BASALTIC CONES: A RELATIVELY COMMON AND DISTINCT STYLE OF LUNAR VOLCANISM.

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Introduction: Mare-style volcanism is generally recognized as the dominant lunar volcanic process; however, a variety of localized volcanic deposits comprising small, several kilometer to sub-kilometer scale cones, fissures, pyroclastic vents and mantles, as well as silicic (possibly granitic) domes indicate that a wide variety of less well characterized volcanism also occurred on the Moon [e.g., 1-7]. Many of these deposits occur in basaltic terrains (with the exception of some silicic domes) and are characterized by irregular morphologies and associated lava flows, similar to those previously described in the Marius Hills [e.g., 8-11]. Meter-scale images allow detailed characterization of these previously poorly resolved, and often unrecognized, volcanic deposits. The goals of this work are to: characterize the global population of lunar cones; determine their association with larger volcanic complexes, pyroclastic deposits, and/or structural features; investigate their composition; and assess the mechanisms of their formation.

Background: Lunar volcanic cones were first described as small ~1-2 km diameter, steep-sided conical to elongate structures with summit craters as part of the Marius Hills complex [8,9], a large plateau in Oceanus Procellarum more than 300 km across. Other lunar cones were identified from a few scattered locations including: Rima Parry, Isis-Osiris, Mons Euler (Mons Vinogradov), the Hortensius-Tobias Meyer region, SW of Lassell, and NW of Aristarchus [e.g., 1-3,12,13]. Similarities between the lunar cones and terrestrial cinder cones in diameter and overall morphology is striking, suggesting a similar formation mechanism [e.g., 8-11,14,15].

Eruption mechanics leading to the generation of a range of cone morphologies were modeled as a function of ejection angle, clast size and density, effusion rate, gas abundance, and stability of eruption (i.e., intermittent or steady) [e.g., 16,17]. Thus, volcanic eruption style is often inferred from basal diameter and shape, cone height, flank slope, and summit crater diameter and shape [e.g., 14,15,18,19]. Head and others [16,17,19-21] described three types of lunar cones: small cones, analogous to terrestrial cinder cones, comprised of cinder, spatter, and/or lava; larger cones with diameters greater than 3 km; and low, broad pyroclastic cones aligned along linear vent systems.

Data Sources: High-resolution (~0.3 to 2.2 m pixel scale) LROC NAC images allow detailed photogeologic interpretation of candidate cones. NAC-derived digital elevation models (DEMs) of Isis-Osiris (5 m sampling), Crisium-1 and -2 (2 m sampling), and several Marius Hills cones (2 m sampling) provide topography [22,23]. NAC DEMs are generated from image pairs and fit by a least error solution to tie-points, sensor position, and camera pointing; reference frame tied to LOLA elevation profiles [22,23]. Spectral properties of candidate cones and associated deposits were determined from the Clementine UVVIS (200 m/pix) global 5-color mosaic.

Results and Discussion: We investigated 180 cones, candidate cones, and groupings of cones (clusters and linear chains), only a few of which were previously studied in detail [e.g., 11,15,24]; 50 are newly recognized. The Marius Hills complex is host to more than 100 cones or groups of cones, and the Hortensius-Tobias Meyer region is host to 30. These two regions account for the bulk of the recognized lunar cones, and the cones may be, in part, parasitic cones formed on the flanks of two large shield volcanoes in these areas [25]. The other 40 cones (18 newly identified) nearly all occur scattered, aligned, or in groupings in mare deposits across the nearside (Frigoris, Imbrium, Vaporum, Tranquilitatis, Nubium, Procellarum) and are not associated with any proposed shield volcanism.

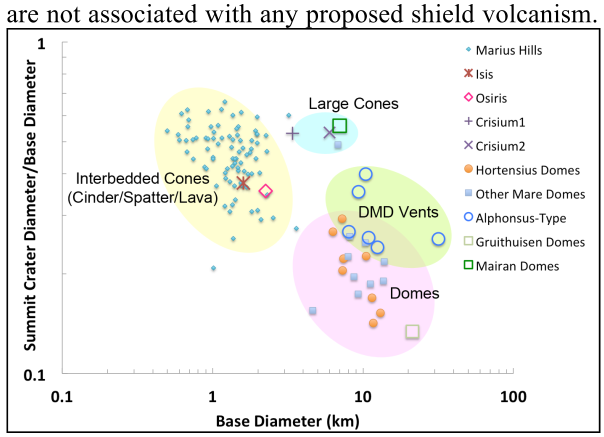

Figure 1. Base and summit crater diameter relationships for representative volcanic features.

Morphology. Lunar cones are subcircular to elongate in plan view, with a circular to elongate summit crater (cones lacking distinct summit craters are difficult to recognize). The summit crater/base diameter ratio is larger than that of lunar domes (**Fig. 1**). Many cones display dark blocky outcrops or coherent draping layers on their summits and flanks that are interpreted as either spatter facies and/or remnants of lava flows. Cones are typically small, < 2 km in diameter, and have average flank slopes ranging from 5-16°. The flank slope is less than the angle of repose, unlike many terrestrial cinder cone flanks (~30°). The shallow flank slopes are likely a primary feature resulting from construction from lava and pyroclastics under lunar eruption conditions [10,11,20]. Mairan T has a base diameter and summit diameter relationship similar to lunar cones, but much steeper flank slopes (~30°) are preserved, suggesting that degradation alone cannot explain the lower slopes of the lunar cones.

The newly characterized cones fit well into existing cone classification schemes. Cones such as those of the Marius Hills and Isis-Osiris are interpreted as basaltic cinder, spatter, and/or lava produced by intermittent or variable eruption conditions. Lava breaches and associated short lava flows with distinct flow fronts are typical of this type of eruption. The summit craters of these cones are generally situated above the surrounding mare plain; height/base diameter ratios range from 0.04 to 0.10.

The Crisium-1 and -2 cones are larger in diameter (3.5 and 6.0 km, respectively) than those of the Marius Hills and Isis-Osiris, but have lower height/base diameter ratios ~0.02-0.03. The two Crisium cones have breached summit craters and are distinct in morphology from typical lunar domes (**Fig. 1**). Both have summit craters below the elevation of the surrounding mare, more typical of Alphonsus-type vents than interbedded cones. Thus, the Crisium cones may represent an intermediate morphology between DMDs and cones (**Fig. 1** "large cones").

Low reflectance (LR) hills, sometimes termed "dark hills", are irregular mounds that often occur in areas with other volcanic features, are lower reflectance than surrounding mare, and may be expressions of lava flows that did not form a cone structure or preserve an obvious source vent. Alternatively, some LR hills may be modified or mantled kipukas draped with pryoclastic or mare deposits.

Spectral Properties. Low reflectance and a weak 1-micron mafic absorption band characterize both lunar cones and LR hills; pyroclastic glasses associated with small dark mantling deposits (DMDs) have similar weak mafic absorptions [26]. This signature is consistent with either basaltic volcanic glass [16] and/or fractured basalt [26,27]. The 415/750 nm ratio, reflecting Ti content, shows a range of values for lunar cones and associated lava flows (**Fig. 2**) and frequently appears enriched over adjacent mare. Marius Hills (MH) redspot cones have stronger mafic absorptions than typical cones; MH darkspot cones have bluer spectra than average MH cones [15,24]. Cones adjacent to non-mare materials, e.g. Rima Parry, or in areas crossed by rays/ejecta from large craters tend to have lower 750/900 and 415/750 nm ratios (**Fig. 2**) that may result from highlands mixing.

Conclusions: Lunar cones are more numerous than previously recognized and represent a distinct and significant style of volcanism. Our observations of lunar cones support the interpretation that they formed from variable and/or intermittent eruptions of basaltic cinder, spatter, and lava. Many of the cones occur in linear chains along graben and ridges, and may form from fissure eruptions, near surface dikes, or as 'squeeze ups' of mare flows. As high-resolution datasets continue to become available and analyzed, more lunar cones will likely be discovered.

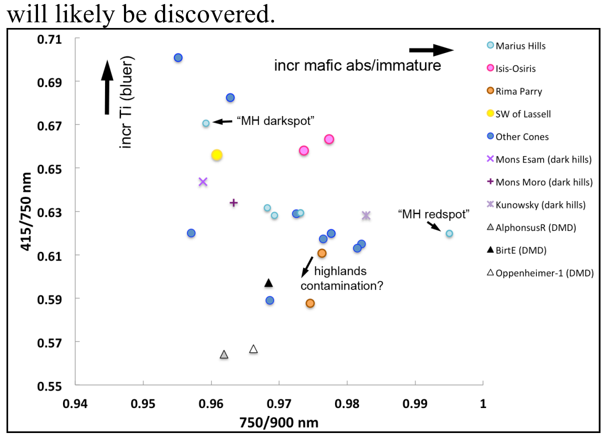

Figure 2. Spectral ratios for representative cones, low reflectance hills, selected dark mantling deposits (DMDs).

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