MARE INFILLING OF TSIOLKOVSKY CRATER, THE MOON

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Introduction: The 180-km diameter Tsiolkovsky crater (20ºS, 129ºE) displays several features which are unique on the lunar farside, including the best example of farside mare volcanism [1] and the enigmatic landslide deposit on the NW rim. Despite analysis of data collected during the Apollo 15 mission [2 – 6], the details by which these mare materials were emplaced remain poorly constrained. Here we utilize topographic and image data from the Lunar Reconnaissance Orbiter (LRO) and Kaguya missions to explore characteristics of the crater's eruptive history, with the ultimate goal of better understanding vent distribution, the size of individual eruptions, and the possible time period over which these lavas were erupted.

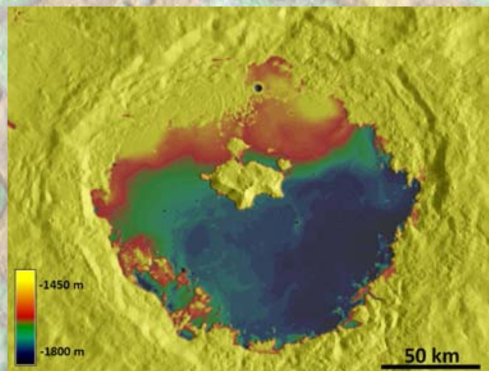
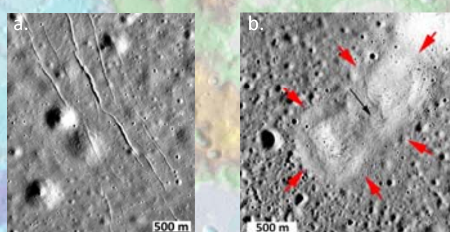


Figure 1: LOLA gridded-topography of Tsiolkovsky crater, illustrating more than 450 m of elevation difference across the mare unit within the crater.

Topography from Lunar Orbiter Laser Altimeter (LOLA) data (Fig. 1) shows that there is >450 m elevation difference between the northern and southern portions of the crater floor. This observation favors the situation where multiple eruptions took place, almost all of which failed to resurface the entire floor. Because the floor is highest on the north-eastern floor, we conclude that the mare-filling eruptions had vents on this part of the floor, and were most likely volume-limited so that each eruption only covered part of the crater floor. Even if the pre-mare floor were tilted towards the SE, flows must have originated from the highest point of the current floor, namely the NE floor.

Mare Morphology: LRO Camera (LROC) Narrow Angle Camera (NAC) images reveal graben and ridges around the perimeter of the mare infill (Fig. 2a), as well as depressions (Fig. 2b) which provide clues to the mare lava emplacement. The fractures may be representative of local subsidence within the mare units, comparable to the extension of the floor of Mare Serenitatis [7], although no mare ridges can be found to indicate compression. The depressions may indicate that the mare flows were produced by low effusion-rate eruptions with associated post-emplacement flow inflation. Comparable "lava pits" are features of low-effusion rate eruptions in Hawaii [8, 9] where inflation occurs in most of the flow but certain areas (the pits) stay at base level.



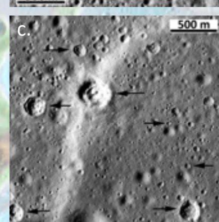


Fig. 2: (a) Multiple circumferential graben exist around the SW perimeter of the mare, as well as elsewhere on the floor. LROC NAC image M130822373R. (b) Example of a partially in-filled depression (outlined by red arrows) with a possible flow (black arrow points down centerline of flow) cutting this depression into two. LROC NAC image M1126825591R. (c) Numerous concentric craters (black arrows) on the mare, indicating that there are numerous layers within the floor units. LROC NAC image M103668324L.

For Hawaiian eruptions where there are perched lava ponds (e.g., the 1959 Mauna Iki eruption [10]), there is typically drain-back into the vents which result in a change in volume of the lava pond; this drain-back results in benches or "bath-tub-rings" around the perimeter of the pond. We find no evidence for these features around the perimeter of the mare to confirm (or refute) changes in mare level at a time when it was still molten, although individual mounds within the floor show benches around their perimeter. A possible interpretation for the Tsiolkovsky eruptions is that numerous flows spread sufficiently far from the vents (or downslope from the vents) that only a small volume of lava could flow back into the vent system. We also find multiple examples of concentric craters (Fig. 2c) which suggest that the mare is layered at a vertical scale of a few tens of meters.

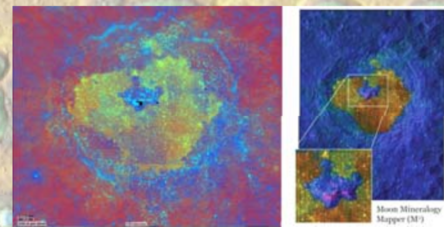


Fig. 3: Left: Clementine multispectral image of the mare within Tsiolkovsky (red = 750 nm/415 nm, green = 750 nm/950 nm; blue = 414 nm/750 nm). Although there appears to be some color variations within these deposits, the majority of the differences correspond the scene boundaries, indicating that there are subtle calibration issues here. Right: M3 data from Cheek and Pieters [11]. Images depict highlands (blue), mare (yellow/orange) and anorthosite (pink). Again, some color variations in the mare are apparent, but there is no strong correlation with those boundaries seen in the Clementine data and so their implications for true compositional variations of the mare units is questionable.

Composition: Clementine multispectral images, and compositional data from the M3 experiment on the Chandrayaan-1 mission, show possible differences in the units on the crater floor (Fig. 3). In each instance, however, there are image seams which appear to mimic different unit boundaries. Furthermore there are no flow lobes of boundaries of the floor which might be indicators of individual lava flows. Thus we are not confident that we can say that there are any compositional differences on the floor of Tsiolkovsky crater.

Deformation of Floor: Kaguya topographic data reveal numerous attributes of the crater floor. For instance, we have found tilted blocks with >100 m of relief and up-doming of the order of ~50 m of the mare floor (Fig. 4). Oblique views of the floor reveal the extent of this deformation, as well as high-stands around topographic highs. The inferred vent area for the mare flows also exhibits almost 400 m of elevation (Fig. 5). Apparent from the vent area topography are three fractures radial to the central portion of the topographic high on the mare floor, suggesting that up-doming perhaps due to late-stage intrusions took place.

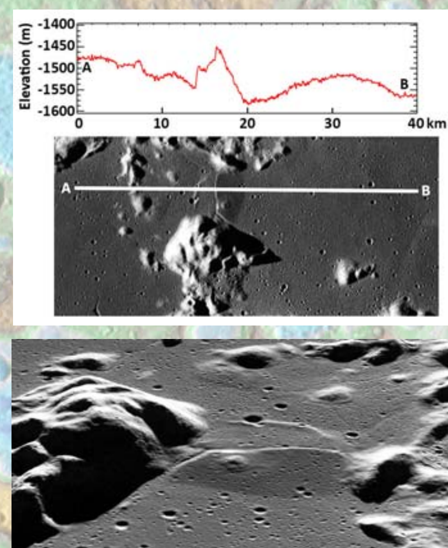


Fig. 4: Kaguya data for part of the mare just north of the central peak. (Top) West-East topographic profile ("A" to "B", middle shows location) across mare units which include a tilted block and up-domed mare. The block has ~100 m of relief and has a cleft at its crest. (Middle) Location image for profile in "a". (Bottom) Oblique view (looking west) generated from Kaguya data of area shown in middle image, with clear evidence for tilting and subsidence of the mare. Kaguya image and DEM frame number DTMCOs01_03403S192E1287SC.

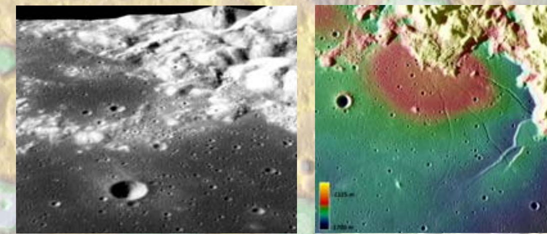
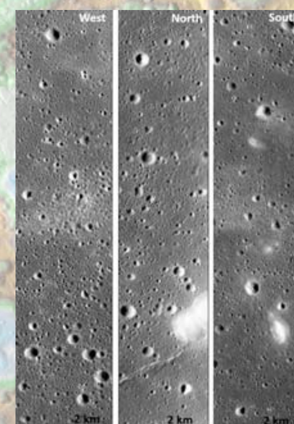
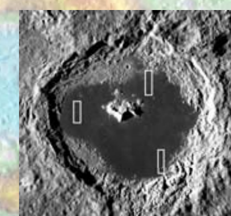


Fig. 5: Left: Oblique view looking across the topographically highest part of the mare floor, where we infer that the vents were located. The high point is at lower right of this image. Note that no collapse features or constructional features suggestive of vents, or lobate boundaries indicative of lava flows, can be identified. Image produced from Kaguya image and DEM frame DTMCOw01_05917S187E1295SC. Right: Topography of inferred vent area, from Kaguya DEM frame DTMTCOs01_03402S1298SC. Note that there is ~375 m difference in elevation from the center of the dome to the flows at lower right.

Chronology: The topographic evidence for multiple lava flows within Tsiolkovsky crater raises the possibility that the eruptions took place over an extended period of time [5, 6]. LROC NAC images allow detailed crater counts to be made for representative parts of the crater floor. However, crater counts for three representative areas of the crater (Fig. 6) reveal that there is little age difference between different parts of the floor, and that these ages cluster around 3.6 Ga. Most likely, the magma source for the Tsiolkovsky flows was molten only once, and that there was no rejuvenation of this magma chamber following the first series of eruptions. We note that these counts also suggest that the mare lavas were erupted soon after the formation of the crater and the collapse which produced the NW landslide on the crater rim.





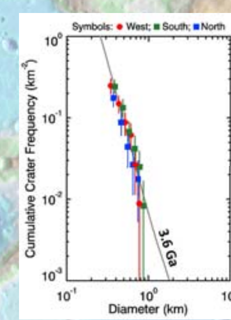


Fig. 6: Crater counts for the floor of Tsiolkovsky crater. NAC images for the areas to the west (NAC image M192123826R), north (NAC image M1107432386R) and south (NAC image M103661219R) of the mare fill. See image at top right for locations. Each area is 100 km² in size. Lower right, cumulative size/frequency curves for these three areas. Note that each area has an approximate age of 3.6 Ga.

Conclusions: LOLA and Kaguya topographic data reveal ~450 m of relief across the crater floor which suggests multiple eruptions produced the mare. From these data, we infer that the vents were most likely located in NE portion of crater floor (Fig. 5), and that the volume of each eruption was typically too small to cover most of the floor. Depressions (Fig. 2b), similar to terrestrial lava pits, suggest that the emplacement of the mare was relatively protracted and that at least some of the flows are inflated flows. However, to date we have found no lava flow fronts or constructional features to confirm this interpretation. Our crater counts (Fig. 6) suggest that these eruptions took place close in time to each other, and followed soon after the formation of the crater. This similarity in surface age has implications for the longevity of the magma chamber which fed the flows; most likely the chamber was molten only once, rather than rejuvenated several times. High stands (benches around topographic highs) indicate that subsidence of the flows on the northern floor took place (Fig. 4), and local uplift produced tilted blocks north of the central peak. To date, we have not found morphologic evidence for filling and subsequent deflation of the lowest parts (i.e., the southern) of the floor.

References: [1] Guest, J. E. and J. B. Murray (1969). *Planet. Space Sci.* 17, 121 – 141. [2] Schultz, P. H. (1976). *Moon Morphology*, Univ. Texas Press, 626 pp. [3] Guest, J. (1971). In: *Geol. and Physics of the Moon*, G. Fielder (Ed.), pp. 93 – 103. [4] El-Baz, F. and A. M. Worden (1972). In: NASA SP-289, pp. 25-122. [5] Tyrie, A. (1988). *Earth, Moon and Planets* 42, 245 – 264. [6] Tyrie, A. (1988). *Earth, Moon and Planets* 42, 265 – 275. [7] Solomon, S. C. and J. W. Head (1979). *J. Geophys. Res.* 84, 1667 – 1682. [8] Walker, G. P. L. (1991). *Bull. Volcanol.* 53, 546 – 558. [9] Hon, K. *et al*. (1994). *Geol. Soc. Amer. Bull.* 106, 351 – 370. [10] Eaton, J. P. *et al*. (1987). In: Volcanism in Hawaii. *US Geol. Surv. Prof. Paper* 1350, 1307 – 1334. [11] Cheek, L. C. and C. M. Pieters (2012). *43rd LPSC* abstract #2624.