Ring-Moat Dome Structures (RMDSs) in the Lunar Maria: Further Statistical and Morphological Characterization.

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Introduction: Lunar mare surface morphologic structures/features are siginificant keys to understanding of the nature of basaltic lava flow emplacement [1], which carries important information on the deep interior mantle [2]. A type of ring-moat structure, characterized by a nearly circular mound surrounded by a ring depression, was first observed during the Apollo exploration phase [3]. The characterization, distribution and interpretation of similar features have been greatly improved by increased image coverage, improved resolution, availability of a wider range of viewing geomitries and illumination conditions, high-resolution altimetry, and the ability to utilize high-resolution stereophotogrammmetry. Specifically, high-resolution Lunar Reconnaissance Orbiter (LRO) images have allowed closer investigation of these still poorly understood features. A recent study [4] defined the features as Ring-Moat Dome Structures (RMDSs) and showed that they were characterized by: a generally circular shape and dome-like morphology, a surrounding moat, a relatively small diameter/height compared with other lunar and planetary volcanic features, concentrated in clusters, in association with the lunar maria, only found in certain mare regions, and a composition similar to the surrounding lunar maria.

Here, we present a more detailed investigation of RMDSs, using images and Digital Elevation Models (DEMs). The low and generally steep-sided RMDSs share a close morphologic association with surrounding basaltic lava flows on which they formed. Thus, a more complete characterization will provide the chance to effectively link lava emplacement mechanisms to flow and RMDS morphology.

Data and Methods: Images obtained by the Narrow-Angle Camera (NAC) [5] (~1 m/pixel), a subsystem of the Lunar Reconnaissance Orbiter Camera (LROC), were used to map RMDSs and derive DEMs at ~1 m scale. Our DEM construction method is based on the refinement of an existing digital topographic model (here: the SLDEM [6]) using shape from shading [7]. The SLDEM was constructed from measurements of the Lunar Orbiter Laser Altimeter (LOLA) and stereo analysis of the SELENE Terrain Camera. It has a resolution of 512 pixels per degree and a vertical accuracy of 3-4 m, covering latitudes between ±60° [6]. Our refined NAC-based high-resolution DEM has a vertical accurancy of ~1 m and it is used to determine the diameter, height and volume of each RMDS, approximated by a circular outline. The RMDS diameter corresponds to the distance between two manually marked reference points on the western and eastern rim of the RMDS, respectively. The RMDS height corresponds to the difference between the maximal DEM value and the average of the DEM values of the eastern and western reference points. For determining the RMDS volume, the average DEM value on the circular RMDS rim is computed first. The RMDS volume is then obtained by integration of the DEM values over the RMDS area relative to the average rim.

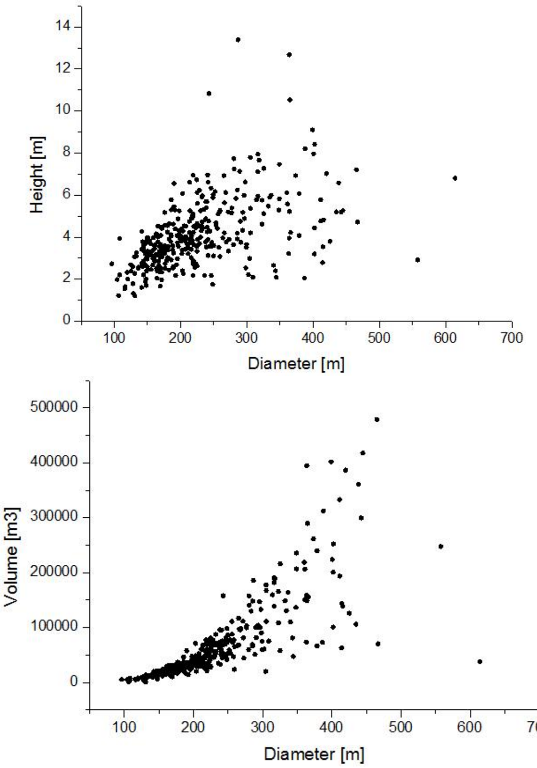

Fig. 1 Scatter plots of diameters, heights, and volumes of the 532 RMDSs measured from NAC-derived DEMs.

Results: A total of 532 RMDSs in twelve different mare regions were analyzed with regard to their diameters, heights, and volumes. Of the 532 RMDSs, the smallest is estimated to be 68 m in diameter, while the largest 645 m. The average diameter is 209 m, and the median 192 m. The largest RMDS height is 13.4 m, and the smallest 0.38 m. The mean height is 3.60 m, while the median height value 3.41 m. The volumes and heights of the RMDSs are shown as a function of their diameters in Fig. 1.

Lunar RMDSs have average summit slopes of <5° and steeper-sided margins with relatively higher slopes between 5° and 10°, in particular for slopes surrounding moat depressions. Lava flows characterized by RMDSs are mostly high-Ti basalts and appear to be emplaced on regional slopes less than 2°.

Ring depressions (moats): Some sections show a local low topography resembling collapsed depressions (black arrow, Fig. 2, top), while others are relatively level with the surrounding mare surface (white arrows, Fig. 2, top and center). The morphology of some RMDSs appears to be controlled by local topography (Fig. 2, center): for instance, several are located next to a crater [4]. Many RMDs feature what appears to be a point depression (white arrow, Fig. 2, bottom), in most cases located at the summit but in some others offset to one side. Such a feature could be caused by a deflation mechanism linked either to outgassing or magma drainage. Clearly, in some instances the depression could also be linked to an impact, although unusually shaped and devoid of diagnostic ejecta features.

Discussion of Candidate Origins:

Tumuli or hornitos on lava flows: This seems unlikely; terrestrial tumuli are typically somewhat smaller (a few meters to tens of meters in diameter [8]), are generally elongate and not circular, do not display surrounding moats, and as a rule show prominent fractures across their structure [9]. In addition, RMDSs are much more abundant than typical tumuli. Rootless terrestrial eruptions (squeeze-ups [10] and hornitos) are typically much smaller, have lower relief than RMDSs and do not display moats.

Comparison to pressure ridges on Earth: Terrestrial pressure ridges are generally elongate and their morphology [11] is not comparable to that of RMDSs.

Extrusive foam mounds: Based on their characteristics (abundance, late stage development of the occurrences, and common occurrence in concentric depressions as predicted by theory as foam extrudes and loads the lava crust [12]), this interpretation seems to be the most plausible [4].

Conclusion: RMDSs are lunar basaltic flow features that formed during the waning stages of basin interior eruptions. Their diverse morphologies (negative and positive features) suggest a possible genetic relationship to surrounding flows. We currently favor a foam-mound hypothesis for their formation [4, 12]. Quantitative measurements of 532 RMDSs from different mare basins along with compositional mapping of the flow field have enabled detailed documentation of the modes of RMDS emplacement.

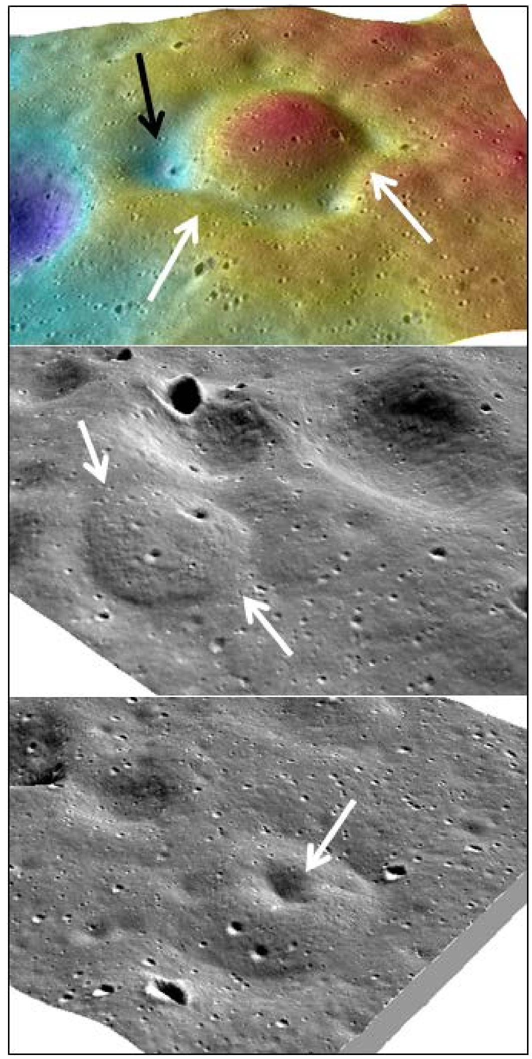

Fig. 2 From top to bottom: 3D views of a ~360-m-diameter RMDS (Height 12.68 m, Volume 3.9×10^5 m^3) in Mare Tranquillitatis, a ~240-m-diameter RMDS (Center) and a ~400-m-diameter RMDS (Bottom; height: 7.90 m) in Mare Fecunditatis.

References: [1] Head J. W. and L. Wilson (2017) *Icarus, 283*, 176–223. [2] Wilson L. and J. W. Head (2017) *Icarus 283*, 146–175. [3] Schultz, P. et al. (1976) *LPS, VII*, 985–1003. [4] Zhang F. et al. (2017) *Geophys. Res. Lett., 44*, 9216–9224. [5] Robinson M. S. et al. (2010) *Space Sci. Rev., 150* (1), 81–124. [6] Barker, M. E. et al. (2016) *Icarus, 273*, 346–355. [7] Grumpe, A. and C. Wöhler (2014) *ISPRS J. Photogramm. Rem. Sens.* 94. [8] Walker, G. P. (1991) *Bull. Volcan., 53*(7), 546–558. [9] Anderson, S. W. et al. (2012) *Bull. Volcan., 74*(4), 931–946. [10] Nichols, R. L. (1939) *Journal of Geology, 47*(4), 421–425. [11] Orr T. R. et al. (2015) *J. Volcan. Geothermal Res. 291*, 35–48. [12] Wilson, L. and J. W. Head (2017) *J. Volcan. Geothermal Res. 335*, 113–127.