INTERPRETATIONS OF VOLCANIC DEPOSITS ASSOCIATED WITH SMALL LUNAR CONES.

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Introduction: A variety of localized topographic features (often less than several square kilometers in extent) on the Moon are interpreted as volcanic [e.g., 1-8] and include cones, lava flows, and pyroclastic deposits. Many of these small-area volcanic deposits are inferred to occur proximal to their source vent and may provide clues about the range, composition, volatility, volume, and timing of lunar magmatism. Here, we focus on those deposits associated with small cone structures (e.g., **Fig. 1**) previously identified [9] in mare terrains. These cones are characterized by irregular morphologies that range from c-shaped to elongate or pit-like. LROC NAC images and derived topographic models (DTMs), combined with other morphologic data sets (see below), allow detailed characterization and interpretation of these previously under-recognized volcanic deposits. The goals of this work are to characterize and determine the extent of volcanic materials associated with small lunar cones, assess formation mechanisms by evaluating potential analogs, and gauge future sampling priorities and strategies.

Data Sources: Small volcanic cones (< 3.5 km in diameter and steep-sided) with conical to elongate summit craters occur in a variety of nearside locations: Marius Hills, Rima Parry, Isis-Osiris, Mons Euler (Vinogradov), Hortensius-Tobias Meyer, SW of Lassell, and N of Aristarchus [e.g., 1-3; 5-6; 9-12]. Summit-diameter-base-diameter relationships of the small cones are distinct from those of domes and pyroclastic (dark mantling deposits - DMD) vents [9]. Previously, we also reported dimensions and slopes derived from LROC NAC DTMs for a number of small cones [9]. Here, additional measurements are derived using NAC-based shadow heights, 2-5-m NAC DTMs [see 9 for references], and the Kaguya 10-m global DTM [13]. Terrestrial cinder cone dimensions, from the literature [14-16] and also determined from 1-m OpenTopography LiDAR-based DTMs [17], are compared.

Results and Discussion: Long-recognized similarities in morphology between small lunar cones and terrestrial cinder cones include summit-diameter/base-diameter ratios, height/diameter ratios, and overall size and shape [e.g., 14, 16]. Both small lunar cones and young cinder cones of the San Francisco (SF) volcanic field (Arizona, USA) [14], as well as examples from Three Sisters (Oregon, USA) and Big Island (Hawaii, USA) volcanoes, have summit diameters ranging from 0.3-0.6 times the base diameter.

Heights of small MH cones (**Fig. 2**) average about one-tenth (~0.1) of the base diameter; other lunar cones have lower relative heights. Tightly grouped lunar cones also have lower relative heights (~0.07) and volumes, like their analogs [18].

Older SF cones exhibit similar height-diameter relationships to the MH cones (~0.1), but the height/diameter ratios of the younger terrestrial cones are greater ~0.2 (**Fig. 2**; [14]). As terrestrial cinder cone height-diameter relationships are thought, at least in part, to reflect degradation [14], the roughly linear fit to MH cone height/diameter ratios (**Fig. 2**) suggests consistent degradation over the range of sampled diameters.

Flank slopes of small lunar cones range from 10 to 20°, lower than most recent terrestrial cinder cones (~30°), but lunar flank slopes are expected to be lower as a result of lower gravity [2]. Nevertheless, the variability of flank slope from edifice-to-edifice could reflect a range of eruption ages (and/or degradation states) that is generally consistent with the wide distribution and stratigraphic relationships of the lunar cones. However, flank slopes also reflect physical properties (e.g., the relative abundances of pyroclastics, spatter, and lava) [6], and coherent materials capping the summits of many small lunar cones suggest that at least some cones are not heavily degraded.

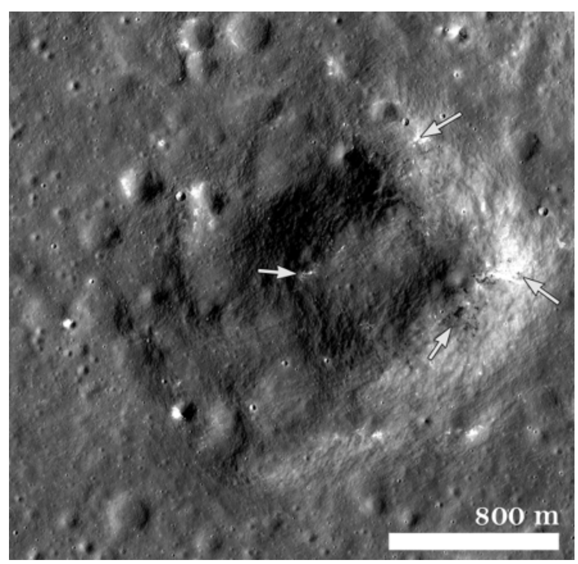

Fig. 1. A small lunar cone with bouldery exposures (arrows); Marius Hills (304.281°E, 13.714°N); NAC M144992741.

Do similar morphologies imply similar eruption mechanisms? Like many terrestrial cinder cones, small lunar cones exhibit layers of lava, breaches, and coherent summit materials (interpreted as spatter or welded deposits). Lava flows and pyroclastic mantles are also common at small lunar cones (like their terrestrial analogs), although many lunar volcanic deposits lack an obvious source vent. Our high-resolution morphologic and topographic analyses comparing small lunar (particularly MH cones) and terrestrial cones across similar scales (1-10 m) further support eruption mechanisms for the small lunar cones akin to the intermittent, monogenetic, basaltic-andesitic, gas-enriched volcanism typifying terrestrial cinder cone formation [e.g., 14-16,18]. Although, the lower relative heights of other lunar cones compared to MH (and terrestrial) cones may reflect differences in degradation, embayment, compositions, and/or eruption mechanisms.

Cone formation mechanisms are also reflected by their densities and distributions. For example, terrestrial cinder cones often form preferrentially along fracture or rift zones of larger volcanic structures or distributed among lava flows and plains [e.g., 18]. Concentrations of small cones in the Marius Hills and Hortensius-Tobias Meyer regions suggest formation as part of regional and/or shield volcanism [e.g., 19]. However, the distributions of cones within the Marius Hills and Hortensius 'shields' do not indicate any dominant, regional-scale, radial fracture or plumbing systems. Nonetheless, local groupings (alignments, clustering) of lunar cones do frequently occur (both in the Marius Hills and elsewhere), consistent with localized volcanic and/or structural patterns.

Exploration Strategies: An *in situ* explorer investigating lunar cones and rough lava flows must first assess the need to traverse relatively rough terrain. Lava flows in the Marius Hills are generally steep-sided (~12°) and blocky (at the 1-to-10-m scale) [e.g., 6, 20]. Interbedded (lava-spatter-cinder) cones are also steep-sided (up to 20°) with localized exposures of blocks (**Fig. 1**). Rough lava flows and steep cones could prove challenging for future explorers; but, many small cones and lava flows are embayed by younger mare basalt flows. This embayment can facilitate travel between a variety of regional features as well as simplify hardware requirements (for slopes and rough terrain) (**Fig. 3**). Because proximal volcanic deposits (flows and cones) are generally characterized by at least some blocky materials, sampling of 'rolled boulders' would limit the necessity to ascend many volcanic landforms. Due to their accessibility and importance to understanding the processes and timing of lunar volcanism, small-area volcanic deposits are high-priority exploration targets.

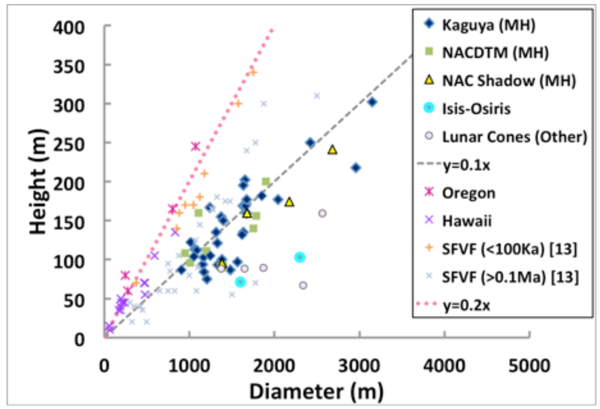

Fig. 2. Heights and diameters of small lunar cones (MH = grey trendline) and analogs (pink trendline). MH cone heights measured by different techniques (with good correlation among them).

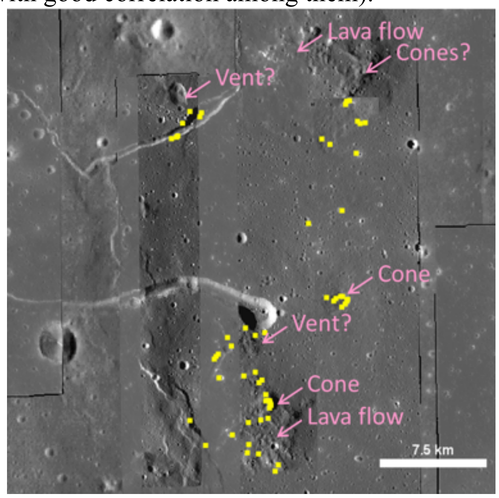

Fig. 3. Boulders/outcrops (yellow dots) within a region of the western MH region providing access to key volcanic materials; NAC mosaic on WAC basemap.

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