MORPHOLOGY AND DISTRIBUTION OF VOLCANIC VENTS IN THE ORIENTALE BASIN FROM CHANDRAYAAN-1 MOON MINERALOGY MAPPER (M3) DATA. J. Head[1], C. Pieters[1], M. Staid[2], J. Mustard[1], L. Taylor[3], T. McCord[4], P. Isaacson[1], R. Klima[1], N. Petro[5], R. Clark[6], J. Nettles[1], J. Whitten[1] and the M3 Team. [1]Brown Univ., Providence RI 02912; [2]PSI, Tucson AZ; [3]Univ. Tenn., Knoxville TN 37996; [4]BFC, Winthrop, WA; [5]NASA GSFC, Greenbelt, MD 20771; [6]USGS, Denver CO 80227 (james_head@brown.edu).

Introduction and Background: One of the most fundamental questions in the geological and thermal evolution of the Moon is the nature and history of mantle melting and its relationship to the formation and evolution of lunar multi-ringed basins. Mare volcanic deposits provide evidence for the nature, magnitude and composition of mantle melting as a function of space and time [1]. Many argue that mantle partial melts are derived from depths well below the influence of multi-ringed basin impact events [1], while others postulate that the formation of these basins can cause mantle perturbations that are more directly linked to the generation ascent and eruption of mare basalts [2,3]. In any case, longer-term basin evolution will considerably influence the state and orientation of stress in the lithosphere, and the location of mare volcanic vents in basins as a function of time [4]. Thus, the location, nature and ages of volcanic vents and deposits in relation to multi-ringed impact basins provides evidence for the role that these basins played in the generation of volcanism or in the influence of the basins on surface volcanic eruption and deposit concentration.

Unfortunately, most lunar multi-ringed impact basins have been eroded by impacts or filled with lunar mare deposits [5-8], with estimates of the thickness of mare fill extending up to more than six km in the central part of some basins [9-11]. The interior of most basins (e.g., Crisium, Serenitatis, Imbrium, Humorum) are almost completely covered and obscured. Although much is known about the lava filling of multi-ringed basins, and particularly the most recent deposits [5-8], little is known about initial stages of mare volcanism and its relationship to the impact event. One multi-ringed basin, Orientale, offers substantial clues to the relationships of basin interiors and mare basalt volcanism.

The Orientale basin (~920 km in diameter), the youngest and most well preserved multi-ringed basin on the Moon, displays remarkably fresh examples of the multiple rings that are the hallmark of these types of structures [12-14]. The Cordillera Mountain ring (CR), an inward facing mountain scarp ~920 km in diameter, defines the basin itself. The next inward ring, the Outer Rook Mountain ring (OR), is characterized by a ring of major interconnected massifs ~620 km in diameter. The next innermost ring, the Inner Rook Mountain ring (IR) ~480 km in diameter, consists of isolated mountain peaks that resemble central peaks and central peak rings in smaller craters and basins. Interior to the IR ring is a central depression approximately 320 km in diameter. Also well-exposed and preserved at Orientale are basin radial ejecta deposits (the Hevelius Formation) and a full range of deposits within the basin interior, including the Montes Rook Formation (MRF), lying between the CR and the OR, and the Maunder Formation, lying within the OR and divided into two facies, an outer corrugated facies occurring mostly between the OR and the edge of the inner depression, and the smooth or plains facies, lying predominantly within the inner depression. All of these rings and units have been interpreted to have formed as part of the Orientale basin event, with the Hevelius and Montes Rook Formation interpreted as variants of basin ejecta, and the Maunder Formation commonly interpreted as impact melt [12-15].

Together, these ring structures and impact basin-related deposits provide a background template on which to analyze and assess: 1) the location, nature, characteristics and distribution of volcanic vents, 2) the volumes and mineralogic characteristics and affinities of the volcanic deposits, 3) the temporal relationships of the deposits with the age of the impact basin itself, and, finally, and 4) the relationship of mare basalt volcanism to the formation and evolution of impact basins. In this study we focus on the first area of analysis, the location, nature, characteristics and distribution of volcanic vents. We use a mosaic of images at 2.9 µm (reflected light and thermal emission) from the Moon Mineralogy Mapper (M3) experiment flown onboard Chandrayaan-1 [16] to define and characterize the array of volcanic vents and their settings, building on numerous previous studies of volcanism in the Orientale region.

Classification and Modes of Emplacement of Mare Basalts in Orientale: Greeley [17] evaluated the modes of emplacement of mare basalt terrains in the Orientale basin on the basis of a tripartite characterization of terrestrial basalt provinces: 1) *flood basalts*, thick flows erupted from fissure vents at very high rates with little evidence of source vents (commonly buried); 2) *volcanic shields*, lower-volume eruptions commonly from point sources and characterized by lava channels and tubes building large edifices; and 3) *basaltic plains*, multiple overlapping and coalescing small shields and flows erupted from both point sources and fissures. Mare units in Orientale postdate the Maunder Formation, a smooth and corrugated unit interpreted by most workers to be impact melt deposits [12-15]. Greeley [17] interpreted a sinuous rille in the Maunder Formation (Fig. 1A) to be formed from eruption of still-molten impact melt and drainage into the basin center prior to the emplacement of mare basalts. Mare Orientale, (MO) occurring in the inner depression, with its high-lava marks, wrinkle ridges, lack of evidence of lava tubes, channels and flows, and lack of evidence of vents (except one sinuous rille and some irregular depressions) was interpreted to represent a flood basalt style of volcanism. Collapse depression scarps with heights of >1 km suggested that the lava fill was at least this thick. According to Greeley [7], Lacus Veris (LV) displays a strikingly different character, with many associated sinuous rilles (originating in the adjacent Rook Mountains), interpreted as lava tubes and channels, and containing several coalescing shield-like structures <10 km diameter. Lacus Autumni (LA) shows a development of sinuous rilles similar to Lacus Veris, suggesting [17] that both Veris and Autumni can be characterized as basaltic plains style of volcanism in contrast to the flood basalt style of Mare Orientale itself.

Vent Locations and Characteristics: New Moon Mineralogy Mapper (M3) data broadly support the previous documentation of vent locations [17] but add very important new details that provide insight into the mode of mare emplacement. First, M3 data (Fig. 1) show that the sinuous rille originating in the Maunder Formation in the southern part of the basin is not related to impact melt itself [17] but is a mare basalt vent that drains into and feeds Mare Orientale; evidence from this comes from mare basalt spectral signatures in the vicinity of the vent, and in a small lava pond that forms as the sinuous rille partly floods, and then breaches one of the concentric fractures in the Maunder Formation (Fig. 1A). M3 data confirm the presence of most of the sinuous rilles mapped by [17], add several more, and confirm that they occur predominantly, but not exclusively, in LV and LA.

In addition to documentation of a major sinuous rille feeding MO (Fig. 1), M3 data reveal the presence of candidate source vents and edifices in the MO interior. North of the exposure of the Maunder Formation in the center of MO, two low shield-like structures occur just west of Hohmann crater (Fig. 1B). These features are located in the center of the basin and differ from shields typical of shallow maria and later basin mare fill [18] in that their central depressions are much larger relative to the diameter of the shield. Their central location (presumably above the most elevated geotherm) and their distinctive characteristics provide important clues to the earliest phases of impact basin mare basalt filling.

One of the most enigmatic features associated with MO is the 41 km diameter crater Kopff, located in the Maunder Formation (Fig. 1C); in contrast to the archetypical nearby impact crater Maunder, Kopff has characteristics suggesting that it might be a large caldera with interior and surrounding volcanic ejecta deposits [19-20]. Clementine data [21] suggested that the rim deposit is not made of volcanic materials. M3 data show that the ejecta is not composed of mafic volcanic material, that it is similar to materials of the Orientale basin interior, and shows that the interior has been modified by mare volcanism. M3 data help resolve this long-standing controversy [19-20] showing that Kopff is an early post-Orientale impact crater modified internally by volcanism and floor fracturing.

Conclusions: M3 data reveal a much more complex interior (MO) flooding style (central shields, sinuous rille emerging from the impact melt sheet), show that Kopff is an impact crater, not a caldera, and demonstrate that the majority of the vents feeding mare basalt eruptions are fed by sinuous rilles, suggesting relatively high effusion rates for these early basin-filling deposits [22] compared to plains volcanism [17]. M3 data are currently being used to revise Orientale mare basalt chronology on the basis of crater counts and discovery of new deposits [23].

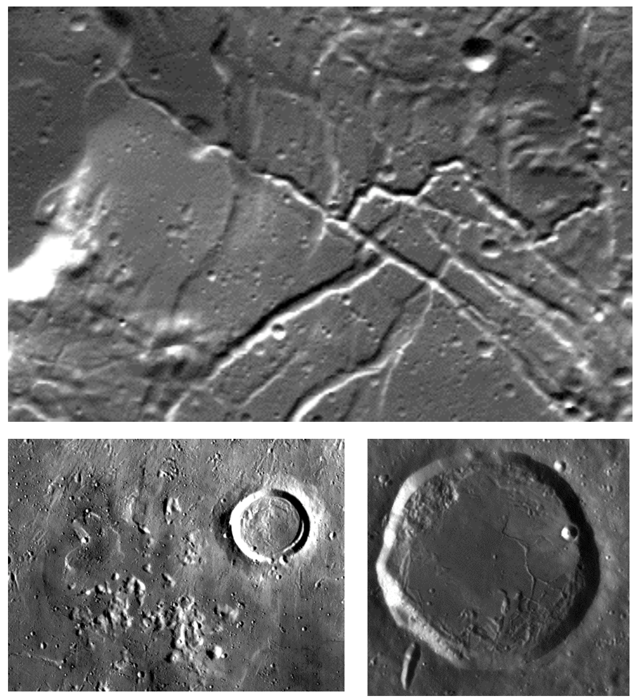

Fig. 1. M3 images from 2.9 μm mosaic: A, top: Sinuous rille entering MO (left) from a fracture in the impact melt (MF); vent region (upper right), parts of graben floors (middle), and MO (left) show mare basalt spectral characteristics; north is to left, image ~48 km wide. B, lower left: Shield volcano-like vents in central MO west of Hohmann crater (16 km). C, lower right: Kopff Crater (41 km) showing the exterior with non-volcanic spectral affinities and the volcanically modified interior.

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