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Key Points:
- We have discovered previously unreported geological features on the Moon, here named ring-moat dome structures
- Their morphologic characteristics, composition, and age are investigated
- Candidate hypotheses for their origin are proposed

Supporting Information:
- Supporting Information S1

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Newly Discovered Ring-Moat Dome Structures in the Lunar Maria: Possible Origins and Implications

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Abstract We report on a newly discovered morphological feature on the lunar surface, here named Ring-Moat Dome Structure (RMDS). These low domes (a few meters to ~20 m height with slopes $<5°$) are typically surrounded by narrow annular depressions or moats. We mapped about 2,600 RMDSs in the lunar maria with diameters ranging from tens to hundreds of meters. Four candidate hypotheses for their origin involving volcanism are considered. We currently favor a mechanism for the formation of the RMDS related to modification of the initial lava flows through inflated flow squeeze-ups and/or extrusion of magmatic foams below a cooling lava flow surface. These newly discovered features provide new insights into the nature of emplacement of lunar lava flows, suggesting that in the waning stages of a dike emplacement event, magmatic foams can be produced, extrude to the surface as the dike closes, and break through the upper lava flow thermal boundary layer (crust) to form foam mounds and surrounding moats.

1. Introduction

Exploration of the lunar maria by the Apollo astronauts and the return and dating of basaltic samples confirmed the volcanic origin, the very ancient age, and the very large abundance of superposed impact craters on the dark plains on the Moon. Despite the intensive study of the lunar maria that has taken place during the last five decades, we report here on the discovery and documentation of a new class of previously unknown features, that we describe as ring-moat dome structures (RMDSs).

Analyses of images taken by the Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) (Chin et al., 2007; Robinson et al., 2010) have revealed for the first time the presence of relatively small, domical features in the lunar maria. These domes are typically surrounded by narrow ring-like moats and we thus named them "ring-moat dome structures" (RMDSs) (see Figure 1 and Figure S1 in the supporting information). They typically form circular, sometimes elongated mounds (Figures 1c–1e), a few to ~20 m high and have a diameter varying from tens to several hundreds of meters in most cases, with only a handful of examples larger than 1 km. Their height-to-diameter ratios are small (0.01–0.04) and indicate that slopes are very gentle (1.5–5°) (see Text S1, Figure S2, and Table S1 in the supporting information). In planimetric view they sometimes coalesce into dumbbell and short chain patterns (Figures 1d and 1e).

2. Data and Methods

Given that they are smaller than kilometer scale and very low features, the RMDSs are identified from the high spatial resolution LROC NAC images (~0.5 to 1.5 m/pixel) that were taken when the Sun was low above the horizon (solar incidence of ≥60°), thus producing elongated shadows and highlighting even subtle morphology changes. A full survey of all RMDSs on the lunar surface is not achievable at present given that the lunar surface has not been completely mapped at the required illumination conditions and spatial resolutions.

In order to constrain the morphology of RMDSs, digital terrain models (DTMs) derived from NAC (Tran et al., 2010) and Kaguya-TC (Terrain Camera, ~10 m/pixel) (Haruyama et al., 2012, 2014) images/sets were used. The LROC NAC DTM (1.6 m horizontal resolution and ~2 m vertical error) used within Mare Tranquillitatis was

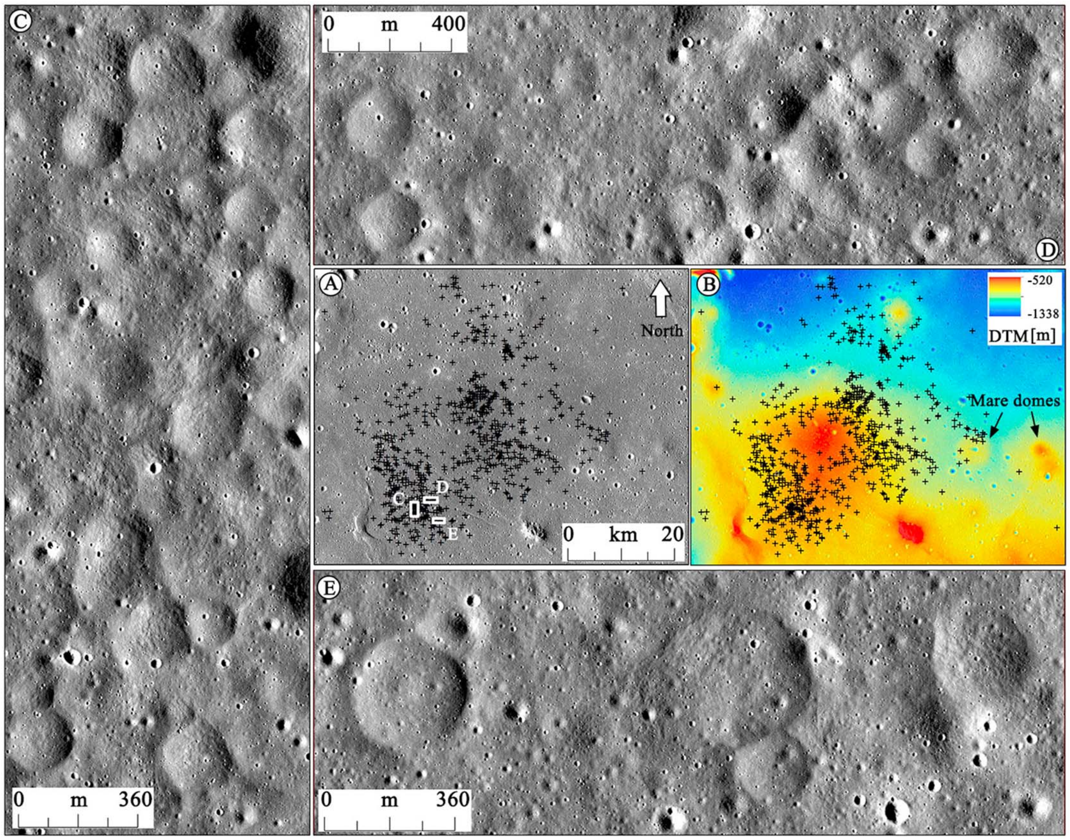

Figure 1. (a) LROC WAC mosaic and (b) Kaguya TC-derived DTM of a ring-moat dome structure (RMDS) terrain (coordinates of the figure center: ~31.4°E, 11.0°N) in Mare Tranquillitatis. (c–e) Enlarged views of RMDSs in LROC NAC mosaic (frames M1096293859LE and RE) and their locations (white boxes) are shown in Figure 1a. The Sun illumination direction in these enlarged views is from left to right. North is up in all images.

created from a LROC NAC pair (Tran et al., 2010). The vertical error for the NAC DTM was derived from the comparison between the Lunar Orbiter Laser Altimeter (LOLA) elevation measurements (Zuber et al., 2010) and the NAC DTM (Tran et al., 2010).

In addition, we derived iron and titanium contents (FeO and TiO_2 wt %) of the surface materials applying established methodologies (Lucey et al., 2000) on ~20 m/pixel SELENE (Kaguya) Multiband Imager data (MI) (Ohtake et al., 2008; Otake, 2012) (Text S2 and Figure S5). A crater count was carried out to derive model ages of surface units using the “standard” CraterStatsII tool within ArcGIS (Kneissl et al., 2011) (Text S3 and Figures S7 and S8).

3. Results

3.1. Distribution and Morphologic Characteristics

We found populations of RMDSs in Maria Tranquillitatis, Fecunditatis, Imbrium, Humorum, Nubium, Australe, Marginis, Oceanus Procellarum, and other locations (Figure 2). These features are not confined within discrete flow surfaces but can occur across several flow unit boundaries. The RMDSs form clusters within which the spatial distribution of individual domes appears random and without preferential alignment in orientation. One of the most prominent and abundant occurrences of RMDSs is near the center of Mare Tranquillitatis (Figures 1 and S1). We use this area as a case study in order to fully characterize the features and subsequent figures, and examples are drawn from this region. Examples of RMDS occurrences in other mare regions can be seen in our supporting information. Based on a series of frames of LRO NAC images, we have so far identified about 2,600 RMDSs in the lunar maria (Figure 2), but this number is likely to rise. We cannot rule out the existence of such features in other maria, including on the lunar farside. A global survey of RMDSs requires

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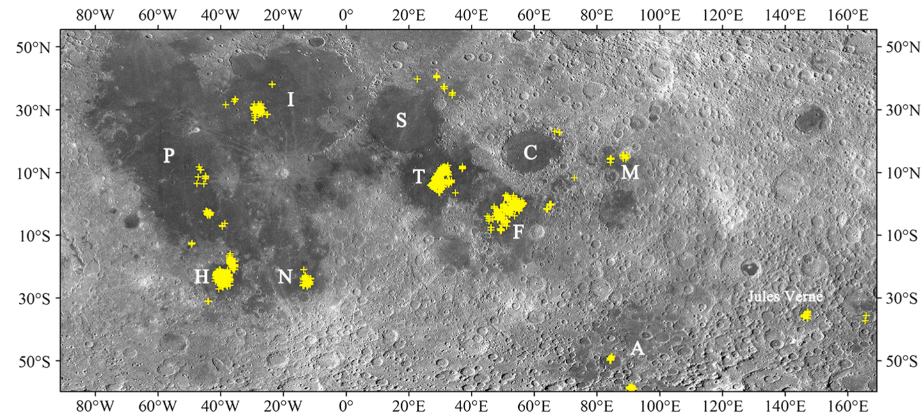

Figure 2. LROC WAC mosaic showing distribution of about 2,600 RMDSs (yellow crosses) identified in the lunar maria. Imbrium (I), Serenitatis (S), Crisium (C), Tranquillitatis (T), Fecunditatis (F), Humorum (H), Nubium (N), Marginis (M), Australe (A), and Oceanus Procellarum (P) are labeled.

high spatial resolution images with low illumination conditions, and the availability of such products has yet to reach global coverage. Nevertheless, we can consider that RMDSs are an important geological feature characterizing lunar maria.

Images of typical RMDSs (Figures 3 and S3) show that the majority of the domes are characterized by a shallow surrounding moat tens of meters wide and a few meters deep. RMDSs often have a slightly asymmetric topographic profile: the elevation of one side is sometimes a few meters higher than the other side (Figure 3b), in a manner similar to mounds associated with the Ina irregular mare patch (Qiao et al., 2017). The surfaces of RMDSs are covered with small craters typically <50 m in diameter similar to those seen on the surface of the adjacent mare plains. Some small craters a few tens of meters in diameter with unusual, crescent shapes occur at the boundary between the domes and the adjacent moats (arrows in Figures 3c and 3d); these craters appear elongated with the long axis tangential to the dome boundary. In some cases, the shapes of the craters appear distorted as if the mound material had been extruded embaying the crater, or slope materials on the previously higher-relief domes partially infilled the much younger impact crater. Indeed, close to the dome boundaries, dome slopes become steeper so that these specific features resemble the much larger Venusian pancake domes (Head et al., 1991; Pavri et al., 1991). Alternatively, these shapes and relationships may be due to different physical properties of the mound and moat material when an impact crater forms at the boundary, and subsequently, steeper slope mound material is mass-wasted downslope, giving the appearance of embayment and distorting the shape of the impact crater.

These RMDSs are essentially devoid of summit depressions. Several examples of relatively large, near-circular, rimless craters (depressions) are superposed on the RMDSs, typically with some offset from the RMDS center (see Figure S4). These features are degraded, and it is difficult to conclude if they are significantly degraded impact craters or collapse pits or possible vent features.

3.2. Evaluation of RMDS Composition

We did not find albedo differences between the RMDSs and the surrounding mare plains (see Figures 1 and S1). We have also carried out an analysis of the mineralogical characteristics of the regional soils within the Mare Tranquillitatis study area based on TiO_2 and FeO wt % estimates (derived from SELENE (Kaguya) Multiband Imager data (20 m/pixel, see Text S2 and Figure S5 in the supporting information)). We found no evidence for variations between the individual RMDS and adjacent maria nor differences between RMDS areas and nearby mare units. In summary, the RMDSs show no spectral (reflectance absorption) anomalies in the region.

3.3. Model Ages of RMDS and Surrounding Maria

Some RMDSs are found adjacent to what appear to be morphologically mature craters (Figures S6b and S6d) or even superpose them (Figures S6a and S6c). This suggests that the RMDSs either postdate or are coeval with these features. In order to assess further the ages of the domes and surrounding mare units, we

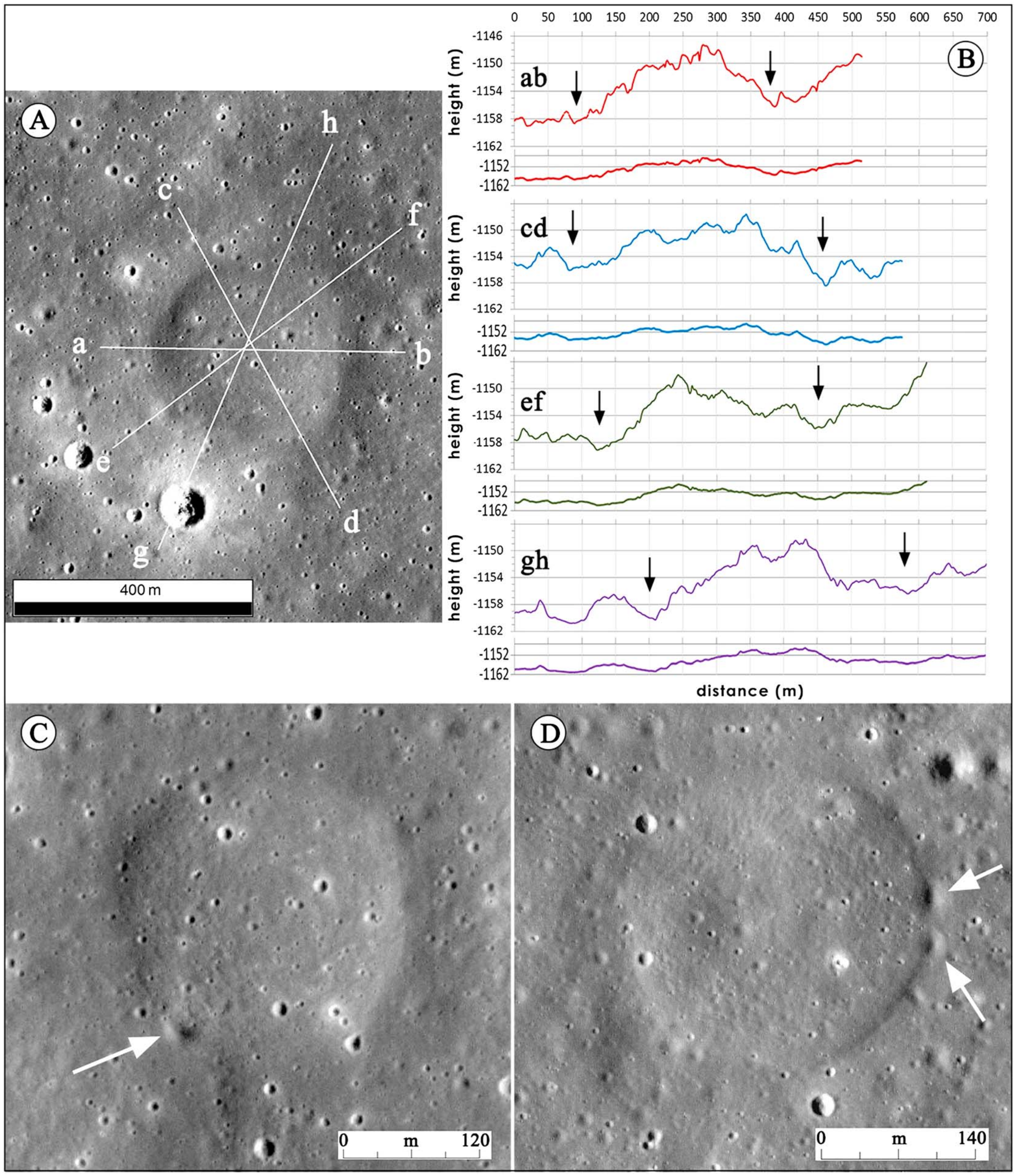

Figure 3. (a) A ~340 m diameter RMDS (10.579°N, 30.689°E) with a maximum height (to the lower point of the moat) of ~11 m (LROC NAC image); (b) NAC-derived (from frames M183325037RE and M1144594365LE) topography profiles of the RMDS along the transects ab, cd, ef, and gh, marked in Figure 3a. The black arrows indicate the location of the moat. To show the detail the top profile in each subfigure is more vertically (~4 times) exaggerated than the bottom one; (c) A ~250 m diameter RMDS (10.137°N, 30.724°E) with a ~20 m diameter crater at the contact between the RMDS and surrounding mare; (d) A ~310 m diameter RMDS (10.885°N, 46.323°W) with two small craters at its eastern edge. North is up in all images.

compiled impact Crater Size-Frequency Distribution (CSFD) data. We counted all craters with diameters >4 m on the mounds and adjacent mare plains in a 60 km^2 area of Mare Tranquillitatis (see Text S3 and Figure S7). Only 12 craters were found ≥300 m and this gave an Absolute Model Age (AMA) of 3.2 + 0.2/−0.7 Ga (Figure S8): this estimate is somewhat younger than other AMAs (region T21, 3.57 Ga, Hiesinger et al., 2000) and sample return radiometric ages (3.6 Ga, BVSP - Basaltic Volcanism Study Project, 1981). However, our sampled area is too small for an accurate estimation of ages of units based on large crater statistics. Therefore, we offer our regional age estimate with caution, although it is still within a plausible age range.

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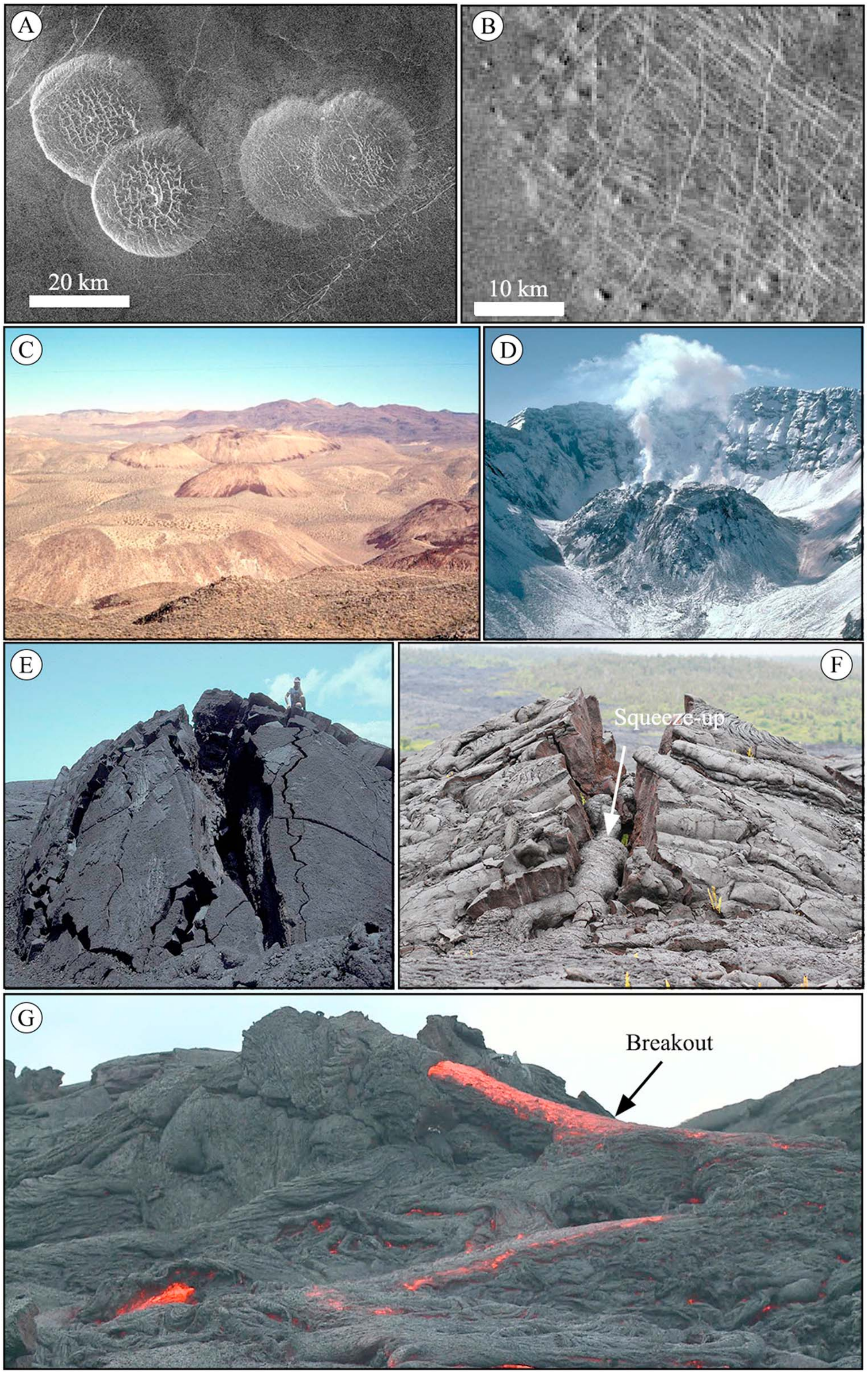

Figure 4. Volcanic features resembling RMDSs. (a) Seoritsu Farra, a group of steep-sided domes located southeast of Alpha Regio (30°S, 12°E), Venus, Magellan SAR image; (b) small volcanic shields of Aino Planitia (50°S, 74°E), Venus, Magellan SAR image; (c) rhyolitic lava domes (length of long axis: ~100–2,000 m) (Global Volcanism Program, 2013) of the Coso volcanic field east of the Sierra Nevada Range (36.03°N, 117.82°W), California, USA; (d) rhyolite dome in summit crater of Mount St. Helens volcano, USA, 1984 USGS photo; (e–g) tumuli located in Hawaiian lava fields: Figure 4e displays fractures and/or cracks on the top of a tumulus, https://tinyurl.Com/y9cs73z2; Figure 4f exhibits a tumulus (mound) of pahoehoe lava in the Kalapana area of Hawaii, USA, https://tinyurl.Com/y9buyjy8; Figure 4g shows a slow tumulus breakout, representing a small extrusion of lava from beneath the lava flow crust, Courtesy of the County of Hawaii, https://tinyurl.Com/y7gxzwu8.

Nonetheless, the aim of this crater survey was to investigate possible variation in CSFD within and outside the RMDS. Logically, given that we are surveying circular features (RMDSs) of about 200 m in diameter, the largest crater sizes within the RMDS cannot be larger than this value. Therefore, we chose the size range 9–50 m (bins 10–50 m) to carry out AMA fitting and comparisons. The data show AMAs of 25 ± 2 Ma for the RMDs ("RMDS_IN," as in Figure S8) and 36 ± 0.5 Ma for the adjacent mare ("RMDS_OUT"), a variance of around 33% based on crater densities (N(1)). This difference could be due to a number of physical factors related to the target's physical properties, such as porosity, thickness of the regolith, angle of slope, etc., affecting the rate of degradation (Fassett & Thomson, 2014), in addition to a straightforward difference in age of exposure.

4. Origin and Formation Timing of RMDS

Characteristics of RMDSs that require explanation are the (1) generally circular shape and dome-like morphology, (2) surrounding moat, (3) relatively small diameter and height compared with other lunar and planetary volcanic features, (4) concentration in clusters, (5) association with the lunar maria, (6) occurrence in only some lunar maria, (7) compositional similarity to surrounding lunar maria, (8) apparent embayment of domes into young-appearing craters in adjacent moats, (9) apparent very young CSFD age of the domes (~25 Ma) compared with the ancient age of the surrounding maria (~3.2 Ga), and (10) similarity of the mounds in morphology and distribution to the mounds in irregular mare patches (IMPs) (Braden et al., 2014; Qiao et al., 2017).

4.1. Candidate Hypotheses for the Origin of RMDS

We outline four candidate hypotheses for the origin of RMDS: (1) Domes composed of material of a different, more viscous composition and emplaced in the period following mare basalt emplacement; (2) geologically very recent small eruptions occurring several billion years after the emplacement of the mare lava flows; (3) small squeeze-ups or hornito-like features formed at the time of the original flow emplacement; (4) development of magmatic foams below a cooling lava flow surface and extrusion of these to form the mounds and moats as the flow evolved.

RMDSs show morphologic similarity to some domes on Mars (Komatsu et al., 2007), Ganymede and Callisto (Moore & Malin, 1988; Patterson et al., 2010; Schenk, 1993; Schenk & Moore, 1995) (see Text S4 and Figure S9), but these examples are typically much larger and formed in ice or involve liquid water, highly unlikely to be the case for the origin of lunar features. The dome-shaped morphology of RMDS and their association with basaltic flows of the lunar maria suggest that they are volcanic landforms (Head & Wilson, 2017). Certain volcanic dome-like features on Venus and Earth (Figures 4a–4d) resemble RMDSs in their broad morphology, but their scale and steepness of their slopes are both much greater than those of the RMDSs. For example, some RMDSs look morphologically very similar to Venusian steep-sided domes (Pavri et al., 1992) (Figure 4a) but the Venus features are tens of kilometers in diameter, significantly larger than RMDSs (hundreds of meters). RMDSs form clusters resembling those of Venusian small shield edifices (Figure 4b) (geologic units psh and sc (Ivanov & Head, 2011)), but these Venusian features are not typically steep sided and are significantly larger than RMDSs. The sometimes steep-sided character of RMDSs somewhat resembles terrestrial rhyolitic domes (Figures 4c and 4d), suggesting that the dome materials may be more viscous than surrounding basaltic lavas, but the estimated RMDSs' basaltic composition argues against a more silicic mound composition. Thus, for the formation of RMDS, the first hypothesis (domes with more viscous composition) is not likely.

The very close association of the RMDSs with the surrounding lunar maria, and their similar composition, strongly suggests a genetic relationship. This suggests that the second hypothesis of very recent small eruptions for the RMDS's formation is also rather unlikely, and this interpretation can be excluded. We explore options for this association and the production of positive features in the mare basaltic lavas. Terrestrial lava flows are known to produce positive features of the scale of RMDS in two ways: (1) as tumuli (cooled pahoehoe lava flow crusts deformed into elliptical domed structures about 2–10 m high caused by inflated lava flow (Text S5) deformation or subsidence (Hon et al., 1994; Self et al., 1998; Walker, 1991)) and (2) rootless eruptions (squeeze-ups, formed when lava below the cooling crust becomes cooler and more viscous and extrudes locally onto the deforming chilled layer as bulbous mounds (Nichols, 1939, 1946) (Figure 5a); and hornitos, rootless cones formed of spatter of still-molten lava emerging through local cracks in the deforming lava crust). There are similarities between RMDSs and terrestrial tumuli (Figures 4e–4g), but tumuli are

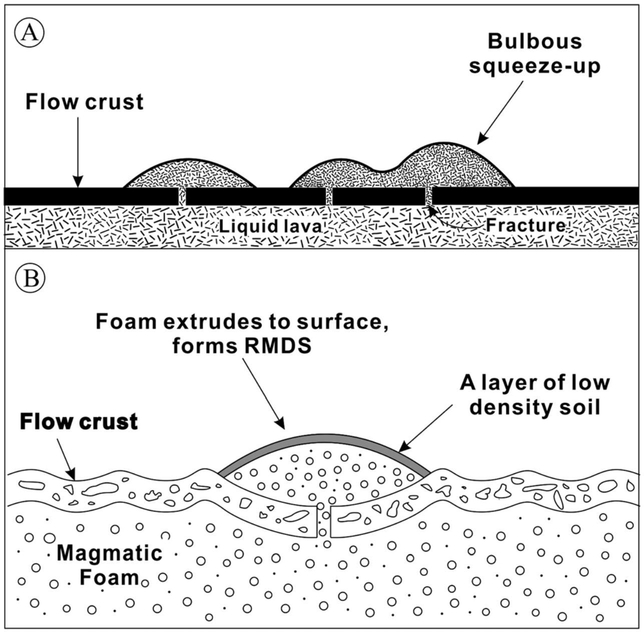

Figure 5. Formation of squeeze-ups and foam mounds in lava flow fields. (a) Formation of bulbous squeeze-ups in inflated lava flow field; (b) formation of RMDS on the mare lava flows due to extrusions of magmatic foams.

typically somewhat smaller (a few meters to tens of meters in diameter (Walker, 1991)), are generally elongate and not circular, do not display surrounding moats, and as a rule show prominent fractures on their tops (Figure 4e) (Anderson et al., 2012). Rootless terrestrial eruptions (squeeze-ups and hornitos) are typically much smaller and lower relief and do not display moats. Rootless cones originate from explosive lava-water interactions (Fagents & Thordarson, 2007; Hamilton et al., 2010a, 2010b). This mechanism is more difficult to envisage on the Moon given the absence of liquid water. In addition, rootless cones often have central pits, which are not common with RMDSs.

Another option that might explain the close association of RMDSs and the basaltic maria is related to the distinctiveness of lunar mare basalt eruptions under conditions of low gravity and negligible atmospheric pressure, compared with those on Earth (Head & Wilson, 2017; Wilson & Head, 2017a). Analysis of the waning stage of the eruption of lunar basaltic magma (Wilson & Head, 2017b) (Figure S10) shows that as the rise rate of the ascending magma slows to zero, volatiles produced in the dike form a very vesicular foam. As the dike begins to close at depth, it extrudes this foam-rich magma out onto the surface. Stresses in the cooling lava flow crust produce fractures through which the foam extrudes at a rate determined by its non-Newtonian rheology. Waning-stage extrusion of viscous magmatic foams to the surface are shown to produce convex mounds similar to the mounds seen in irregular mare patches in Ina (Qiao et al., 2017). This mechanism for the production and extrusion of very vesicular magmatic foams (Figures 5b and S10) could thus be applicable to waning-stage dike closure associated with fissure eruptions in the lunar maria, such as the RMDSs. We conclude that the extrusion of magmatic foams is the most likely origin of RMDS.

4.2. Further Discussion on the Foam Mound Formation Hypothesis

In this interpretation, RMDSs could be formed as a result of numerous areally disseminated eruptions of small volumes of viscous foams from beneath chilled crust to produce the often steep-sided domes (Figure 5b). The widespread occurrence of RMDSs (dome fields several tens of kilometers across) suggests that they are associated with areally extensive lava flows typical of those on the Moon (Figure S10). Thus, in this interpretation, basaltic lava erupts to the surface, forms a cooling boundary layer and then basaltic foams erupt from beneath the chilled lava crust and extrude to the surface in many spots. Evacuation of the foam from beneath the crust, aided by the load of the RMDS on the lava flow crust, is interpreted to be a factor in the formation of the ring-like moats surrounding the domes, a condition similar to the presence of moats adjacent to Ina mounds (Garry et al., 2012; Qiao et al., 2017).

In this scenario, the formation of RMDSs is part of the mare-forming lava volcanism and thus their age should be the same as the age of the adjacent mare plains (Figure S10). We estimated the age of the adjacent mare plains from crater counts in the Tranquillitatis study area using the large (>300 m) impact crater size-frequency distribution; this yielded an age of ~3.2 + 0.2/−0.7 Ga (see Figure S8), similar to other mare ages in this region (Hiesinger et al., 2011). When we considered only small craters, our counts led to an estimated age of 36 ± 0.5 Ma for the mare plains and 25 ± 2 Ma for the RMDS mounds. These similar ages for small craters on the mounds and in the adjacent mare strongly suggests that the young ages for the mounds are due to their very small areal coverage and their deficiency in larger craters, thus biasing their age to very young values.

In some cases the margins of the mounds appear to have partially covered (or crept into) small craters (as small as ~20 m) in the adjacent moats (Figures 3c and 3d), thus suggesting a relatively young age of formation (even Copernican) (Gault, 1970; Stöffler & Ryder, 2001; Trask, 1971). However, this interpretation is in conflict with the genetic relationship between RMDSs and the surrounding lava flows, based on current modeled ages of mare emplacement (in the order of billions of years against the millions for the RMDSs) (Hiesinger et al., 2011).

There are abundant examples of similarly "embayed" craters of this size at sharp contacts between mare surfaces and steep highland slopes. This observation probably results from the nonlinearly intensive creep of regolith and/or rocks on steep slopes (Highland & Bobrowsky, 2008; Lindsay, 1976; Melosh, 2011; Xiao et al., 2013), which can mimic embayment. Creep can be considered a type of gravity-controlled slow flow process (Melosh, 2011) caused by continuous downslope movement of regolith (Lindsay, 1976). Examples of this type of morphology (regolith creep) can be found at almost all lunar surfaces (Melosh, 2011; Xiao et al., 2013). Regolith creep, perhaps aided by differences in the physical properties of the mound and substrate, might help to explain the apparent embayment adjacent to some RMDSs such as those shown in Figures 3c and 3d.

5. Summary and Conclusions

Analysis of LRO NAC images has led to the discovery of a new type of surface feature in the lunar maria: relatively small domes that are interpreted to be of volcanic origin. They are typically tens to hundreds of meters in diameter and a few meters to ~20 m high and have ring-like moats encircling them. We thus designate them "ring-moat dome structures" (RMDSs). We interpret their formation as a final stage of typical basaltic lava mare-forming eruptions (Figure S10) and thus their age to be old, consistent with the surrounding mare basalt ages (~3.2 Ga). In the pre-LROC-NAC era, RMDSs were overlooked because of their relatively small sizes and generally gentle-sloping morphology. LRO NAC images show that the surface albedo of RMDSs are essentially the same as those of the adjacent mare plains, and the spatial distribution of the TiO_2 and FeO contents (Kaguya Multiband Imager) are not influenced by their presence/absence and thus RMDSs seem to be similar in composition to the adjacent mare lavas.

RMDSs are sometimes relatively steep sloped ($<5°$), resembling somewhat steep-sided viscous domes on Earth and Venus, but the viscosity could be due to the foamy character of the melt (Wilson & Head, 2017b). We conclude that in the process of the mare-forming emplacement of basaltic lavas, a chilled crust was formed, and its flexure and cracking led to eruption of the subcrustal foam onto the surface forming RMDSs and the surrounding moats.

The process of the RMDS formation appears to be a common product of late-stage lunar mare lava extrusions. The melt composing these domes is likely to be composed of relatively viscous basaltic foams. The domes, as well as the adjacent lava plains, were formed more than 3 Ga ago, and the very young (25–36 Ma) apparent ages of the domes and plains deduced from the small crater counts are the result of the small sampling area that underrepresents large craters and the unusual nature of impacts into foamy materials that cause smaller and deeper craters (Wilson & Head, 2017b).

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