MARE VOLCANIC DEPOSITS IN THE ORIENTALE BASIN: DISTRIBUTION AND THICKNESSES FROM CHANDRAYAAN-1 MOON MINERALOGY MAPPER (M3) DATA.

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Introduction and Background: An important question in assessing the relationship between impact basin formation and mare volcanism [1-2] is the distribution and volumetric significance of mare deposits in the central part of the basin following the impact event [3]. The ~920 km diameter Orientale basin, the youngest and most well preserved multi-ringed basin on the Moon, displays a remarkably fresh and very sparsely flooded basin interior [4-7] and thus is an important laboratory for studying this relationship. In this analysis we use a mosaic of images and spectra from the Moon Mineralogy Mapper (M3) experiment flown onboard Chandrayaan-1 [8] to define and characterize the distribution and thickness of mare basalts in the basin interior, building on numerous previous studies of volcanism in the Orientale region.

Estimating Mare Orientale Deposit Thicknesses: Mare Orientale, occurring in the central part of the basin, covers ~47,000 km^2 and was estimated on the basis of Lunar Orbiter data to be less than ~1 km thick [4] and perhaps up to several km in some areas [9]. M3 image and spectral data provide information to assess and refine these earlier estimates.

The Maunder Formation: The Basement of Mare Orientale: The Maunder Formation [6], consisting of a rough/corrugated facies and a smooth/fractured plains facies, comprises the major unit lying inside the Outer Rook Mountain ring; the Maunder has been interpreted as an impact melt deposit that lined the cavity; the corrugated facies is interpreted to be melt mixed with breccia material, while the plains facies is interpreted to consist of more pure impact melt [4,7]. Analysis of Earth-based [11-12], Galileo [7,10], Clementine [9] and M3 [13] data show that the Maunder Formation is related to Orientale impact basin deposits, and spectrally very distinctive from the later mare deposits [14]; this contrast provides strong evidence for the configuration of sub-Mare Orientale topography (the mare basement). Here we use M3 data to assess the configuration and depth of this Maunder basement surface.

The Maunder Formation dominates the plateau outside the inner depression and the walls of the inner depression; it can also be seen within the inner depression in the basin center as an irregularly-shaped, 30 x 50 km hummocky rise (Fig. 1, 2) that has clearly been embayed by mare basalts. The presence of this central rise led [4] to hypothesize that the Mare Orientale basalt deposits were relatively thin (<1 km), but detailed measurements were not made. M3 data also show other exposures of the Maunder Formation in the basin interior, most prominently an isthmus extending about 40 km into the basin interior in a N30ºW direction (Fig. 3). Beyond and parallel to this isthmus lie a series of elongate islands of Maunder Formation that have been variously embayed and flooded by mare basalts (Fig. 4). Together (Figs. 2-4) these outcrops provide evidence for the widespread presence of surface exposures of the Maunder Formation and suggest that between these outcrops, the Maunder Formation underlies the mare at relatively shallow depths. M3 spectra show that these Maunder occurrences are characterized by feldspathic breccias, typical of the Maunder elsewhere [13].

Impact Craters and Mare Orientale Thicknesses: Impact craters also provide information about the thickness and geometry of the mare fill in the basin interior.

Hohmann Crater: In the north-central part of Mare Orientale (Fig. 5), the rim crest of the 16 km diameter Hohmann crater is characterized by feldspathic breccias, but its interior and rim have been flooded by mare basalts. Taking the depth of sampling to be 1/10 the crater diameter, this implies that the rim sampled 1.6 km deep into Orientale basin deposits, and that the crater most likely formed before mare flooding; if so, then it provides a template for assessing subsequent flooding. Fresh craters of this size are characterized by a rim crest height of several hundred meters [15]. Since the rim crest is still well-preserved and the exterior inner rim is only partly flooded with basalts (Fig. 5), the thickness of the mare basalt is likely to be less than a few hundred meters.

Maunder Crater: The 55 km diameter crater Maunder is much younger and fresher and impacts into both the Maunder Formation and the overlying mare basalts (Fig. 6). Bussey and Spudis [9] interpreted the color anomalies in the Clementine data inside Maunder to mean that Maunder had excavated only mare basalt and had not penetrated down to underlying Orientale deposits; given the size of Maunder, they interpreted this to mean that the mare basalts could be as deep as the depth of sampling of Maunder, 3-4 km. M3 image data clearly show the superposition of Maunder ejecta on much of northern Mare Orientale, and subsequent impact dark-halo craters excavating underling mare material (Fig. 6). M3 spectra also show that excavated mare materials are exposed in the southwest Maunder rim deposits where the Mare Orientale basalts flooded the higher Maunder Formatoin topography prior to the Maunder impact. The Maunder central peaks and interior, however, are dominated by noritic signatures, interpreted to represent deeper crustal material excavated from lower crustal depths below the Orientale basin deposits (Fig. 6). Thus, M3 data show that Maunder crater itself does not place constraints on the depth of mare fill in the basin interior.

Il'in Crater: The 13 km diameter post-mare crater Il'in (Fig. 7) is superposed on the major north-south striking wrinkle-ridge and arch complex that extends through western Mare Orientale (Fig. 1). M3 data show that the interior of Il'in (walls and floor) are dominated by mare basalt signatures and that the pre-mare substrate of the Hevelius Formation is apparently not exposed. To a first order, these relationships could suggest that mare basalts below Il'in might be at least 1.3 km thick. Caution should be exercised, however, due to the fact that: 1) Il'in lies directly on a deformed mare arch, and thus the basaltic strata may be duplicated and thickened by shortening, folding and faulting; 2) mare basalts from the upper crater walls could mass-waste to the lower crater walls and floor, obscuring deeper signatures; and 3) two nearby exposures of Hevelius Formaton basement (about 10 km to the east and about 20 km to the west) suggest that the Hevelius basement lies relatively close to the surface.

Conclusions: The M3 data permit mapping of the distribution of Maunder Formation kipukas (islands) in the basin interior (Fig. 1), and show that the basement of Maunder lying below Mare Orientale is likely to be within a few hundred meters of the surface over most of the interior. The spectral characteristics of post-Orientale basin impact craters provide probes into the subsurface and templates for flooding thickness to assess the depth to basement and thickness of mare lavas. In contrast to earlier estimates of Mare Orientale basalt thicknesses of as much as 1-4 km, the M3 data suggest that thicknesses are less than a km and may average only several hundred meters over a significant part of Mare Orientale.

References: 1. L. Elkins-Tanton et al., EPSL 222, 17, 2004; 2. A. Ghods & J. Arkani-Hamed, JGR E03005, 2007; 3. A. Yingst & J. Head, JGR 102, 10909, 1997; 4. J. Head, Moon 11, 327, 1974; 5. K. Howard et al., RGSP 12, 309, 1974; 6. J. McCauley, PEPI 15, 220, 1977; 7. J. Head et al., JGR 98, 17149, 1993; 8. C. Pieters et al., Current Science 96, 500, 2009; 9. B. Bussey & P. Spudis, GRL 24, 445, 1997; 10. C. Pieters et al, JGR98, 17127, 1993; 11. P. Spudis et al., JGR 89, C197,1984; 12. B. Hawke et al., GRL 18, 2141, 1991; 13. C. Pieters et al., LPSC 40, 2052, 2157, 2009; 14. R. Greeley et al., JGR 98, 78183, 1993; 15. R. Pike, USGS PP-1046C, 77 p., 1980.

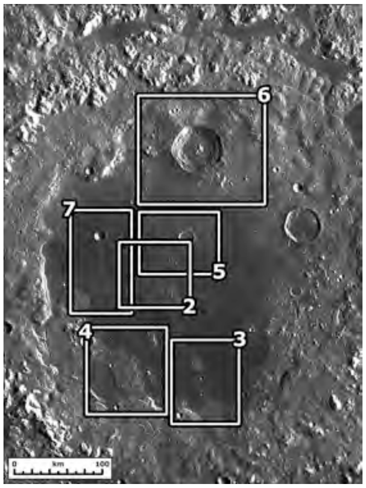

Fig. 1. Central Mare Orientale with locations of Figs. 2-7 shown; all images are from an M3 0.2.9 µm mosaic.

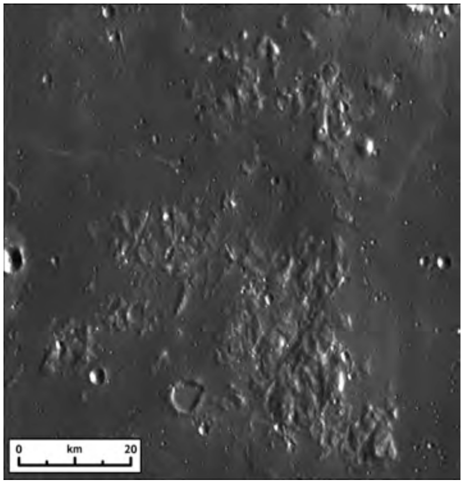

Fig. 2. Maunder Formation exposures in central Mare Orientale.

Fig. 3. Peninsula/archipeligo of Maunder exposures in Mare Orientale.

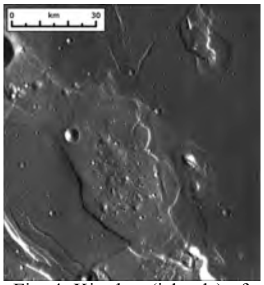

Fig. 4. Kipukas (islands) of Maunder at the edge and within Mare Orientale.

Fig. 5. Crater Hohmann (16 km), Maunder exposures, and embaying mare deposits.

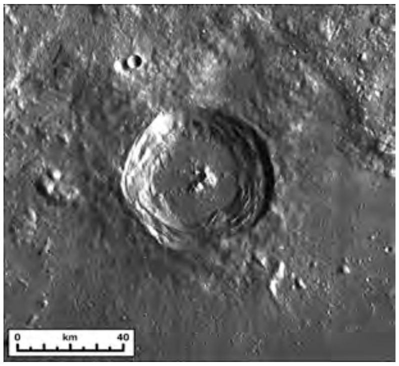

Fig. 6. Maunder crater (55 km diameter) impacted on the Maunder Formation (high topography) and embaying mare from the southwest. Central peaks are noritic, not basaltic as previously thought [9].

Fig. 7. Il'in crater (13 km diameter) is superposed on a mare ridge-arch, and Maunder Formation is exposed on the arch to the south and in nearby kipukas to the northwest and northeast.