average regolith accumulation rate of ~1 mm/Myr in the last billion  
 641 years (Quaide and Oberbeck 1975), the surface regolith developed on the ~18  
 642 Ma-aged mare deposits should be significantly thinner than 0.1 m. However, this is  
 643 inconsistent with regolith thickness estimations for the Sosigenes mounds from (a)  
 644 observed superposed boulder trails (meters thick, section 3.3.1) and (b) Diviner  
 645 thermophysical analysis (>0.1 m, Elder et al. 2016). (2) The recent lava extrusion  
 646 hypothesis also contradicts the absence of excavated boulders on crater walls at the  
 647 Sosigenes mounds; this absence suggests hundreds of millions years of degradation  
 648 processes, or impacting into unconsolidated materials, e.g., solidified magmatic foams  
 649 (section 3.3.1). (3) Additionally, as suggested by Bennett et al. (2015), the recent lava  
 650 extrusion hypothesis is also inconsistent with the mineralogy (high-Ca  
 651 pyroxene-dominated) of the different units within Ina and the surrounding mare being  
 652 the same (Schultz et al. 2006; Bennett et al. 2015), because neither a long-lived  
 653 magma reservoir nor late-stage magma is likely to have the same mineralogy as the  
 654 original ancient magma source. The same mineralogy strongly suggests that different  
 655 units of lunar IMPs are emplaced contemporaneously with the surrounding mare  
 656 deposits, but may have experienced variable subsequent modification processes. (4)  
 657 Finally, theoretical and observational treatments of the thermal and tectonic evolution  
 658 of the Moon demonstrate that the continued net cooling of the Moon decreased the  
 659 volume of mantle melting, thickened the lithosphere, and caused the global state of  
 660 stress to be increasingly contractional. All of these factors progressively inhibited the  
 661 generation, ascent and eruption of basaltic magma (e.g., Head and Wilson 1992; 2017),  
 662 leading to volcanism having waned in middle lunar history and ceased sometime in  
 663 the last ~1 Ga, consistent with extensive analyses of returned samples and remote  
 664 sensing data (e.g., Hiesinger et al. 2011; Morota et al. 2011). It seems very unlikely  
 665 that lunar extrusive eruptions would have been dormant for over 1 Ga, while became  
 666 active again very recently (18–58 Ma; Braden et al. 2014).

667

#### 668 4.1.2. Lava flow inflation

669 Based on morphologic and topographic analyses of Ina and terrestrial analogues,  
 670 Garry et al. (2012) interpreted Ina to resemble some terrestrial inflated lava flows (in  
 671 particular, the McCarty's flow in New Mexico), mainly in dimensions and  
 672 topographic relief. Thus, Ina was suggested to be formed by lava flow inflation  
 673 processes, in which the mounds were inflated lava sheet lobes, the hummocky units  
 674 were breakouts from the margins of the mounds, and blocky units were fresh surfaces  
 675 exposed by mass wasting of both units (Fig. 22). The Garry et al. (2012) lava inflation

676 model does not clearly propose a formation age for Ina.

677 Large volume lava flows on terrestrial bodies commonly experience inflation  
678 processes (e.g., Hon et al. 1994); however, inflated terrestrial flows are still dissimilar  
679 to lunar IMPs in many aspects, and the lava inflation processes alone cannot readily  
680 explain the range of distinctive characteristics of different morphologic units of  
681 Sosigenes and other major IMPs that indicate a much more complex set of  
682 formation/modification processes for their origin. For example, (1) Garry et al. (2012)  
683 showed that the Ina mounds have dimensions and heights comparable to those of  
684 inflated lava sheet lobes in the McCarty's flows. The McCarty's inflated flow features  
685 are generally spatially connected (e.g., Fig. 8a in Garry et al. 2012), as these flows  
686 were initially emplaced as broad sheets of lava, while dozens of spatially separated  
687 mounds are mapped out at several IMPs (e.g., Ina (Fig. 2 in Garry et al. 2012),  
688 Sosigenes (Fig. 6b)), suggesting they were initially emplaced separately. The  
689 McCarty's inflated flows also do not have the roughly elliptical planform outlines of  
690 some IMP mounds. (2) No associated source vents have been unambiguously  
691 identified in lunar IMPs. Although Garry et al. (2012) suggested that some rimless  
692 depressions on the tops of Ina mounds were potential vent features, NAC images  
693 obtained under very low sun illuminations ( $<3^\circ$ ) clearly reveal the rim crest structures  
694 of these summit depressions (Fig. 23), indicating that they are more likely to be  
695 impact craters. (3) The lava flow inflation hypothesis suggested that all the  
696 morphologic units of IMPs (e.g., mound and hummocky units) were emplaced  
697 geologically contemporaneously (though they may have developed differently in a  
698 stratigraphic sequence); this is inconsistent with the significant differences between  
699 the mound and hummocky units in both superposed impact crater density and optical  
700 maturity (indicating either a much younger age for the hummocky units than the  
701 mounds, or variable formation/modification processes). (4) The lava inflation  
702 hypothesis suggested that the blocky units were fresh surfaces exposed by mass  
703 wasting processes. However, we find that many blocky units occur on relatively flat  
704 regions (with 6-m-baseline slope  $<3^\circ$ , Figs. 6, 9c, 9d and 17), which is inconsistent  
705 with the sloped surface (typically  $>10^\circ$ ) required for the mass wasting process on the  
706 Moon (Xiao et al. 2013). (5) Flow features in the lower units of terrestrial lava flow  
707 fields are observed to embay the margins of the higher units (inflated flows), but this  
708 is not seen at lunar IMPs, and it actually appears that the mounds embay the  
709 hummocky terrain. In summary, we suggest that although lava flow inflation may  
710 have played some role in the initial stage of the IMP formation process (Wilson and  
711 Head 2016, 2017b; Qiao et al. 2016b, 2017), additional subsequent surface  
712 modification processes are required to produce the highly variable characteristics of  
713 different units within lunar IMPs, including regolith thickness, sub-resolution  
714 roughness, impact crater density, and optical freshness.

715

#### 716 4.1.3. Pyroclastic deposits

717 Radar data showed that lunar IMPs exhibited a range of variable radar  
718 backscatter properties. In particular, one of the three studied IMPs (i.e., Cauchy-5)  
719 showed unusual low radar circular polarization ratio (CPR) values compared with the  
720 background mare, interpreted as mantling by fine-grained and block-free materials  
721 (Carter et al. 2013). Carter et al. (2013) thus proposed pyroclastic deposition for the  
722 origin of some lunar IMPs. Facilitated by the much higher spatial sampling resolution  
723 of LROC NAC images ( $\sim 1$  m) than the radar experiments (80 m for Arecibo S-band  
724 data), our phase ratio techniques reveal the confined spatial extent of the finer  
725 materials at Sosigenes IMP, which cannot be resolved on relatively coarser radar data

726 sets. However, the gas expansion mechanism that drives explosive eruptions causes  
727 them to disperse ash and pyroclasts continuously over a wide area (e.g., Gaddis et al.  
728 2003; Wilson et al. 2015; Blewett et al. 2014). Therefore, we suggest that pyroclastic  
729 eruptions are not likely to be responsible for the formation of lunar IMPs, although  
730 they may play a role in the initial opening stage of the eruption (Wilson and Head  
731 2016, 2017a; Head and Wilson 2017). Our suggestion is also supported by M<sup>3</sup>  
732 spectroscopic observations, which show similar mineralogy for the different  
733 morphologic units of IMPs and the surrounding mare basalt deposits, and no detection  
734 of glass-bearing materials (Bennett et al. 2015; Grice et al. 2016), which are often  
735 observed in M<sup>3</sup> spectroscopic data of pyroclastic deposits (e.g., Jawin et al. 2015).

#### 736 4.1.4. Out-gassing removal of surface regolith

737 Schultz et al. (2006) hypothesized another formation process for lunar IMPs, in  
738 which the mounds are ancient volcanic features formed at least 3.5 Byr ago,  
739 contemporaneous with the surrounding mare basalts, but episodic out-gassing of  
740 juvenile volatiles (e.g., CO<sub>2</sub>, H<sub>2</sub>O) trapped deep in the Moon within the past ~10 Myr  
741 removed multiple parts of the surface fine materials, and exposed the underlying  
742 long-buried basaltic bedrock, thus forming the lower hummocky/blocky units of IMPs  
743 (Fig. 22). However, in a manner similar to explosive volcanic eruptions, out-gassing  
744 removal of surface regolith will also generate finer-particle materials with a diffuse  
745 extent, which is again inconsistent with our phase ratio observations. LROC NAC  
746 sub-resolution roughness investigations of Apollo landing sites, where the surface  
747 regolith materials are blown by the gas jets below the lunar descent modules, also  
748 show regions of lower sub-resolution roughness with diffuse extent (e.g., Kaydash et  
749 al. 2011). The proposed out-gassing events for the origin of IMPs would also rapidly  
750 emit gas, thus diffusively smoothing the surface. Therefore, we suggest that recent  
751 out-gassing event is also not likely to be the origin of lunar IMPs.

#### 752 4.2. A new origin for lunar IMPs

753 As none of the common geological processes discussed above are fully  
754 consistent with all the observed characteristics, we here focus on the Sosigenes IMP,  
755 and explore the applicability of a new formation mechanism, which was suggested  
756 recently based on physical volcanology analyses of late-stage lunar eruptions (Wilson  
757 and Head 2016, 2017b) and observations of Ina (Qiao et al. 2016b, 2017), for the  
758 Sosigenes IMP. Following the latest assessment on the generation, ascent and eruption  
759 of magma on the Moon (Wilson and Head 2016, 2017a; Head and Wilson 2017) and  
760 documentation of magmatic-volcanic processes from terrestrial volcanic fields (Qiao  
761 et al. 2016b, 2017), we interpret the Sosigenes IMP and related features to be  
762 consistent with an origin as the products of the waning stages of an eruption in a  
763 linear pit crater atop a dike.

#### 764 4.2.1. Waning stages of dike-tip pit crater eruptions

765 During the major phase of lava filling of the Mare Tranquillitatis basin interior,  
766 magmatic dikes are emplaced below the basin (Fig. 4a). Among these dozens of dikes  
767 developed in the western Tranquillitatis basin, some dikes with sufficient magma  
768 overpressure will propagate all the way to the surface and initiate effusive and  
769 explosive eruptions along the strike of the dike, as evidenced by the observation of  
770 numerous lava flows streaming from western Tranquillitatis down into the basin  
771 center (Tye and Head 2013). Some dikes, propagating only into the shallower parts of  
772 the crust, can introduce near-surface extensional stress fields above the dike (Fig. 4d),  
773  
774  
775

776 and generate the Rimae Sosigenes graben system, one of which is cross-cut by the  
777 Sosigenes depression feature (Fig. 1c). The cross-cut Rima Sosigenes graben is  
778 narrowest in the area adjacent to the superposed Sosigenes feature, which typically  
779 represents the part of the dike closest to the surface (Fig. 5a). Then, a new  
780 gas/foam-filled dike propagates to the shallow subsurface and intrudes normal to  
781 Rima Sosigenes (Fig. 5b), but the dike emplacement-generated near-surface stress  
782 field is insufficient to cause graben-forming deformation (Fig. 4c). Initially, the  
783 magma ascent speed is so great (many tens of m/s) that the gas bubbles (mainly CO)  
784 are essentially uniformly distributed in the magma as it approaches the surface. The  
785 eruption of these bubbles into the lunar vacuum allows the magma to fragment into  
786 sub-mm-sized droplets and gas to expand indefinitely in all directions; this is the lunar  
787 equivalent of a relatively steady hawaiian-style eruption (Wilson and Head 2017a,  
788 2017b). The venting of these pyroclastic components causes the collapse, subsidence  
789 and drainage of the materials overlaying the dike, forming a series of co-aligned pit  
790 craters and crater chains, as observed at the Sosigenes linear features (Fig. 4c), i.e.,  
791 the Sosigenes depression, the west-most pit craters and the pit chains east of the  
792 Sosigenes depression (Fig. 2). As the maximum shallow-subsurface void space is  
793 expected at the intersection of the two dike tips, it is very likely that this part of the  
794 dike tip would experience the most collapse (Fig. 5c), as evidenced by the deepest  
795 part of the Sosigenes depression among the co-aligned linear features (Figs. 2b and 3).  
796 Extruded lava from the dike will enter the collapsed Sosigenes pit crater floor,  
797 flooding it, and producing a lava lake with a maximum area of  $\sim 6 \text{ km}^2$  (Fig. 5).  
798 During the terminal stage of dike emplacement outside the pit crater and the closing  
799 of the dike, residual magma formed a minor lava extrusion, producing a narrow ridge  
800 atop the dike (Head and Wilson 2017), namely the east-most narrow ridges (Fig. 2).  
801 As the excess pressure in the dike is lost, the magma rise speed must decrease  
802 and eventually become very small (close to or less than  $\sim 1 \text{ m/s}$ ). The difference  
803 between the ascent speed of the magma and the buoyant rise of gas bubbles becomes  
804 less, and the prolonged transit time allows bubbles (mainly CO) to coalesce. This  
805 leads to a change in eruption style towards strombolian activity, in which large  
806 bubbles emerge intermittently through the surface of the overlying lava lake (Fig. 24).  
807 During this period, radiative cooling of the lava lake surface begins. Within a period  
808 of several months, the lava lake surface crust grows up to several meters thickness,  
809 forming a rigid and platy thermal boundary layer (Wilson and Head 2016, 2017b).  
810 During lava lake inflation and deflation, the magma continuously degasses and  
811 bubbles and foams accumulate below the lava crust; during deflation, the surface crust  
812 is locally deformed into pressure ridges. The bubbles formed during the strombolian  
813 explosive phase would have updomed the lava lake surface crust, and ejected large  
814 (up to meter scale) disrupted lava lake fragments. The fall-back of these ejecta into the  
815 cooling lake surface will further deform the lava lake crust (Fig. 24). Taken together,  
816 the nature of the lava lake magma (volatile-rich), the evolution of the lava lake surface  
817 (inflation, deflation and subsidence) and its subsequent modification (ejecting and  
818 deposition of the lava lake fragments) all make the surface topography and the interior  
819 structure more porous and complex: the lava lake surface is topographically tilted,  
820 with abundant ejecta fragments and ridged and pitted structures; the upper meters of  
821 the lava lake crust are characterized by abundant vesicles (micro-vesicular) and meter  
822 scale flat blisters (macro-vesicular) (Fig. 24). Furthermore, additional subsurface void  
823 space is predicted due to (1) the abundance of vesicles in the uppermost layers of the  
824 lava lake due to bubble flotation and (2) subsurface volume decreasing as a result of  
825 the thermal contraction and solidification of the lava (Richter and Moore 1966). We



826 interpret the topographically low hummocky/blocky terrain at Sosigenes IMP to  
827 originate from the heavily deformed lava lake crust and its associated structures.

828 In the final stage of the eruptive process (Wilson and Head 2016, 2017b), as the  
829 rise speed of the ascending magma slows to zero, no additional magma from deeper  
830 (>10 km) will migrate upward, no more CO will be released, and the only gas  
831 production in the dike will be the release of water vapor. The final slug or giant  
832 bubble of CO that emerges at the surface marks the last strombolian explosion (Fig.  
833 24). The combination of the near-zero magma rise rate and the several hundred ppm  
834 water contents typical of many lunar magmas (Saal et al. 2008; Hauri et al. 2011,  
835 2015) allows the water vapor bubble sizes to be small (~20  $\mu\text{m}$  radius) so that surface  
836 tension forces enable them to remain stable against the internal gas pressures, and thus  
837 to form a water vapor-dominated magmatic foam layer (Fig. 25). The foam can extend  
838 for several hundred meters below the surface in the lava lake crust, and have a  
839 vesicularity up to ~95% (Wilson and Head 2016, 2017b). As the excess pressure in the  
840 dike decreases to zero, the elastic response of the wall rock attempts to close the dike,  
841 slowly squeezing the magmatic foam up toward the surface (~1 cm/s) and deforming  
842 the growing lava lake crust (Fig. 25). As the overlying crust is already highly  
843 fractured, it is very likely that some of the magmatic foam will be extruded out onto  
844 the surface, and produce convex mounds (Fig. 25). Calculations by Wilson and Head  
845 (2016, 2017b) indicate that the Sosigenes mounds, with characteristic dimensions of  
846 ~400×230×8 m (Fig. 10), can be emplaced over a period of ~10 days. It is probable  
847 that the vesicles in the upper part of the mound will pop into the vacuum, in a  
848 mini-strombolian style, producing a decimeter to meter-thick layer of low-density,  
849 finer soil (upper right panel of Fig. 25; Wilson and Head 2017b). The weight of this  
850 thin surface layer will protect the foam materials from further disruption. This popped  
851 surface foam layer would have smaller particles size than typical lunar mature regolith,  
852 producing a smoother sub-resolution surface texture than that of the background mare,  
853 consistent with our phase-ratio imagery results (Fig. 12, Table 2). Extrusion of the  
854 foam causes central crust subsidence and local flexure of the crust in the immediate  
855 vicinity of the foam, enhancing the meniscus-like borders of the mounds and creating  
856 marginal moats and depressions (Fig. 25).

857 In summary, the final product of the waning stages of the eruptive process  
858 associated with a pit crater atop a dike is the superposition and solidification of  
859 magmatic foam mounds on a lava lake crust characterized by abundant micro- and  
860 macro-vesicularity, and overlying a residual highly porous substrate (Fig. 26). These  
861 processes are predicted to operate at the time of formation of the pit crater floor  
862 billions of years ago, contemporaneous with the major phase of the Mare  
863 Tranquillitatis lava filling process (consisting with the high-Ca pyroxene-dominated  
864 high-Ti basalt mineralogy of different IMP units and the surrounding maria (Bennett  
865 et al. 2015)). This proposed emplacement model stands in stark contrast to  
866 emplacement in the last few millions of years (Schultz et al. 2006; Braden et al. 2014).  
867 Can these characteristics, predicted from lunar magma ascent and eruption theory,  
868 account for the morphologic crispness, optical immaturity and extremely young crater  
869 retention ages of the surface of the Sosigenes pit crater?

870  
871 4.2.2. Post-emplacement impact cratering, regolith formation and landscape evolution

872 Impact cratering has been widely regarded as one of the most important  
873 geological processes on all planetary bodies with a solid surface, especially for bodies  
874 with relatively minor endogenic activity, like the Moon. Impact is a ubiquitous  
875 process which operates during the entire lifetime of the Moon, and has significant



876 effects on virtually all surface materials and processes, leading to crater formation,  
877 regolith development and landscape degradation.

878 Impact cratering on typical lunar lava deposits is generally characterized by the  
879 fracturing, brittle deformation and comminution of the solid bedrock substrate, and  
880 excavation and ejection of solid fragments (Fig. 27a). The final products are mainly  
881 well-formed, relatively shallow and blocky craters, as ubiquitously observed on the  
882 lunar surface, and lateral ejecta materials. Continuous impacting over billions of years  
883 builds up a fragmental layer that increases in thickness with time; this layer is the  
884 lunar regolith. Surface regoliths that accumulated on ancient mare basalts like those  
885 surrounding the Sosigenes IMP (~2–3 Ga, Hiesinger et al. 2011 and section 3.5) have  
886 a typical thickness of 4–5 meters (Bart et al. 2011). Steady bombardment of these  
887 fragmented components by charged solar and cosmic particles, and by the  
888 micrometeorite flux, results in surface optical maturity (McKay et al. 1991; Lucey et  
889 al. 2006). Small impacts on the succeeding regolith and lateral mobilization of ejecta  
890 will progressively mute the pristine surface topography over time, leading to the  
891 degradation of crisp and sharp landforms and boundaries typical of initially-formed  
892 lava flows (Soderblom 1970; Fassett and Thompson 2014).

893 In contrast, impact cratering on a lava lake crust, such as the topographically low  
894 hummocky/blocky terrain of Sosigenes IMP, operates in a markedly different style  
895 from that on solid lava deposits (Fig. 27b; Wilson and Head 2016, 2017b). The chilled  
896 lava lake crust substrate consists of a highly porous medium, both at the  
897 micro-vesicular scale and at the macro-porosity scale due to the presence of large  
898 voids produced by crust deformation and disruption during the strombolian phase.  
899 Underlying this lake crust is solidified foam with a vertical extent of several hundred  
900 meters (Fig. 26). Instead of excavating and ejecting the fragmented substrate materials,  
901 impacts into this medium would be characterized by (1) permanent crushing and  
902 compaction of the target material, (2) a negligible amount of lateral ejection beyond  
903 the crater rim, and (3) infiltration of the finer components of the developing regolith  
904 into the abundant macro-porosity of the substrate (Fig. 27b). This unusual cratering  
905 mechanism will cause craters to be poorly formed, difficult to recognize, and to  
906 degrade rapidly (Fig. 11f and section 3.3.2). The continuous regolith infiltration and  
907 absence of abundant lateral ejecta changes the landscape evolution from  
908 predominantly lateral diffusion (Fassett and Thompson 2014) to predominantly  
909 vertical regolith infiltration, serving to maintain the visual freshness of the terrain and  
910 its boundaries with the mounds and other landscape features. The constant infiltration  
911 of the fine component of the developing regolith into the underlying void space  
912 preferentially exposes larger blocks and boulders, and inhibits the vertical  
913 accumulation of regolith materials (<~1.7 m or nearly absence) and optical maturation  
914 of the substrate (Fig. 27b). The infiltration process also causes mechanical disturbance  
915 of the regolith materials, destroying the porous (“fairy castle”) structure of the upmost  
916 portion, and resulting in surface smoothing and brightening (Kreslavsky and  
917 Shkuratov 2003; Shkuratov et al. 2011; Kaydash et al. 2011), which is consistent with  
918 the radiance factor and sub-resolution roughness observations from LROC NAC  
919 images (section 3.4). This process is assisted by “seismic sieving”, by which the  
920 multiple impacts forming the regolith cause seismic shaking, enhancing the sieving  
921 and infiltration of finer regolith components into the void space and eliminating any  
922 potential regolith choking issues (Qiao et al. 2016b, 2017). Together, the presence of  
923 abundant small vesicles and large void spaces, and the continuous “seismic sieving”  
924 process, combine to inhibit surface regolith development, to cause craters to be poorly  
925 formed, to maintain the observed topographic relief and optically immaturity, to

926 expose large blocks and boulders, and to smooth the sub-resolution surface textures  
927 (Fig. 27b).

928 The unusual physical properties of the extruded magmatic foam mounds  
929 (abundant micro-vesicularity with bulk porosity >75%) make impact cratering  
930 processes differ significantly from those on both lava flow surfaces and the pit crater  
931 lava lake crust (Fig. 27c). Extensive laboratory experiments (e.g., Housen and  
932 Holsapple 2003, 2011; Schultz et al. 2002; Flynn et al., 2010), numerical modeling  
933 (e.g., Wünnemann et al. 2006, 2011, 2012) and spacecraft observations at several  
934 asteroids interpreted to have porous interiors (e.g., the NEAR spacecraft at asteroid  
935 Mathilde, Housen et al. 1999) have shown the significant effect of target porosity on  
936 the impact cratering processes. Highly porous targets are known to efficiently absorb  
937 impact shock waves, causing a markedly different cratering mechanism, dominated by  
938 permanent crushing and compaction of the target materials, rather than excavating and  
939 ejecting of the substrate as in typical non-porous targets (Fig. 27c). Regolith  
940 development on these porous materials is inhibited, due to dominantly non-blocky  
941 craters and the small amount of ejecta material. This unusual cratering mechanism  
942 results in enhanced projectile penetration depths, substantially lower ejection  
943 velocities, a negligible amount of material ejected beyond the crater rim, and a  
944 significant decrease in crater diameter relative to a similar impact into solid basalt or  
945 typical regolith. Thus, the successive accumulation of craters on the magmatic foam  
946 mounds results in a population of relatively smaller craters, rapid degradation of  
947 newly-formed craters, a minimization of lateral transport of regolith, and a finer  
948 grain-size compared to impacts in solid basalt/regolith targets (Fig. 27c).

949  
950 4.2.3. The anomalously young impact crater retention ages of the Sosigenes IMP  
951 interior

952 We interpret the Sosigenes IMP and related features to originate from the waning  
953 stages of dike-tip pit crater eruptions billions of years ago, with production of  
954 solidified magmatic foam mounds on a lava lake crust characterized by abundant  
955 micro- and macro-vesicularity (Fig. 26). How, then, can these unique products and  
956 subsequent surface modification processes account for the impact crater density  
957 (CSFD) discrepancy, especially in crater retention ages, between the Sosigenes IMP  
958 interior terrain (<100 Ma) and the surrounding ancient mare deposits (~2–3 Ga)? We  
959 address this issue using three approaches. Firstly, NAC images with a range of  
960 illumination geometries permit us to identify more impact craters (section 3.5 and  
961 Table 3) than previous approaches (e.g., Braden et al., 2014), suggesting that craters  
962 formed on Sosigenes interior terrains are poorly preserved and easily degraded  
963 beyond recognition. Secondly, investigations of the distribution of superposed craters  
964 as a function of slope on the mounds clearly shows that there are many fewer small  
965 craters where slopes exceed 6 degrees than on the flatter part of the mounds (Fig. 18  
966 and Table 4). This slope-related crater modification is consistent with  
967 elephant-hide-like textures observed on the mounds (Fig. 11b). Thus, we conclude  
968 that the convex shape of the mounds leads to loss of superposed craters as a function  
969 of time.

970 Finally, we ask the question: could the unique physical properties of the  
971 magmatic foam substrate be responsible for altering the superposed CSFD compared  
972 with what would be expected in normal basalt lava flows (as observed on the  
973 surrounding mare deposits; ~2–3 Ga)? Target property variations have been  
974 previously invoked to explain the cratering record discrepancies between coeval  
975 surface units observed on the Moon (e.g., van der Bogert et al. 2010, 2013, 2017) and

976 Mars (Dundas et al. 2010). Experimental impacts show that cratering efficiency  
 977 (excavated mass/projectile mass) on highly porous targets can be readily reduced by  
 978 two orders of magnitude compared with cratering on low-porosity materials (Poelchau  
 979 et al. 2013; Schultz et al. 2002). On the basis of these observations, assuming a  
 980 porosity of 75% for the extruded magmatic foam of the Sosigenes mounds (the  
 981 average lunar crust porosity was estimated as 12%; Wieczorek et al. 2013), and  
 982 considering the effect of porosity on the target density, the predicted one hundred-fold  
 983 decrease in cratering efficiency would result in a factor of three crater diameter  
 984 decrease. How does this porosity effect on crater size assist us in interpreting the  
 985 CSFD disparity between the Sosigenes mounds and the surrounding mare areas (Fig.  
 986 21)? We scale all the impact craters recognized on the 2×2 km<sup>2</sup> surrounding mare  
 987 region with a factor of three diameter decrease (Fig. 28). The CSFD of these scaled  
 988 mare craters is indistinguishable from the Sosigenes mound CSFD at larger diameters,  
 989 and yields a model age of 60 Ma for craters ≥57 m (1/3 of the equilibrium onset  
 990 diameter (170 m) of the 2×2 km<sup>2</sup> surrounding mare crater counting area), very close  
 991 to our model age of the Sosigenes mound (51 Ma).

992 On the basis of this analysis, we conclude that the discrepancy in the impact  
 993 CSFD data between the < 100 Ma age obtained by Braden et al. (2014) for the  
 994 mounds, and the ~2–3 Ga age obtained here for the surrounding ancient mare can be  
 995 readily explained primarily by the response of the magmatic foam substrate to the  
 996 reduced formation size of superposed craters.

997

## 998 5. Conclusions

999 We present a detailed characterization of the geologic context, topography,  
 1000 morphology, sub-resolution roughness and superposed impact craters of one of the  
 1001 major lunar IMP features, Sosigenes, using the most recent orbiter data sets. We  
 1002 assemble key observations from previous literature and this work to evaluate several  
 1003 previously proposed hypotheses for the origin of lunar IMPs.

1004 The wide range of characteristics of the associated interior terrains of the  
 1005 Sosigenes IMP and surrounding mare, including topography, morphology, regolith  
 1006 thickness, sub-resolution roughness, impact crater density, optical maturity and  
 1007 mineralogy, requires complex, and potentially different, formation/modification  
 1008 processes for its origin. None of the several previously proposed lunar IMP formation  
 1009 mechanisms, including recent individual lava extrusions, lava flow inflation,  
 1010 pyroclastic deposits, and out-gassing removal of surface regolith, can fully reproduce  
 1011 all the observed characteristics.

1012 Based on our latest assessments of the generation, ascent and eruption of magma  
 1013 on the Moon and observations of Ina, we interpret the Sosigenes IMP and related floor  
 1014 units to originate as a portion of a subsurface shallow dike collapsed to create the pit  
 1015 crater, followed by flooding of the pit crater floor with a lava lake, formation of a  
 1016 strombolian phase as the lava lake surface cooled, and finally the extrusion, as the  
 1017 dike closed, of magmatic foams through cracks in the lava lake crust to produce the  
 1018 mounds. The final product of the waning stages of the dike-tip eruptive process is  
 1019 therefore the superposition and solidification of magmatic foam mounds on a lava  
 1020 lake crust (hummocky and blocky units) characterized by abundant micro- and  
 1021 macro-vesicularity, and overlying a residual magmatic foam substrate. The unique  
 1022 physical properties of these final products would make the post-emplacement surface  
 1023 modification processes, including meteoritic impacting, regolith development and  
 1024 landscape degradation, markedly different from those on typical solid lava flows or  
 1025 regolith, maintaining the observed topographic relief and optical immaturity and

1026 resulting in an anomalously young crater retention age for the Sosigenes pit crater  
 1027 floor. Accounting for the effects of the reduced diameter of craters formed in  
 1028 magmatic foam results in a shift of the CSFD ages from less than 100 million years to  
 1029 billions of years, contemporaneous with the surrounding ancient mare basalts. We  
 1030 conclude that extremely young mare basalt eruptions, and re-evaluation of lunar  
 1031 thermal evolution models, are not required. We interpret other IMP occurrences  
 1032 associated with pit craters atop dikes (e.g., Cauchy-5, Hyginus) and fissure eruptions  
 1033 in the lunar maria (e.g., the small locality in western Mare Tranquillitatis (9.58°N,  
 1034 25.51°E), IMP #13 in Braden et al. 2014) to have had similar ancient origins.

1035

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- 1308



1309 **Tables:**

1310

1311 Table 1. Characteristics of the LROC NAC images used for phase ratio calculations of  
1312 Sosigenes IMP.

Image ID	Orbit #	Resolution (m/pixel)	Incidence angle (°)	Emission angle (°)	Phase angle (°)	Sub-solar azimuth (°)	Center latitude (°)	Center longitude (°)
M1129354261R	18571	1.174	45.95	21.25	67.01	190.93	8.33	19.07
M1175290064L	25030	1.104	45.99	15.96	30.27	187.82	8.3	19.11

1313

1314 Table 2. Mean values with one standard deviation of radiance factor and phase ratio  
1315 for the image regions of interest (ROIs) of Sosigenes (see Fig. 12c). The values in  
1316 brackets are multiples scaled to the background values.

ROI	Radiance factor in $\alpha = 30^\circ$ image	Radiance factor in $\alpha = 67^\circ$ image	Phase ratio $f(30^\circ)/f(67^\circ)$
Mound unit	$0.0315 \pm 0.0012$ (1.0430)	$0.0208 \pm 0.0011$ (1.0612)	$1.5157 \pm 0.0334$ (0.9819)
Hummocky unit	$0.0402 \pm 0.0042$ (1.3311)	$0.0310 \pm 0.0032$ (1.5816)	$1.2972 \pm 0.0601$ (0.8404)
Blocky unit	$0.0499 \pm 0.0074$ (1.6523)	$0.0311 \pm 0.0058$ (1.5867)	$1.6546 \pm 0.4732$ (1.0719)
Background	$0.0302 \pm 0.0017$	$0.0196 \pm 0.0015$	$1.5436 \pm 0.0452$

1317

1318 Table 3. Information on the crater counts performed on the Sosigenes mounds (Fig. 16)  
1319 and surrounding  $2 \times 2$  km<sup>2</sup> mare area (Fig. 19).

Count area	Size of counting area (km <sup>2</sup> )	# of craters D $\geq 10$ m	# of craters D $\geq 25$ m	# of craters D $\geq 50$ m
Sosigenes mounds	4.46	683	47	5
Surrounding mare	3.96	1870	212	54

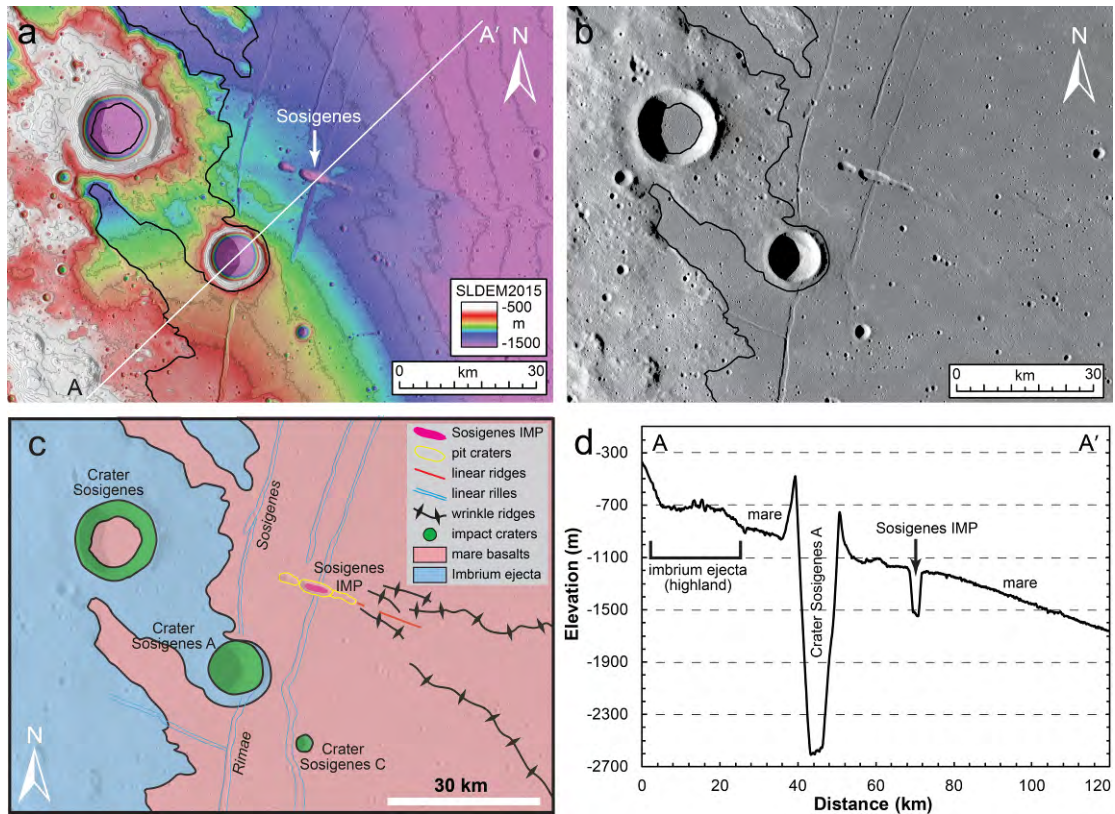
1320

1321 Table 4. Crater statistics results for representatively-sloped areas in Sosigenes mounds  
1322 and surrounding mare, with variable crater diameter (D) range. See Figs. 16 and 19  
1323 for full crater count map, and Figs. 17 and 20 for the areas studied.

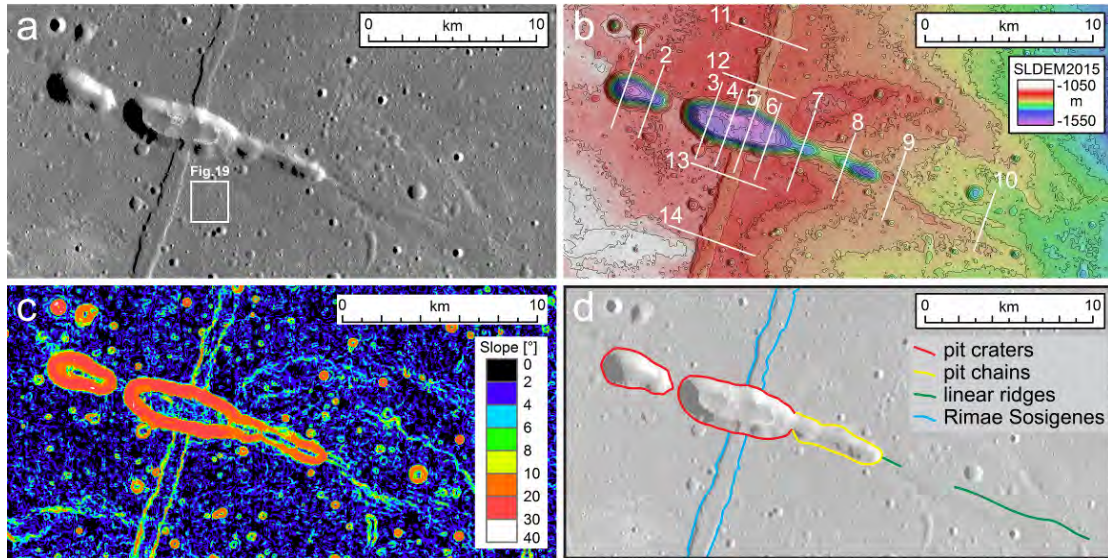
Areas	Flat	Median-sloped	Steep	Mare
NAC DTM Slope (°)	1.8 $\pm$ 1.2	4.3 $\pm$ 1.3	8.9 $\pm$ 3.1	2.8 $\pm$ 2.3
Area (km <sup>2</sup> )	0.69	0.33	0.20	0.71
# of craters $\geq 10$ m	190	34	11	339
D: 10–15 m				
# of craters	140	26	9	236
R-value	0.0745	0.0287	0.0146	0.1229
D: 15–20 m				
# of craters	31	6	1	48
R-value	0.0466	0.0187	0.0046	0.0707
D: 20–30 m				
# of craters	12	1	0	36
R-value	0.0255	0.0044	0.0000	0.0750

1324

1325 **Figures:**  
 1326

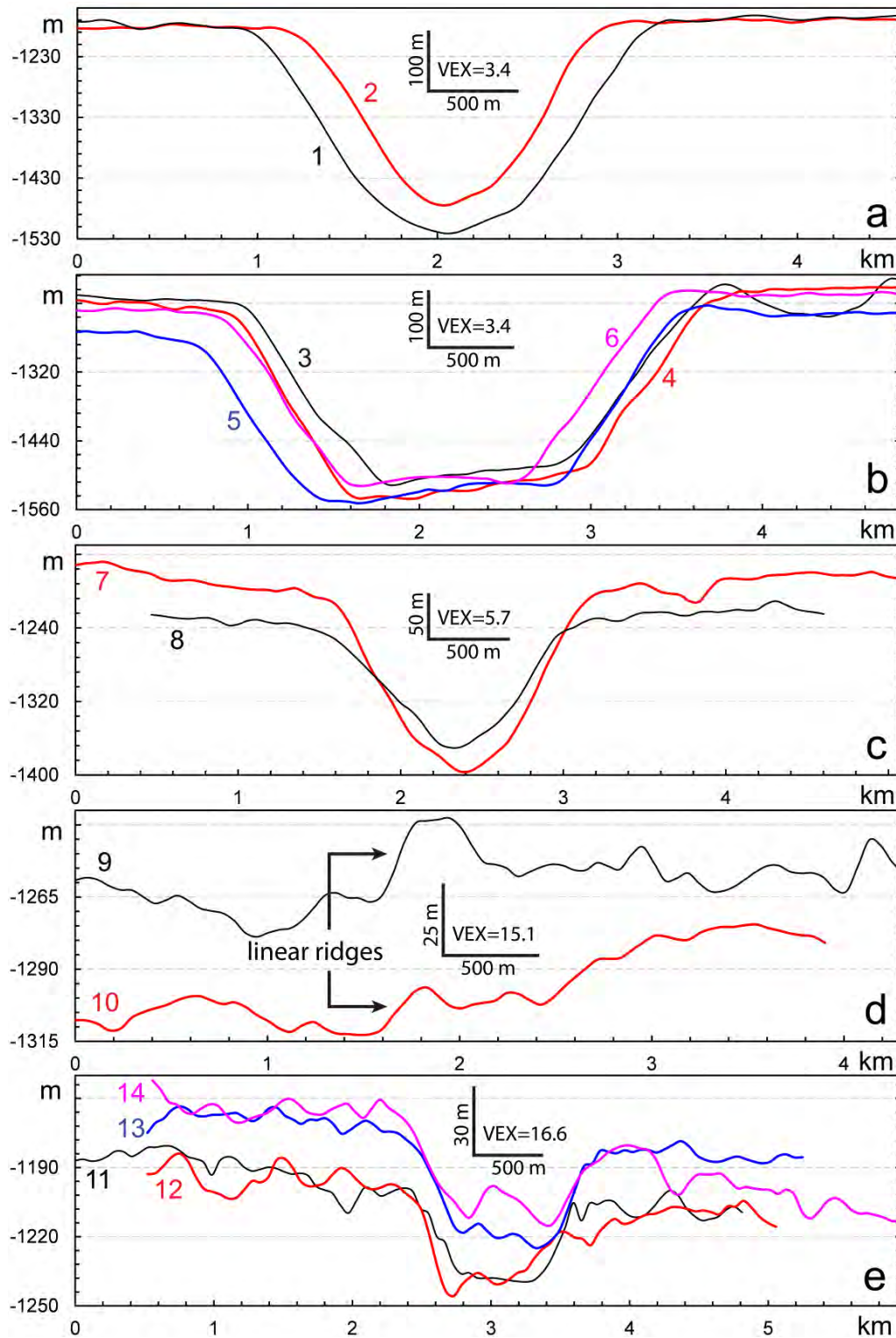


1327  
 1328 Fig. 1. Topographic and morphological maps of the Sosigenes context region. (a)  
 1329 SLDEM2015 512 ppd grid topography overlain on Kaguya TC evening mosaic. The  
 1330 black lines indicate the boundary of mare regions, and the white line marks the  
 1331 location of the topographic profile in (d). Contour interval is 100 m. (b) Kaguya TC  
 1332 evening mosaic, spatial resolution is ~10 m/pixel. (c) Sketch map of the geologic  
 1333 context of the Sosigenes IMP feature. (d) Topographic cross-section profile from  
 1334 SLDEM2015 gridded DTM shown in (a). All the maps for the Sosigenes region in  
 1335 this paper are projected into sinusoidal projection with a central meridian of  
 1336 19.0883°E, and north is up.  
 1337

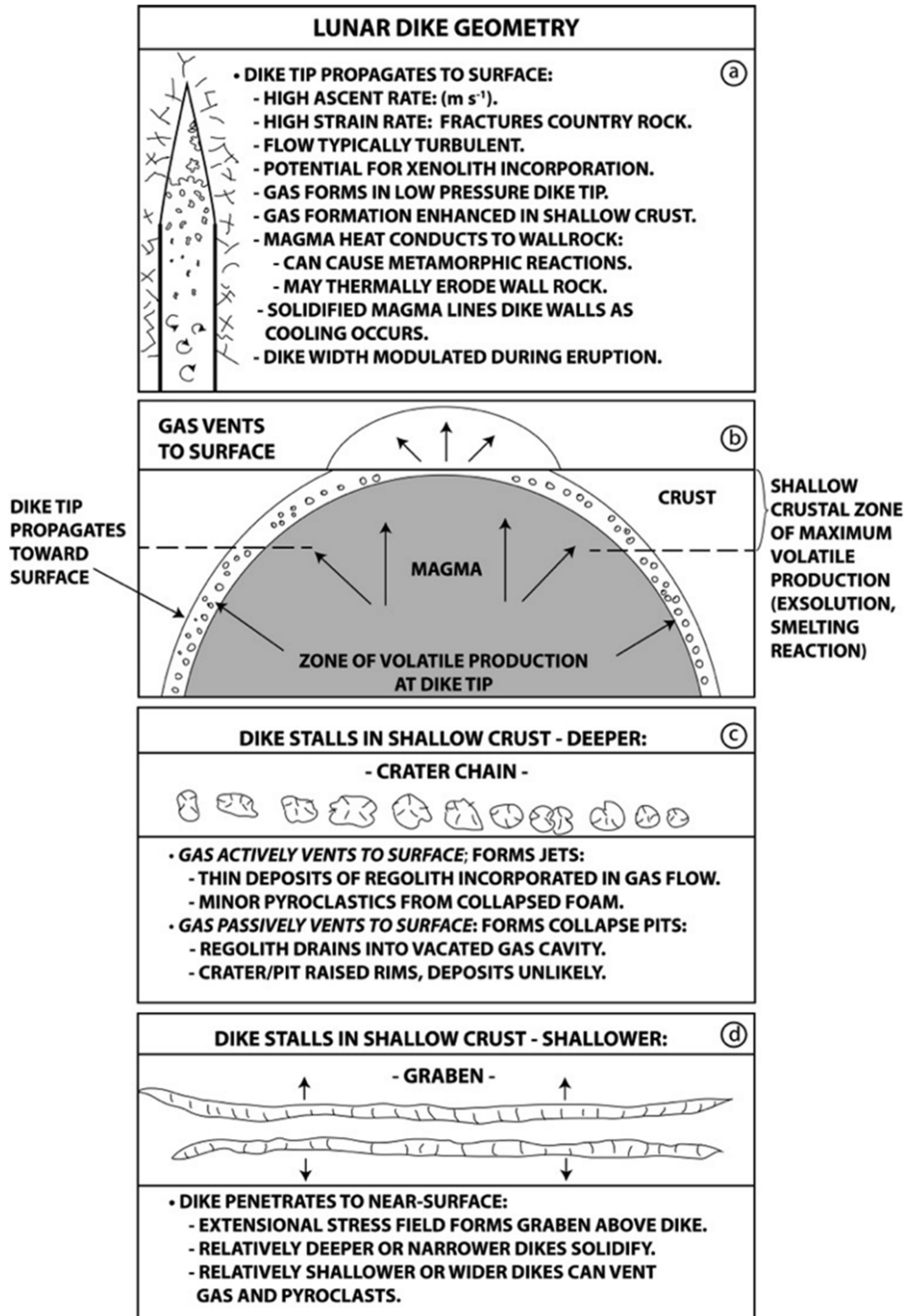


1338  
 1339 Fig. 2. Maps of the Sosigenes linear feature and one of the Rimae Sosigenes graben:  
 1340 (a) Kaguya TC evening mosaic; extent of Fig. 19 is marked by the white box, (b)  
 1341 SLDEM2015 512 ppd grid topography overlain on Kaguya TC evening mosaic;  
 1342 locations of topographic profiles in Fig. 3 are marked by white lines, with their  
 1343 starting points labeled by the profile numbers, and contour interval is 25 m, (c)  
 1344 SLDEM2015 topographic slope map, and (d) sketch geologic map, with boundaries of  
 1345 Sosigenes linear feature and Rimae Sosigenes marked by lines of different colors.





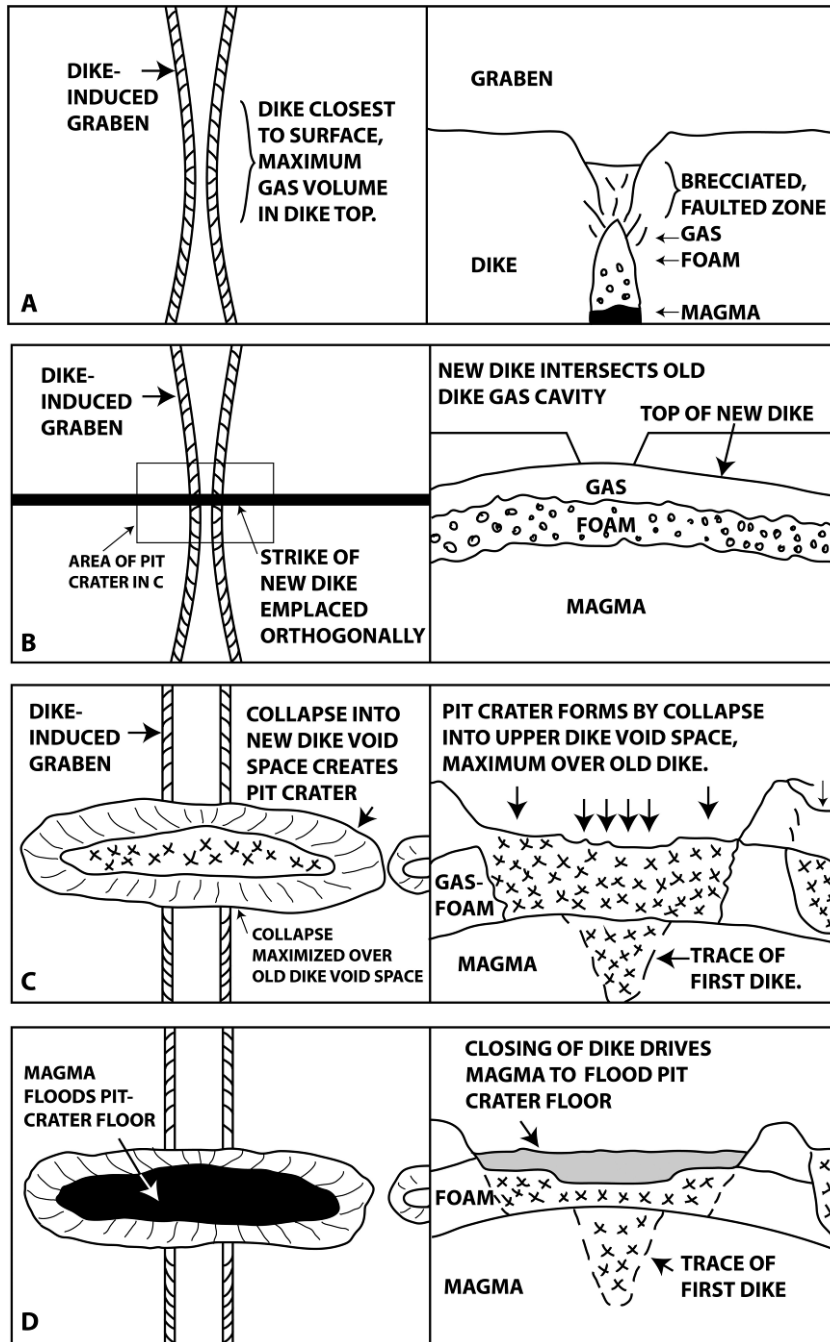
1346  
 1347 Fig. 3. Stacked topographic profiles of the Sosigenes linear features and one of the  
 1348 Rimae Sosigenes graben derived from SLDEM2015 topography: (a) western-most pit crater,  
 1349 Sosigenes depression, (c) eastern crater chain, (d) eastern-most linear ridge  
 1350 and (e) N-S trending Rimae Sosigenes graben. The horizontal axes are distances in  
 1351 kilometers, and vertical axes are elevations in meters. The locations of these profiles  
 1352 are shown in Fig. 2b, and the profile numbers correspond to those shown there.



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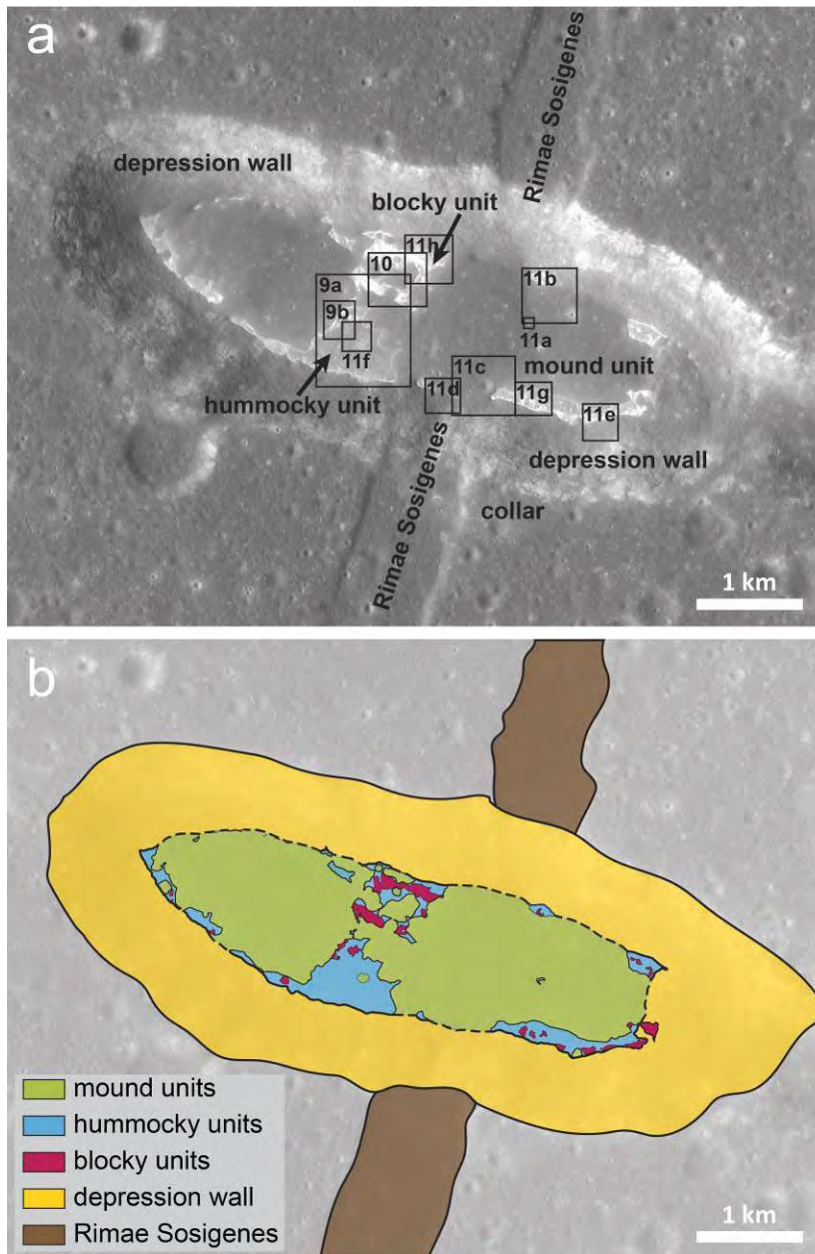
Fig. 4. Block diagrams (from Fig. 6 in Head and Wilson 2017) illustrating lunar dike propagation processes and associated surface manifestation: (a) general lunar dike geometry, (b) processes at the dike tip, (c) dike stalls in shallower crust, resulting in crater chains at the surface, and (d) dikes stall in shallow subsurface, resulting in graben.





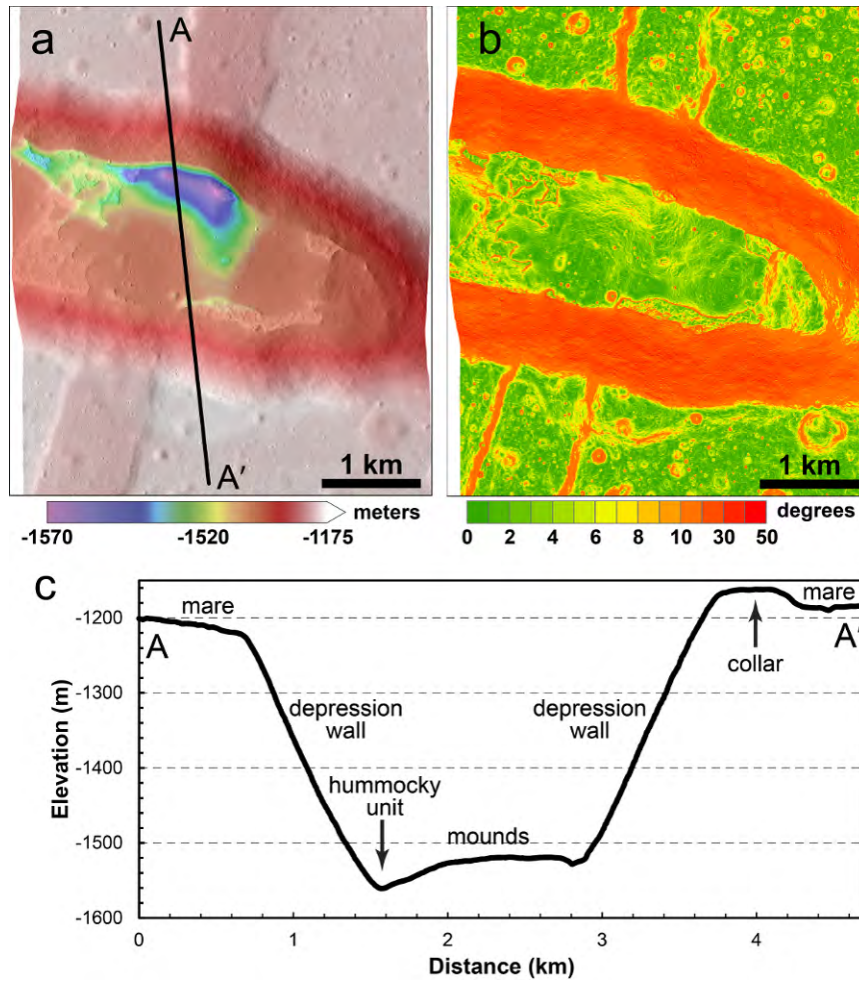
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Fig. 5. Interpretative diagram for formation of Sosigenes linear features and Rimae Sosigenes graben. Left column, map view; right column, cross section view.



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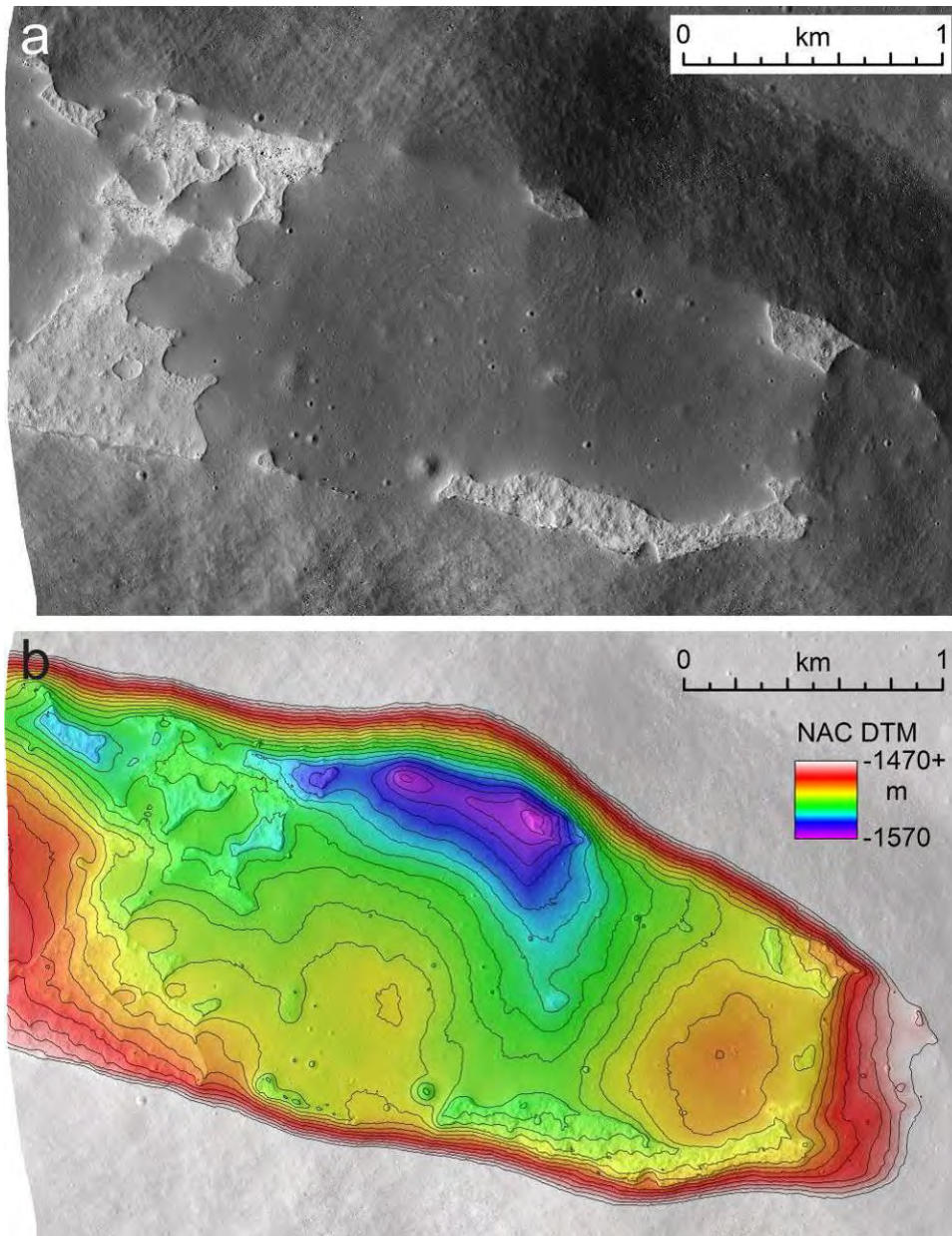
Fig. 6. Sosigenes depression and IMP. (a) LROC NAC (M1129354261) image of Sosigenes, incidence angle =  $\sim 46^\circ$ , pixel size =  $\sim 1.2$  m. Representative morphologic units are labeled. Locations of Figs. 9–11 are indicated by black boxes. (b) Geologic sketch map shows the distribution of the different morphologic units associated with the Sosigenes IMP.



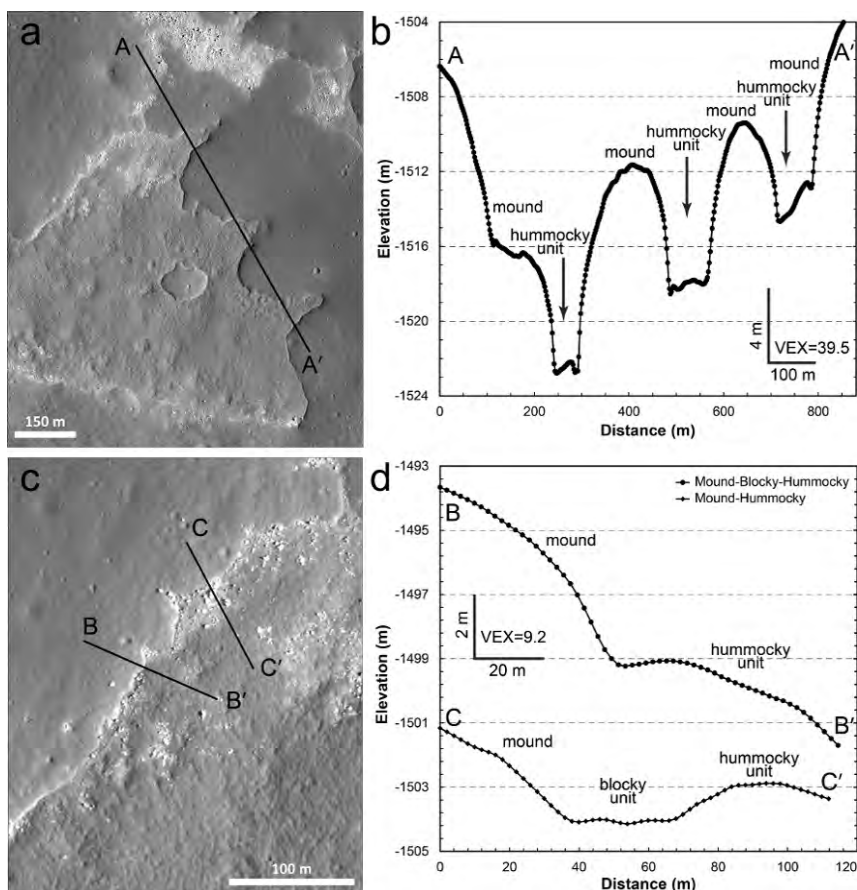
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1369 Fig. 7. Topography and slope of Sosigenes depression and IMP. (a) Color NAC DTM  
 1370 topography overlain on LROC NAC images (portion of frame M177508146). The  
 1371 DTM data are displayed with a two-component piecewise linear stretch (-1570 –  
 1372 -1520 m and -1520 – -1175 m) to highlight the topographic relief within the floor of  
 1373 the Sosigenes depression. The line shows the location of the topographic profile in (c).  
 1374 (b) Slope map, and (c) topographic profiles derived from LROC NAC DTM in (a).  
 1375 LROC NAC DTM topography is available at <http://lroc.sese.asu.edu/>.

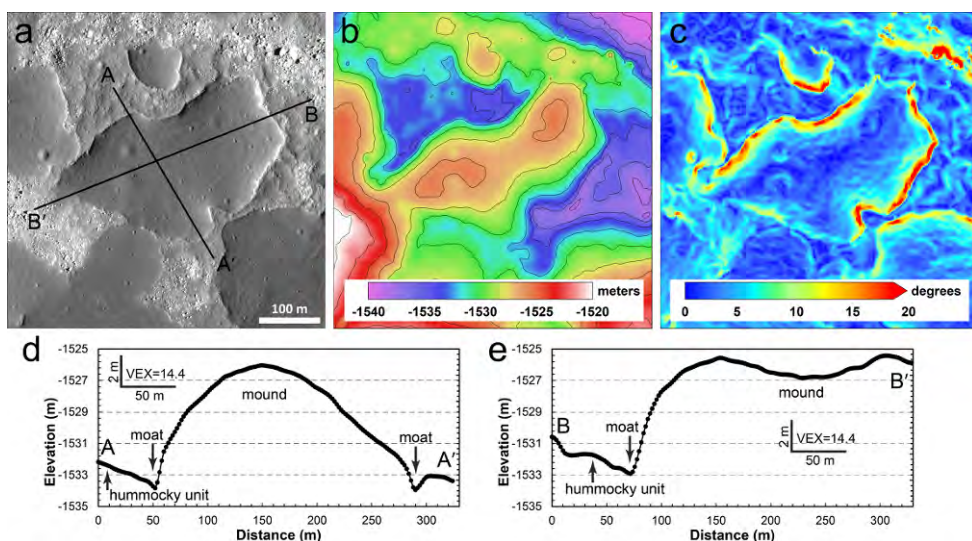




1376  
1377 Fig. 8. Topographic variations of the Sosigenes floor. (a) Portion of LROC NAC  
1378 NACM177514916. (b) Same area shown by color-shaded NAC DTM topography  
1379 overlain on LROC NAC NACM177514916; contour interval is 5 m.



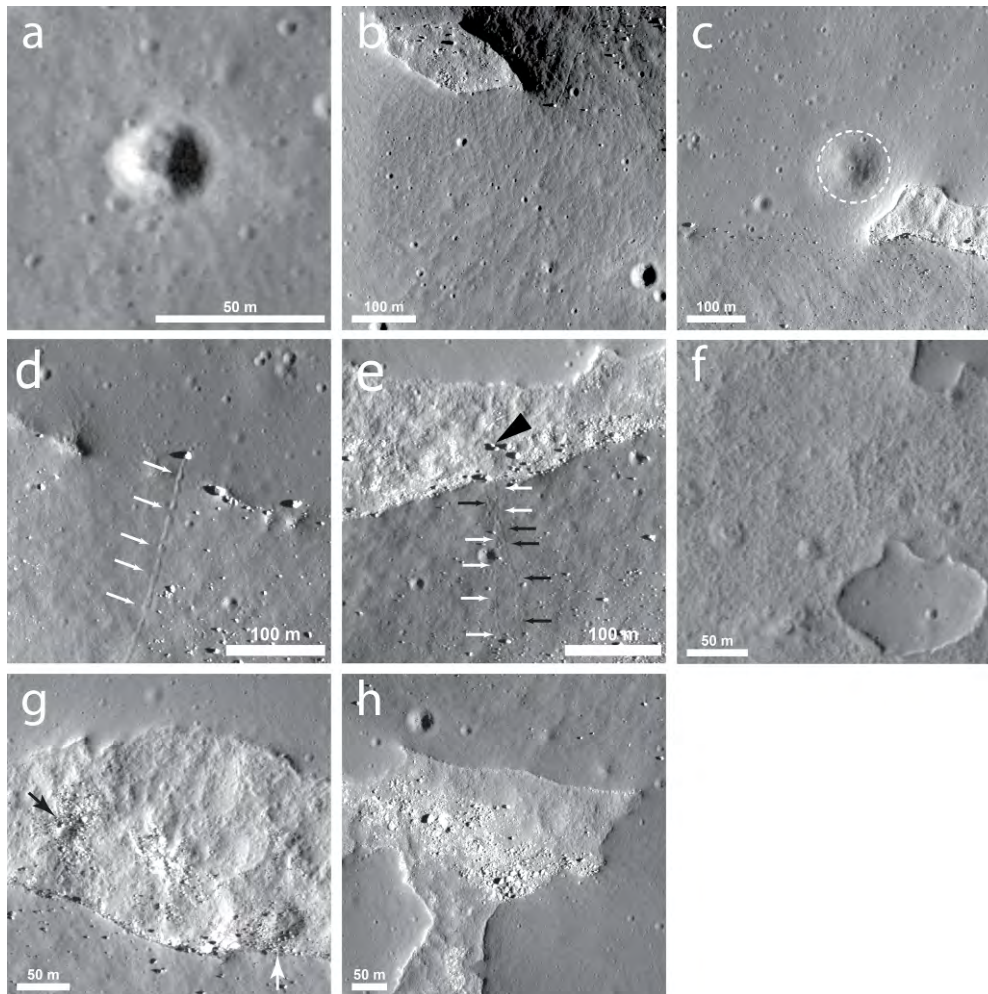
1380 Fig. 9. (a) Contacts between mound and hummocky units near the center of Sosigenes,  
 1381 LROC NAC frame M177508146, 0.48 m/pixel. (b) Topographic profile across the  
 1383 mound and hummocky units shown in (a). Elevation is derived from NAC DTM data,  
 1384 2 m/pixel. (c) Portion of LROC NAC frame M177508146R shows the contact  
 1385 between the mound and hummocky units, with some blocky materials present along  
 1386 along the contact. (d) A NAC DTM-derived profile shows the topographic relief from  
 1387 mound, blocky to hummocky units (C-C'). For comparison, a profile directly crossing  
 1388 from the mound to the hummocky unit is also illustrated (B-B').  
 1389



1390 Fig. 10. Morphology and topography of an almost completely isolated mound on the  
 1391 floor of the Sosigenes pit crater. (a) Portion of LROC NAC frame M177508146, 0.48  
 1392 m/pixel. Black lines show locations of topographic profiles in (d) and (e). (b) NAC  
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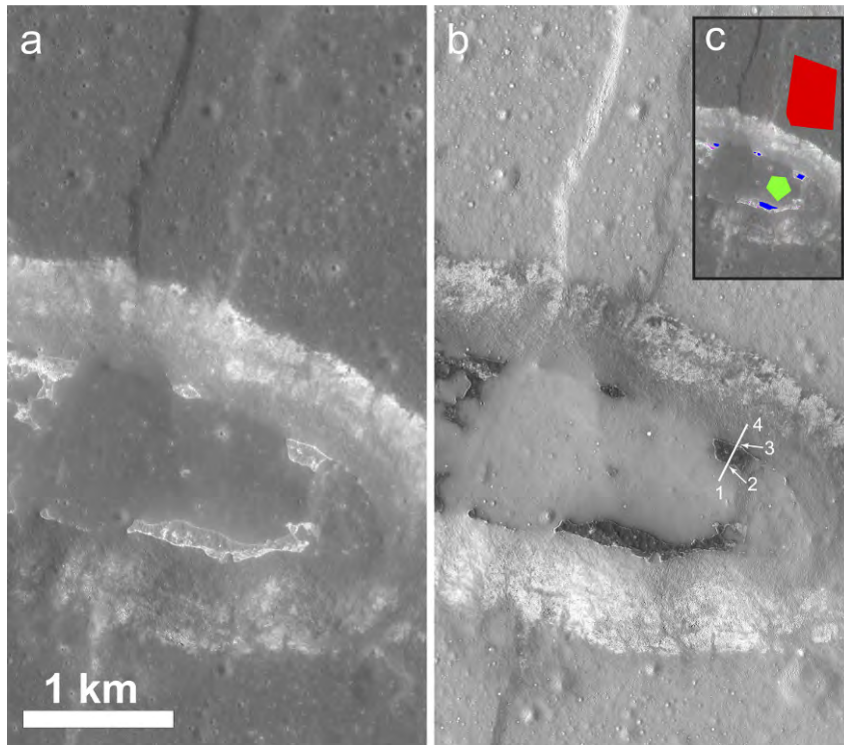


1394 DTM topography with overlying 2 m interval contour. (c) Topographic slope map. (d  
 1395 and e) Topographic profiles derived NAC DTM data in (a).  
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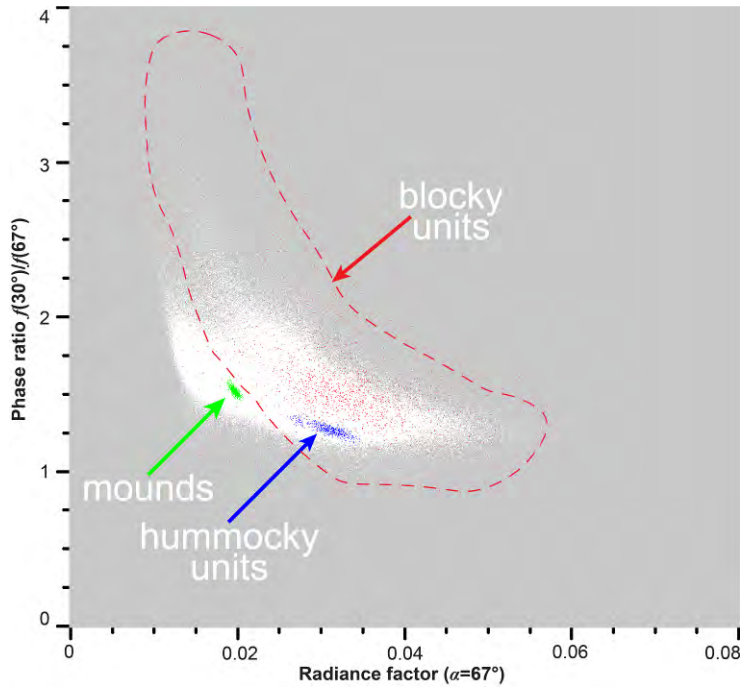


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 1398 Fig. 11. Morphology of the Sosigenes IMP interior illustrated with LROC NAC  
 1399 images. (a) A fresh impact crater superposed on the mound units, with a diameter of  
 1400  $\sim 30$  m and a floor depth of 4.8 m (depth/diameter =  $\sim 0.16$ ). (b) Elephant-hide textured  
 1401 regolith observed on the northern floor. (c) An impact crater with diameter of  $\sim 130$  m  
 1402 (white dashed circle) superposed on the mound units. (d) A boulder trail (5–8 m wide,  
 1403 traced by white arrows) develops at the depression wall and extends to the mound  
 1404 units. The boulder ( $\sim 8 \times 8$  m in dimension) rolls  $\sim 25$  m on the mound units, and  
 1405 generates an obvious boulder trail (linear depression), indicating a layer of  
 1406 unconsolidated materials (meters thick) on the mound units. (e) A boulder trail ( $\sim 3$ – $6$   
 1407 m wide, traced by white arrows) originates from the wall slope but terminates at the  
 1408 contact between the wall and hummocky units of Sosigenes. However, no boulders  
 1409 which should be large enough to generate the trail (with dimension comparable with  
 1410 the width of the trail) are observed at the ending of the trail. A large boulder  $\sim 33$  m  
 1411 from the contact ( $\sim 6 \times 4$  m in size, marked by the black triangle) is a candidate for the  
 1412 rolling boulder, but it does not generate any resolved trails on the hummocky units  
 1413 where it crosses, indicating a very thin layer or even absence of mantling  
 1414 unconsolidated materials on the hummocky units. Another boulder trail ( $\sim 4$ – $7$  m wide)  
 1415 is also observed (traced by the black arrows), which also terminates at the contact  
 1416 between the wall and the hummocky units, but a large boulder ( $\sim 8 \times 6$  m in size) is  
 1417 found at the end of the trail. (f) Ridged and pitted surface texture of the hummocky

1418 units. A small mound is present at the lower right corner of the panel. Many irregular  
 1419 depressions are also observed on the hummocky units. (g) Two small craters present  
 1420 on the hummocky units of Sosigenes; the diameter of the western crater (black arrow)  
 1421 is ~20 m, and the eastern one (white arrow) is ~35 m. (h) Blocky units surrounded by  
 1422 the hummocky units at Sosigenes; massive boulders are observed. Panels (a), (c), (f)  
 1423 and (g) are portions of LROC NAC frame M177514916, 0.52 m/pixel; panels (b), (d),  
 1424 (e) and (h) are portions of LROC NAC frame M177508146, 0.48 m/pixel. A raw  
 1425 resolution version of this figure is provided as supporting information.  
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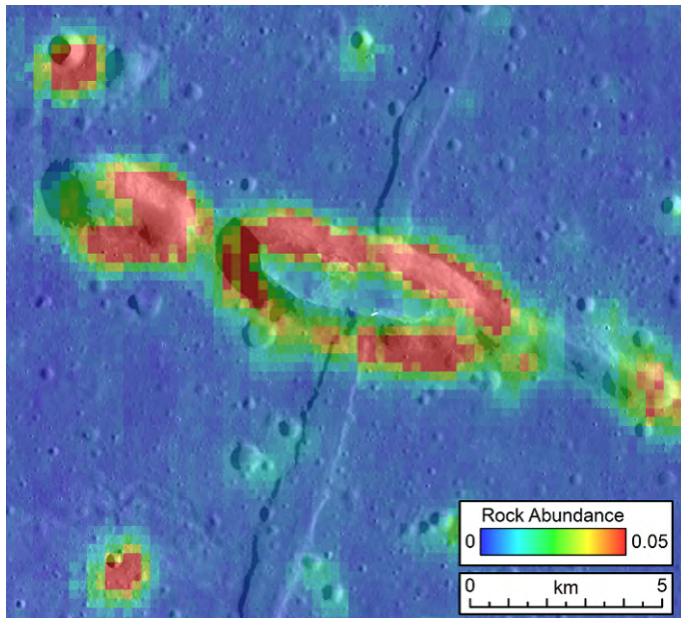


1427  
 1428 Fig. 12. The eastern part of the Sosigenes depression imaged by LROC NAC. (a)  
 1429 Portion of LROC NAC frame M1175290064L at 1.104 m/pixel resolution,  $\alpha = 30.27^\circ$ ,  
 1430 stretched from a radiance factor value of 0.006 to 0.06. (b) Phase-ratio image,  
 1431  $f(30^\circ)/f(67^\circ)$ , stretched from a phase ratio value of 1.1 to 1.8. The white line shows the  
 1432 locations where the phase ratio profile is derived in Fig. 15, and the numbers  
 1433 correspond to the numbers in Fig. 15. (c) Image regions of interest (ROIs) for  
 1434 evaluating the brightness and phase ratio values of different units: red = mare  
 1435 background (1,233,144 pixels), green = mound units (164,714 pixels), blue =  
 1436 hummocky units (47,975 pixels), magenta = blocky units (5,175 pixels). A raw  
 1437 resolution version of panel c is provided as supporting information.



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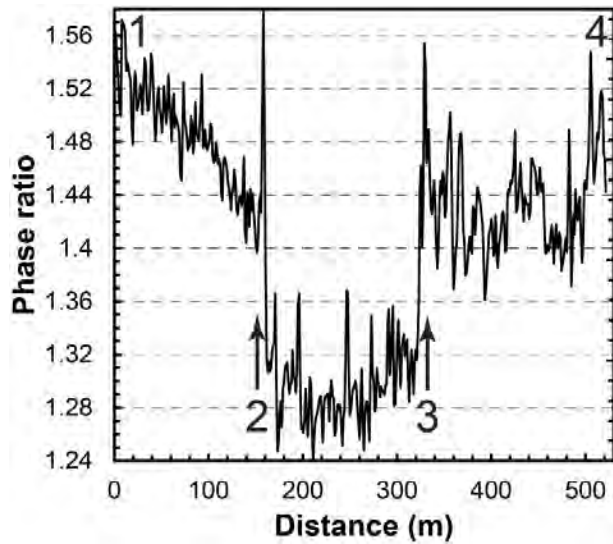
Fig. 13. Two-dimensional scatter plot of phase ratio  $f(30^\circ)/f(67^\circ)$  and radiance factor  $f(67^\circ)$ , for western part of Fig. 12. Locations of typical morphological terrains within Sosigenes interior are marked: green points (mounds), blue points (hummocky units) and magenta points (blocky units). A very weak correlation is observed for the whole plot, and the Sosigenes interior morphological units are generally not in line with the background pixels.



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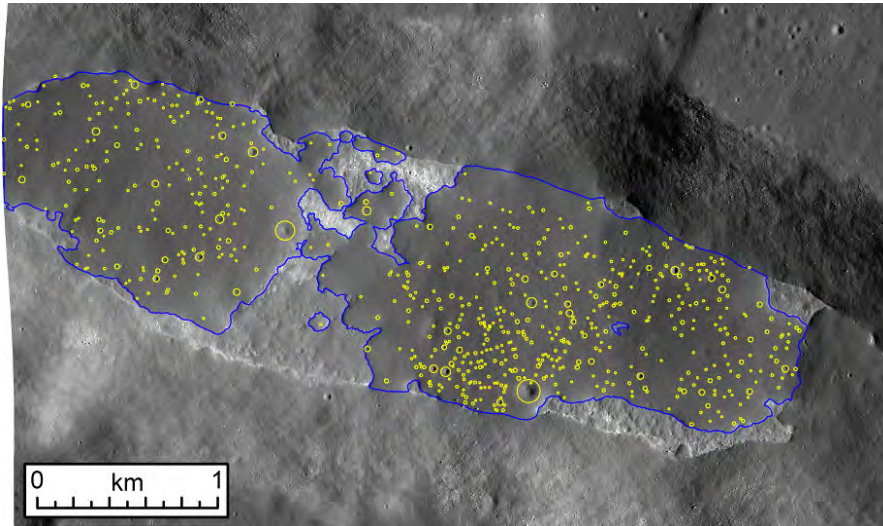
Fig. 14. Diviner rock abundance (areal fraction of each scene occupied by exposed rocks  $\sim 1$  m or larger) in color overlain on Kaguya TC evening image mosaic.





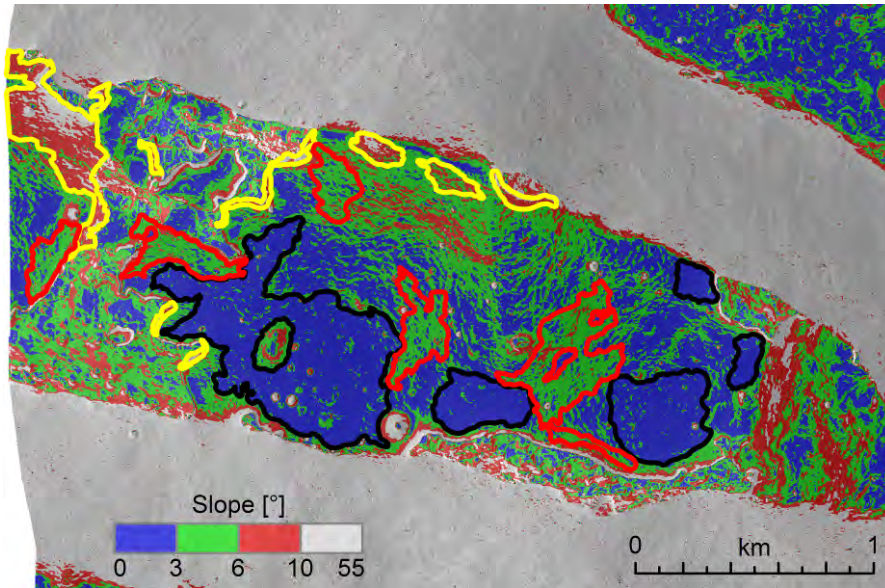
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Fig. 15. Phase ratio profile derived from the  $f(30^\circ)/f(67^\circ)$  image of Sosigenes (Fig. 12b). The location of the profile is marked by the white line and corresponding numbers in Fig. 12b.



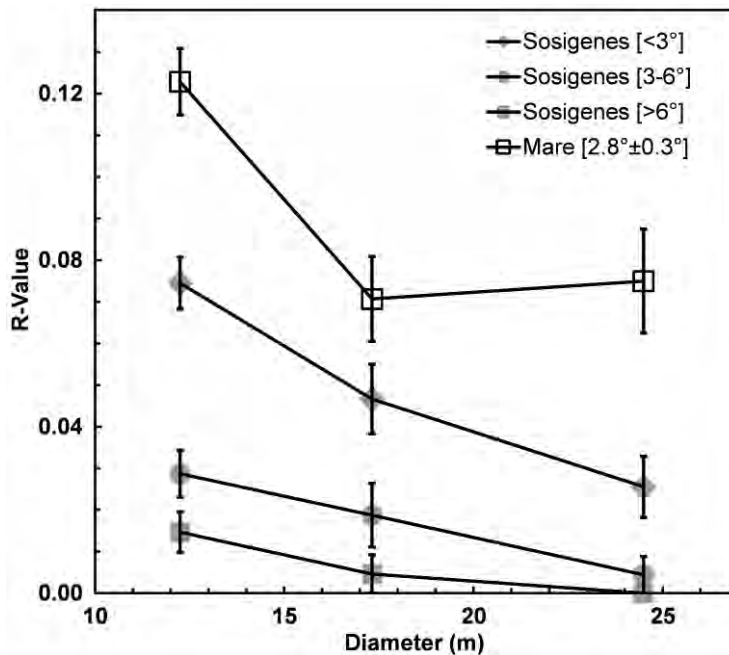
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Fig. 16. Impact craters (with estimated rim positions marked by yellow circles) accumulated on the mound units of the Sosigenes IMP; the background image is a portion of LROC NAC frame M192824968R. A raw resolution version of this figure is provided as supporting information.



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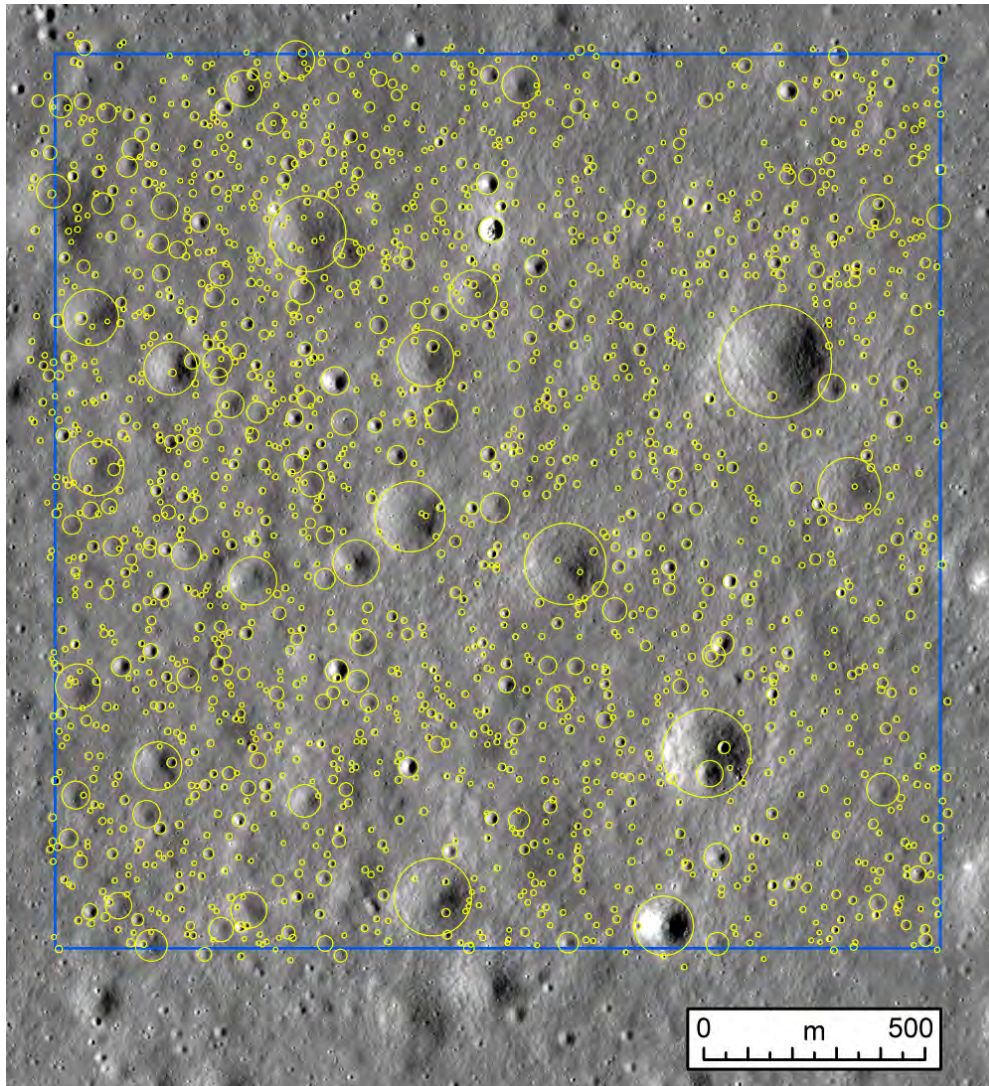
Fig. 17. NAC DTM slope map for the Sosigenes depression floor. In order to highlight the slope variation of the Sosigenes mounds, the color ramp is concentrated in the 0–10° slope range. Several patches with representative topographic slopes are outlined for investigating the potential correlation between crater density and regional slope: black outlines for relatively flat areas (<3°), red for medium-sloped areas (dominantly ~3–6°), and yellow for relatively steep areas (dominantly >6°). See Fig. 18 and Table 4 for the analysis results.



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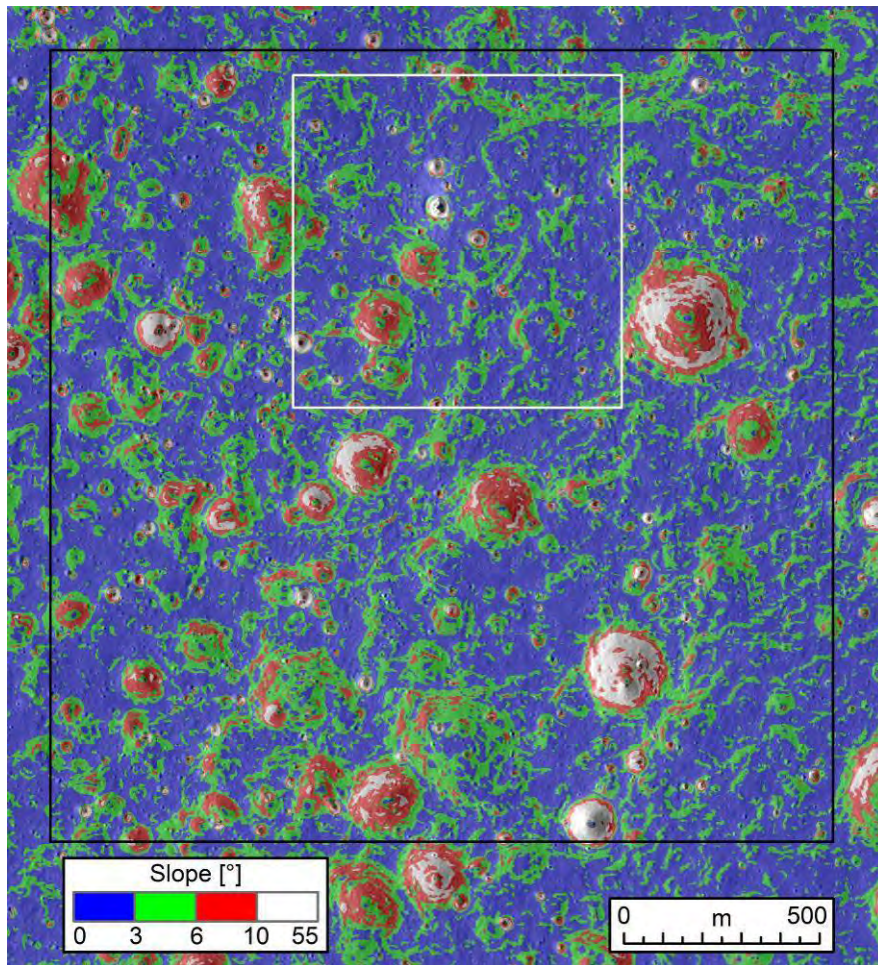
Fig. 18. Plot of CSFD (R-values) with several crater diameter range (10–15 m, 15–20 m, and 20–30 m) for representatively-sloped areas in Sosigenes mounds outlined in Fig. 17 and surrounding mare region outlined in Fig. 20 (white square). See Table 4 for the detailed values.





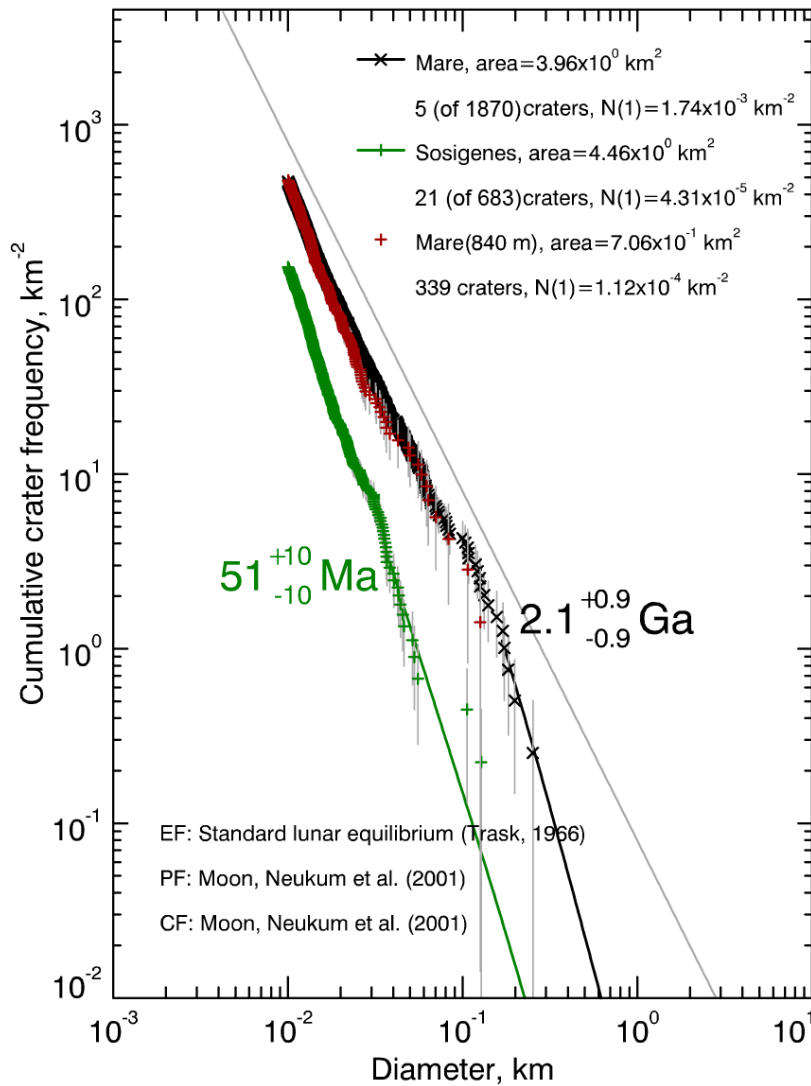
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Fig. 19. Crater counts for a  $2 \times 2$  km<sup>2</sup> square mare area south Sosigenes IMP. The location of this panel is shown as the white box in Fig. 2a. A raw resolution version of this figure is provided as supporting information.



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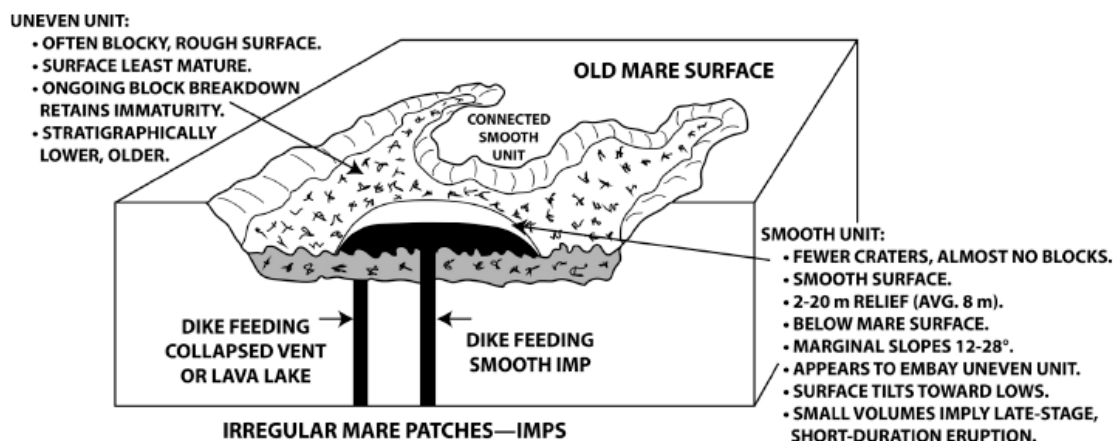
Fig. 20. NAC DTM slope of the mare crater-counting area (black square); the white square is the area where crater density-topographic slope correlation is analyzed (Fig. 18 and Table 4).



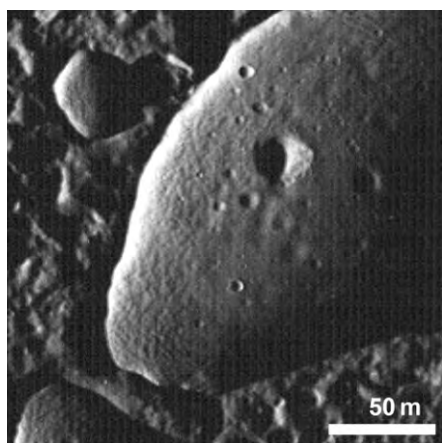
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Fig. 21. Cumulative size frequency distribution of impact craters superposed on the Sosigenes mounds (green crosses), surrounding mare  $2 \times 2 \text{ km}^2$  area (black ‘ $\times$ ’s), and  $840 \times 840 \text{ m}^2$  sub-area (red crosses, for slope effect investigation). The gray line on the right is the lunar equilibrium function (EF) curve from Trask (1966). The model age fitting is based on production function (PF) and chronology function (CF) from Neukum et al. (2001), using the CraterStats software package (Micheal and Neukum, 2010).

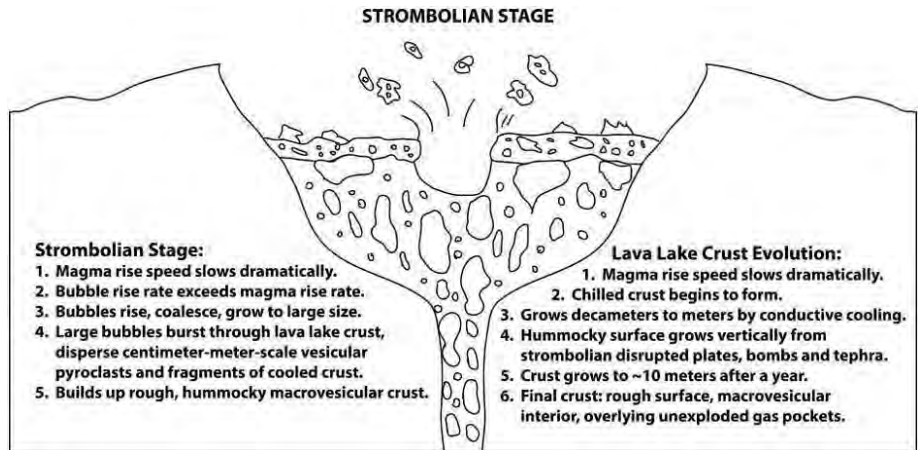




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 1491 Fig. 22. Block diagram illustrating the major characteristics of the irregular mare  
 1492 patches, and highlighting the interpretation of Braden et al. (2014) that the floor and  
 1493 mounds represent very late-stage extrusions (<100 Ma) compared with the  
 1494 surrounding ancient mare basalts (~2–3 Ga in the case of Ina and Sosigenes). In the  
 1495 Braden et al. (2014) interpretation, the floor units and mounds are both extremely  
 1496 young, but the mounds postdate the floor units. In the interpretation of Garry et al.  
 1497 (2012), the mounds are inflated lava flows and the rough floor units extrude from the  
 1498 base of the inflated flow. In the interpretation of Schultz et al. (2006) the anomalously  
 1499 young ages (<10 Ma in the case of Ina) are caused by deep-seated gas release that  
 1500 elutriates, blows out and ejects the fines, causing the observed rough, immature and  
 1501 blocky/hummocky floor units. In our interpretation, the rough floor units are the  
 1502 surface of a lava lake and the mounds are extrusion of late-stage magmatic foams. The  
 1503 young ages are attributed to the unusual properties of the magmatic foam and the  
 1504 solidified micro/macrovesicular lava lake.  
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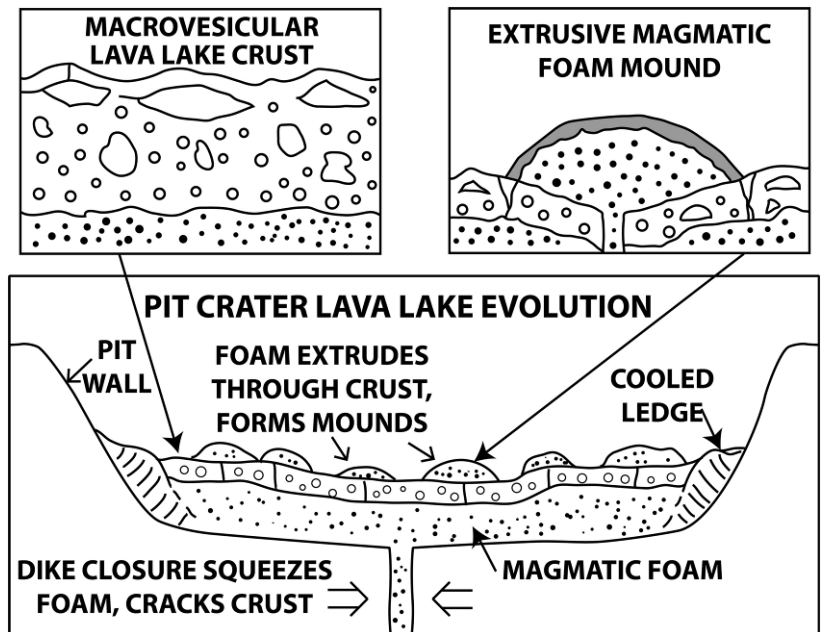


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 1507 Fig. 23. Depressions at the Ina mound summits. LROC NAC M132800178, ~0.57  
 1508 m/pixel, incidence angle= $\sim 87.2^\circ$ . The largest depression is the same one shown in Fig.  
 1509 4d of Garry et al. (2012).



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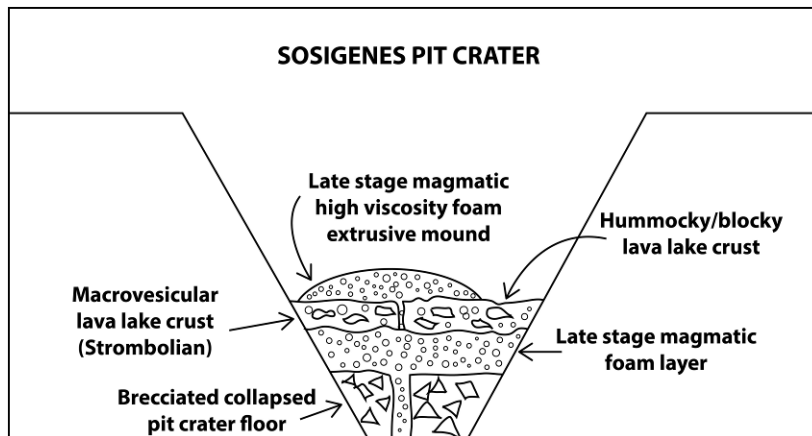
Fig. 24. Diagram (from Fig. 3 in Wilson and Head 2017b) illustrating processes operating in the waning stages of an eruption in Sosigenes pit crater: the strombolian-style eruption phase of lava lake evolution (left text) and development of the lava lake crust (floor hummocky/blocky units) (right text).



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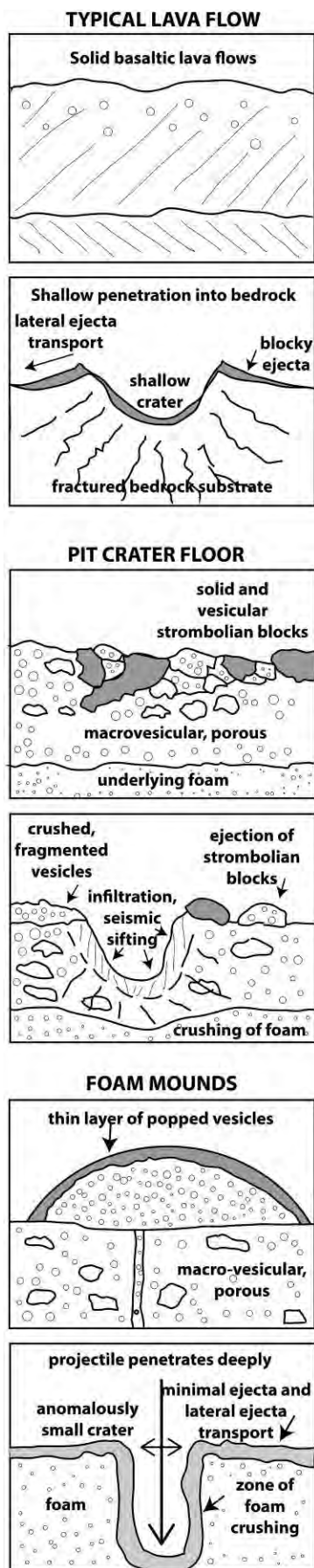
Fig. 25. Cross section (from Fig. 3 in Qiao et al. 2017) of magmatic foam emplacement during the final stage of eruption process in the Sosigenes pit crater.





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Fig. 26. Cross section of the final products of waning stage of eruptive processes in the Sosigenes pit crater.



**a) Typical Lava Flow:**

**Top: Emplacement Phase:**

1. Lava flow emplaced during main eruptive phase.
2. Pyroclasts coalesce to form flow, lava flows laterally, chills, solidifies.
3. Produces low porosity, low vesicularity, solid substrate.

**Bottom: Regolith-Building Phase:**

1. Subsequent impacts form in solid bedrock substrate.
2. Energy partitioning focused on fracturing, brittle deformation, comminution, ejection of solid particles.
3. Produces well-formed, relatively shallow, blocky craters, lateral ejecta.
4. Crater preservation favored.
5. Result: Typical mare regolith, fragmental ejecta layer buildup, optical maturity from accumulation of impact-melt-welded agglutinates, micrometeorite degradation of boulders.

**b) Pit Crater Floor:**

**Top: Emplacement Phase:**

1. Pit crater floor is lava lake cooling thermal boundary layer, modified by impact of strombolian ejecta.
2. Solidifies, grows to meters-thick layer in less than a year.
3. Top of crust consists of rough surface of solid and macro/micro-vesicular blocks ejected by strombolian bubble bursts; macro-porosity among, between blocks.
4. Bottom of crust consists of cooling and downward-growing layer of macro-vesicles from larger coalesced vapor bubbles and meso-vesicles from smaller bubbles.
5. Chilled lava lake crust then overlies trapped bubbles and magmatic foam.

**Bottom: Regolith-Building Phase:**

1. Subsequent impacts form in macro-porous, macro/meso-vesicular substrate.
2. Energy partitioning focused on crushing of substrate that is extremely porous at a variety of scales, breakdown of bubble walls, excavation of blocky parts of strombolian substrate; lateral ejection is inhibited.
3. Craters in porous/vesicular portions produce hummocky substrate; those in coarser substrate produce blockier ejecta.
4. Extremely porous nature of the substrate at several different scales results in sifting of finer regolith particles (broken bubble walls, comminuted vesicular debris) into substrate; this retards surface regolith buildup and regolith optical maturation.
5. Subsequent impacts induce further "seismic sifting" of fines into substrate, maintaining "fresh" appearance of hummocky/blocky terrain.
6. Result: Craters are poorly formed, difficult to recognize, and degrade rapidly; seismic sifting into extremely porous substrate enhances loss of fines, exposes blocks, and obscures craters.

**c) Foam Mounds:**

**Top: Emplacement Phase:**

1. Viscous magmatic foam (micro-vesicular) extruded through cracks in lava lake floor at low effusion rates as dike relaxes and closes.
2. Viscous foams extrude vertically, flow and spread laterally, coalesce, to produce mounds.
3. Mounds may initially be covered with decimeters thick layer of popped vesicles.
4. Lava lake crust may flex, subside below erupted foam mounds due to loading.

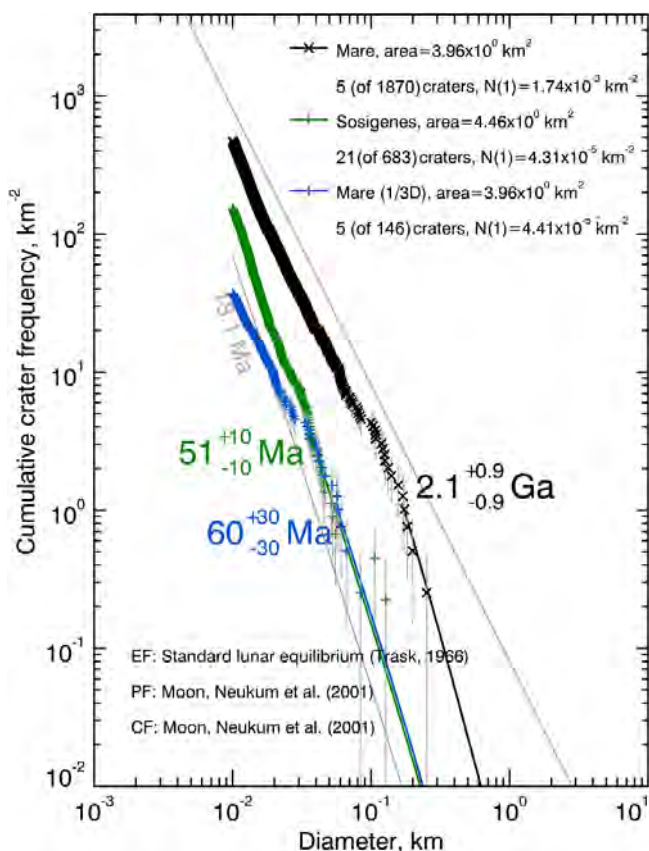
**Bottom: Regolith-Building Phase:**

1. Subsequent impacts form in solidified magmatic foam.
2. Energy partitioning favors foam penetration (the aerogel effect) and foam crushing over brittle deformation, crater formation and lateral ejection.
3. Regolith formation is dominated by poorly formed and anomalously small diameter superposed craters, and minimal lateral transport of any ejecta.
4. Result: Regolith dominantly non-blocky, formed of crushed and broken micro-vesicles, craters are much smaller, poorly preserved, easily degraded; little lateral ejection (aided by seismic sifting in adjacent hummocky/blocky terrain) retains sharp mound boundaries. The combination of processes yields anomalously young crater retention ages even though mounds formed at the same time as adjacent pit crater floor and shield volcano.

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Fig. 27. Block diagrams (from Fig. 9 in Wilson and Head 2017b) illustrating the substrate characteristics (top) of (a) normal basaltic lava flows, (b) lava lake crusts

1528 and (c) extruded foam mounds. Bottom panels and texts of each diagram (a–c) show  
 1529 the nature and results of post-emplacment impact cratering, regolith formation and  
 1530 landscape evolution operating on their surfaces.  
 1531



1532 Fig. 28. The effects of cratering a highly porous target (magmatic foam of the mounds)  
 1533 on the crater retention ages. The original crater size frequency distribution of the 2×2  
 1534 km surrounding mare region is plotted as black ‘×’s. All the craters counted on the  
 1535 mare are scaled with a factor of three diameter decrease (plotted as blue crosses); this  
 1536 produces a similar CSFD to the Sosigenes mounds (green crosses), and yields a model  
 1537 age of <100 Ma. The gray line on the right is the lunar equilibrium curve from Trask  
 1538 (1966), and the left gray line is the isochron for the 18.1 Ma age reported by Braden et  
 1539 al. (2014).  
 1540