SOSIGENES LUNAR IRREGULAR MARE PATCH (IMP): MORPHOLOGY, TOPOGRAPHY, SUB-RESOLUTION ROUGHNESS AND IMPLICATIONS FOR ORIGIN.

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Introduction: Lunar Irregular Mare Patches (IMPs) [1] are distinctive and enigmatic landforms widely distributed in nearside mare regions of the Moon. Characterized by their irregular shape, well-preserved state of relief, significantly low spectral maturity and few superposed impact craters [1-4] (Fig. 1), lunar IMPs have been interpreted to be formed by geologically recent processes [1-4]. However, the specific formation mechanism is highly debated. Candidates include: individual lava extrusions [1] (Fig. 1), lava flow inflation [2], pyroclastic deposits [3], and out-gassing, causing removal of surface regolith [4]. Here we report on an analysis of one of the major IMPs, Sosigenes, located in western Mare Tranquillitatis. We compile key morphologic and topographic observations of the Sosigenes IMP, make comparisons to Ina, and determine sub-resolution roughness (with a baseline of centimeters to decimeters) from LROC NAC images using phase ratio images. We then evaluate the several previously proposed formation hypotheses to assess their ability to account for the observed photometric, spectral, morphological and stratigraphic properties.

Morphology, Topography and Roughness: Morphologic units associated with IMPs are described as follows [1] (Fig. 2): 1) topographically higher, bulbous shaped mounds, 2) topographically lower, hummocky units and 3) topographically lower rocky material units. Integrated observations from LROC NAC image and DTMs show: 1) The Sosigenes IMP-like materials (Fig.. 2) are located on the floor of an enlarged graben structure where it crosses a pre-existing graben, both of which are part of a regional linear rille system [5] formed in 3.6.-3.8 Gyr-aged maria [6]; this setting is different from that of the Ina feature, which is broader and more equidimensional (D-shaped) (Fig. 3). 2) In Sosigeners (and Ina) the mounds are 5–8 m (10-20 m) higher than the lower hummocky unit and have scarp contacts with the adjacent lower units, but also show seamless junctures with surrounding mare deposits. 3) Some relatively large craters (diameter ~45–155 m) are observed on the mounds; these craters display normal bowl-shaped topographic profiles and an absence of exposed boulders on crater walls, indicating that these craters are either fully developed within the regolith layer, or heavily degraded and thus ancient. 4) Few boulders are observed on the lower units. 5) Smaller craters (diameter ~20–35 m) on the lower units show local massive excavated boulders suggesting that the lower units are mantled by a thin (<~1.5–2.5 m thick) layer of unconsolidated materials, with bedrock below. 6) The rocky units are extensive fresh boulder fields with individual boulders approaching ~12 m in dimension, suggesting close underlying bedrock proximity.

The reflectance of each location on the lunar surface generally decreases with the phase angle α, and the rate of this decrease is directly related to the surface roughness at the sub-resolution scale [7]. This change can be characterized by phase-ratio images For LROC NAC images with a pixel size of ~1 m [8], the derived phase-ratio images are sensitive to surface texture with a baseline of centimeters to decimeters.

In order to assess the sub-resolution roughness, we calculate phase ratio images of eastern Sosigenes from images acquired at 30° and 67° phase angles and, for comparison, of eastern Ina from images acquired at 52° and 87° phase angles (Fig. 3). Examination of the phase-ratio images shows: 1) the surface materials of the *mound units* have slightly smoother sub-resolution surface texture than typical lunar mature regolith; 2) the *lower uneven hummocky unit* is mantled by a layer of materials with significantly lower sub-resolution roughness and confined spatial extent; 3) the *rocky units* are composed of fresh boulders, with rougher sub-resolution surface texture.

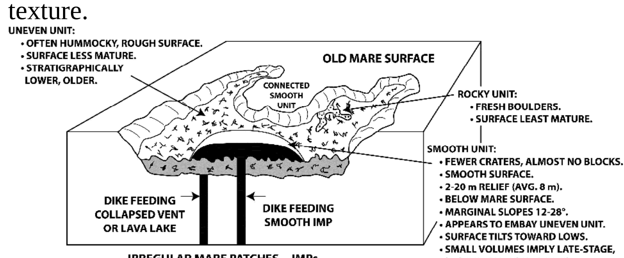

Fig. 1. Synthesis of IMP observations, interpretation [1]; from [5, 14].

Discussion: We integrate these morphological, topographic and photometric observations to assess several formation hypotheses proposed previously for lunar IMPs. *Geologically recent individual lava extrusions* [1]: This hypothesis (Fig. 1) appears inconsistent with the ages implied by the observed larger craters on mounds with normal bowl-shaped topographic profiles and few exposed boulders on crater walls/rims; they suggest a highly degraded crater morphology or a thick layer of regolith developed on top the mounds, both pointing to an old formation age for the mounds, which is inconsistent with the recent lava extrusion hypothesis for the mounds [1]. *Lava flow infla*tion [2]: Comparison of typical terrestrial inflated lava flow textures and impact melt materials shows that inflated lava flows should have similar sub-resolution surface roughness. However, impact melt deposits on the Moon [9] and Mercury [10] have rougher sub-resolution surface texture, inconsistent with a lava flow inflation formation mechanism. *Pyroclastic deposits* [3]: Pyroclastic eruptions are predicted to deposit a layer of finer particle size than that of the lunar regolith, which is similar to the particle size of the IMP materials. However, lunar pyroclastic deposits generally exhibit diffuse spatial extent [11], which is inconsistent with the confined spatial extent of the finer materials at lunar IMPs. *Out-gassing removal of surface regolith* [4]: LROC NAC sub-resolution roughness investigations of Apollo landing sites, where the surface regolith materials are blown by the descent module gas jets, also show diffuse regions of lower sub-pixel roughness, which is inconsistent with our photometric observations. None of the common geological processes outlined above can fully reproduce all of the observed properties of the Sosigenes and Ina IMPs (including sub-resolution roughness (this work), spectroscopy [12], geomorphology ([2] and this work) and stratigraphy [13]).

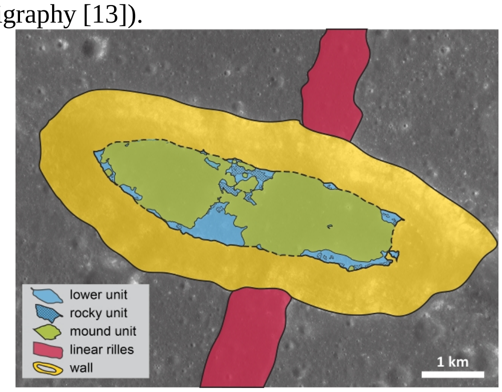

Fig. 2. Sketch geologic map of Sosigenes based on LROC NAC image.

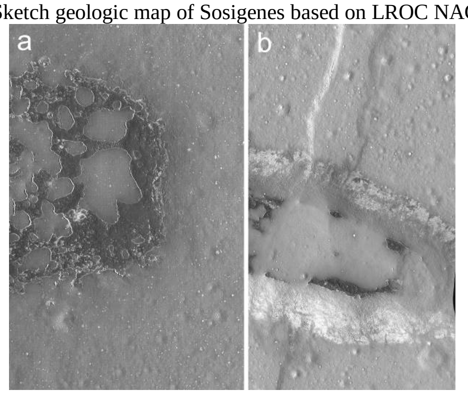

Fig. 3. LROC NAC phase-ratio images. (a) 52°/87° of Ina, stretched from 0.9 to 1.6. (b) 30°/67° of Sosigenes, stretched from 1.1 to 1.8.

A New Formation Hypothesis [5, 14]: We here focus on the IMP Sosigenes (Fig. 2, 3b) and propose a new formation mechanism in which the IMPs and related units on the floor of Sosigenes originate from regolith drainage processes into the floor of the graben/depression [5,14] and drainage of regolith into the top of the dike that produced the initial graben. In this hypothesis (Fig. 4), a gas/foam filled dike propagates to the shallow subsurface and stalls, forming a downdropped graben block and a gas/foam filled void at the top of the dike [14]. Diffusion of the gas leaves a void and subsequent seismic shaking by impacts causes sifting of the regolith and drainage into the void through the highly fractured downdropped graben block. Over time, the overlying regolith materials (~10 m thick for this age of maria [6]) drain through the cracks developed in the collapsed mare graben blocks.

On parts of the floor of the collapsed graben block, some of the surface regolith materials drain into the subsurface voids, thus generating the present lower units at Sosigenes (Fig. 2, 3b, 4). The regolith drainage process significantly thins the surface regolith mantling the lower units (thickness <~1.5–2.5 m). The collapsing and draining processes may also cause mechanical disturbance of regolith materials, altering their porous structure, and resulting in surface smoothing and brightening [6, 15], which is consistent with the radiance factor and sub-resolution roughness observations from LROC NAC images. Additionally, a small portion of the collapsed blocks have surface regolith totally drained, thus exposing the subsurface basaltic bedrock. These exposed boulders constitute the present rocky units at Sosignes. In this scenario, the negative topographic relief of the rocky units relative to the lower units (~2 m) can be attributed to variable regolith drainage processes, and should be comparable to the thickness of surface regolith layer on the present lower units (<~1.5–2.5 m). We are currently assessing the applicability of this mechanism of regolith drainage for Ina, and other areas of IMPs which are not directly associated with dike emplacement-related graben voids.

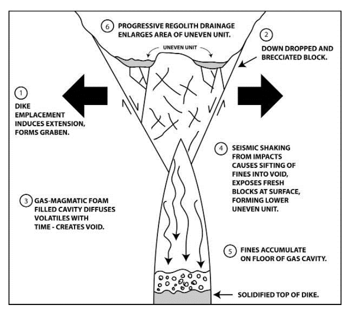

Fig. 4. Sosigenes IMP formation interpretative diagram [5, 14].

References: [1] Braden et al. (2014) *NGEO* 7, 787-791. [2] Garry et al. (2012) *JGR* 117, E00H31. [3] Carter et al. (2013) *LPSC XLIV*, #2146. [4] Schultz et al. (2006) *Nature* 444, 184. [5] Head & Wilson (2016) *LPSC 47*, #1189. [6] Hiesinger et al. (2011) GSA SP 477, 1. [7] Shkuratov et al. (2011) *PSS*, 59, 1326. [8] Robinson et al. (2010) *SSR*, 150, 81. [9] Shkuratov et al. (2012) *Icarus*, 218, 525. [10] Blewett et al. (2014) *Icarus*, 242, 142. [11] Gaddis et al., (1985) *Icarus*, 61, 461. [12] Bennett et al. (2015) *LPSC XLVI*, #2646. [13] Robinson et al. (2010) *LPSC XLI*, #2592. [14] Wilson & Head (2015) *Icarus*, in press. [15] Kaydash et al. (2011) *Icarus*, 211(1), 89.