CHARACTERIZING VOLCANIC CONES IN THE MARIUS HILLS REGION. S. J. Lawrence[1], J. D. Stopar[1], B. R. Hawke[2], B. L. Jolliff[3], M. S. Robinson[1], P. D. Spudis[4], and T. A. Giguere[2] [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ (samuel.lawrence@asu.edu) [2]HIGP/SOEST, University of Hawaii at Manoa, Honolulu, HI [3]Department of Earth and Planetary Sciences, Washington University in St. Louis, St. Louis, MO [4]Lunar and Planetary Institute, Universities Space Research Association, Houston, TX.

Introduction: Marius Hills (MH) is a large (~35,000 km^2) volcanic complex on a broad low relief plateau in Oceanus Procellarum (13.4°N, 304.6°E) ranging in age from Imbrian to Eratosthenian [1,2]. The MH complex includes volcanic domes, cones, flood basalts, and rilles [1–4] and is a high-priority target for human and robotic exploration [5–9]. Over 50 C-shaped (also referred to as "horseshoe"-shaped) cones ~1-2 km diameter were observed by [1–4,10] throughout the MH on domes and isolated in the mare. Small associated lava flows [4] may be evidence for spatter-style eruptions or volatile-enriched lava eruptions producing pyroclastics [2]. Here, we use Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) and Narrow Angle Camera (NAC) observations to characterize volcanic cones in the MH region to complement our previous observations of domes and lava flows [11,12].

Methods: LROC NAC frames in MH have pixel scales ~0.2-1.3 m [14]. LROC NAC right and left image pairs were map-projected and mosaicked for morphometric measurements. NAC stereo pairs were used to create three 2 m/pixel Digital Elevation Models using the techniques of [15] for quantitative determinations of cone slopes, heights, and lava flow thickness. LROC WAC images of the MH region, mosaicked to create a morphology basemap, were used to map the distribution and density of volcanic cones at the 100 m scale. The LROC WAC Global Lunar DTM 100 m, or GLD100 [16], coupled with shadow measurements were also used to measure the heights and slopes of MH volcanic constructs.

Results: Using LROC images, we identified 90 candidate MH volcanic cones. We propose the following classes to distinguish different MH cone morphologies.

C-class cone [C-Shaped]: C-Shaped cones (n=33) have steep exterior slopes (avg:13º) and are 0.5-2 km diameter (Fig. 1). The C-shape is formed by a gap in the cone that generally contains at least one lava flow. The point of highest topography along the cone rim is typically opposite the gap. Associated lobate flows radiate from the central region of the cone and out the gap. These flows contribute to dome topography and build lava shields. Some C-class cones occur on domes, others are standalone features unassociated with a dome. Many C-shaped cones are embayed by younger mare. The C-class cones typically have meter-scale blocks or fractured material on the upper slopes. We observe discrete layers of materials in some cones, consistent with [4]. These layers dip downslope toward the path of lava flows that erupted out of the cone. Layers, when present, are coherent and have associated aligned blocks that we interpret to represent the original volcanic stratigraphy in the cone, produced by variable eruption conditions over time, similar to those suggested for Rima Parry V [17].

E-class cone [Elongate]: Elongate cones (n=7) are similar to C-class cones, with more elliptical shape in plan and a gap containing distinct lava channels indicating flow direction. The point of highest topography along the cone rim is roughly opposite the gap.

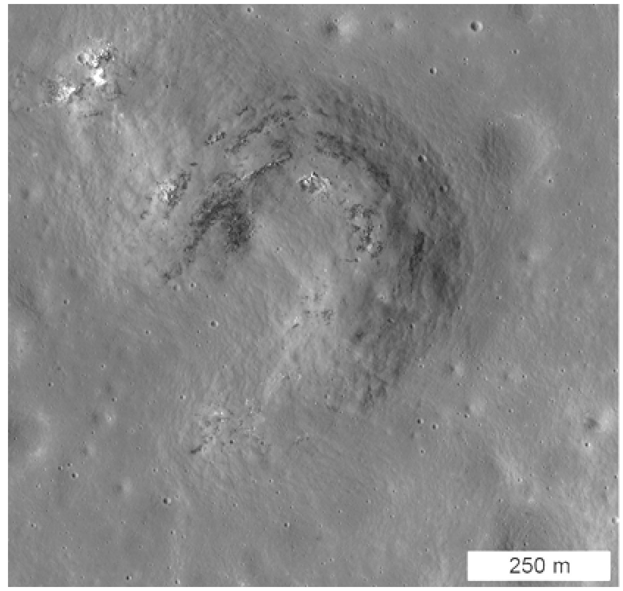

Figure 1: 800 m diameter C-class cone in the MH with distinct layers. NAC frame M150870879.

N-class cone [No gap]: These cones (n=2) have a subcircular to elongate summit crater without the gap associated with the C- and E-class cones. Like C- and E-class cones, the exterior slopes are steep with smooth surfaces, except for the occasional exposed boulder field or blocky layer.

P-class cone [Probable]: Probable cones (n=12) have relief and areal extents similar to C- and E-class cones but are more irregular in plan. One side of these features is topographically lower than the other side and associated with an elongate channel. However, discrete flows are not easily discerned. The exterior slope of one P-class vent where shadow length was measurable was ~22°.

U-class cone [Uncertain]: These positive relief features (n=36) are not easily distinguished from mantled impact craters or other topographic features, but are included here for completeness. Boundaries are generally less distinct from their surroundings and lack smooth sides. The exterior slopes, as measured from shadow lengths, are more variable (up to 16°) from feature to feature. They have morphology not typically observed in non-volcanic landforms, but, either due to degradation and/or illumination, we cannot positively identify these features as volcanic cones.

Discussion: The C-shaped cones are morphologically similar to terrestrial cinder cones [4,18–22] and are of smaller size [21,22], but have lower slopes (16º for MH, ~30° terrestrial) [18, 21, 23]. The distinct "horseshoe" shape of many terrestrial cinder cones commonly results from an asymmetric distribution of pyroclastic material primarily due to the prevailing wind direction [18]. On the Moon, the formation of asymmetrical C-class cones requires a different mechanism (e.g., breaching by lava flows). We observe that the point of highest topography along the rim of a C-class cone is roughly opposite the gap, meaning the gap is likely a lava flow breach. The direction of C-class cone gaps (measured from rim high point through low point) are generally in agreement with the local topographic gradient, suggesting formation of the C-shape is partly driven by pre-existing topography. This mechanism has been considered in terrestrial cinder cone construction where prevailing winds could not adequately explain cone shapes [24,25]. In the MH, cones are sometimes observed in clusters. Breaches in clustered cones usually occur in different directions and are not always in alignment with regional topographic contours, possibly due to local topography and/or "obstacle" effects created by the neighboring cones. In terrestrial analogs, cone distribution and alignment can provide information about the subsurface structure, because cinder cones can concentrate along fracture zones. MH cone clusters may also result from similar factors that concentrate the magma supply, such as dikes and subsurface fractures [17,18,26].

Cone Density and Diameter: The total number of likely volcanic cones (52, with 36 additional uncertains) identified in this study is similar to the numbers previously reported (46 [2], 59 [4]). In the center of the MH, the local volcanic cone density is 0.038 cones/km^2. For comparison, local cone densities can be as high as 8 cones/km^2 on Mauna Kea, Hawaii [18]. The total density of cones when averaged over the entire Marius Hills plateau is 0.0012 cones/km^2. If P- and U-class cones are included, the density of volcanic cones increases to 0.0026 cones/km^2. This is less than the regional cone density for some terrestrial analogs, including Mauna Kea, Hawaii (0.664-0.126 cones/km^2); San Francisco volcanic complex, Arizona (0.087 cones/km^2); Paricutin, Mexico (0.049 cones/km^2); and Nunivak Island, Alaska (0.024 cones/km^2) [2, 18, 26], suggesting that volcanism on the MH plateau was less intense. However, the localized volcanic cone density of 0.038 cones/km^2 near the center of the plateau is comparable to the reported cone densities of Paricutin and Nunivak Island.

Analog studies [26] suggest that the density of cinder cones on the flanks of large shield volcanoes (i.e., Mauna Kea) is lower than on volcanic plains. On large shields, cones are typically < 1km in diameter, whereas on volcanic plains (e.g., Nunivak Island), where cones are typically 1-2 km in diameter [26]. MH cones are 0.6-2.6 km in diameter and thus overlap the diameter range for both kinds of terrestrial cinder cone fields.

Comparison to Other Lunar Features: There are few recognized lunar volcanic cones similar in size in shape to the MH outside the plateau [28]. One is Isis, (18.96ºN, 27.48ºE) a 1.5 km diameter cone that is also C-shaped, smooth-sided, and has a gap containing a lava flow. Topographic data produced from Apollo 17 orbital photography indicate that Isis is ~ 70 m high and has a slope of 7.1° [4]. This feature is similar in size and morphology to some Marius Hills cones. This feature is in geographic proximity to a linear rille suggested to be involved in its formation [4,28,29]. Osiris is a similar geologic feature ~1.9 km in diameter, located southeast of Isis (18.6ºN, 27.6ºE), but like a MH N-class cone, does not have a gap. This feature is ~90 m high, and has a slope of 7° [4]. The scarcity of cones like those of MH suggest that volcanic cone formation processes are uncommon on the Moon.

Conclusions: We have identified five classes of volcanic cones in the MH region analogous to terrestrial cinder cones based on morphology, size, and geographic distribution. The density and diameter of MH cones are similar to cone fields found in some terrestrial volcanic plains. The superposition of the cones atop many domes led [1] and [10] to propose that the cones are younger than the domes and represent a more viscous, but still basaltic, eruption style, during the final stages of volcanism in the MH. LROC observations show that lava flows from some C-class cones contribute to dome morphology. This implies that when C-class cones are found on a dome, cone formation is an aspect of the dome-building process.

Spectral differences between the domes and cones in the MH were interpreted by [4,12,13] to represent a change in eruption mechanics or lava composition, possibly reflecting an increase in glassy or opaque components produced in pyroclastic and/or spatter (possibly cinder) eruptive materials. The variable layering in some C-class cones supports eruptions of a mixture of lava and pyroclastic materials, consistent with [4,12,13]. The apparent rarity of MH-style cones suggests volcanic processes that occurred at MH were unique to the MH region.

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