THE LUNAR ORIENTALE BASIN: STRUCTURE AND MINERALOGY FROM CHANDRAYAAN-1 MOON MINERALOGY MAPPER (M3) DATA. J. Head[1], C. Pieters[1], J. Boardman[2], B. Burratti[3], L. Cheek[1], R. Clark[4], J-P. Combe[5], C. Fassett[1], R. Green[3], M. Hicks[3], P. Isaacson[1], R. Klima[1], G. Kramer[5], S. Lundeen[3], E. Malaret[6], T. McCord[5], J. Mustard[1], J. Nettles[1], N. Petro[7], C. Runyon[8], M. Staid[9], J. Sunshine[10], L. Taylor[11], S. Tompkins[12], P. Varanasi[3], [1]Brown Univ., Providence, RI (james_head@brown.edu), [2]AIGLLC, Boulder, CO, [3]JPL, Pasadena, CA, [4]USGS, Denver, CO, [5]Bear Fight Center, Winthrop, WA, [6]ACT, Herndon, VA, [7]NASA GSFC, Greenbelt, MD, [8]College of Charleston, Charleston, SC, [9]PSI, Tucson, AZ, [10]U MD, College Park, MD, [11]U TN, Knoxville, TN, [12]DARPA, Arlington, VA.

Introduction: Most lunar multi-ringed impact basins have been eroded by impacts or filled by mare volcanism [5-8]; the interiors of most basins (e.g., Crisium, Serenitatis, Imbrium, Humorum) are almost completely covered and obscured. Thus, unlike fresh impact craters (Tycho, Aristarchus and Copernicus), little is known about the primary interior deposits and initial stages of evolution of large multi-ringed impact basins. One multi-ringed basin, Orientale, remains largely unfilled and offers substantial clues to the nature of basin forming events and their early evolution. The Orientale basin (~930 km in diameter) (Fig. 1), 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 [1-4]. The Cordillera Mountain ring (CR), an inward facing mountain scarp ~930 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 [1-4].

Together, these ring structures and impact basin-related deposits provide a template on which to analyze and assess: 1) *The impact and excavation stage*: The distribution and mode of emplacement of ejecta, the nature of basin rings and their relation to features in smaller basins and craters, the approximate location of the transient cavity rim, and the direction of impact; 2) *The short-term modification stage (the first ~100 Ma)*: The nature of the terminal stages of the event, the collapse and immediate readjustments of the transient cavity, the flow and cooling of impact melt deposits, and the thermal equilibration of heat deposited by the impact and brought to the near-surface by uplifted geotherms [5]; 3) *The longer-term modification stage (post ~100 Ma)*: The continued readjustment of the basin interior by longer-term viscous relaxation, and its modification by mare basalt filling, post-basin impact craters, and their proximal and distal ejecta. Models of the relationship of basin formation and mare basalt evolution can be tested; 4) *The nature of the basin-forming process and the mineralogy and stratigraphy of the target region*: Develop a conceptual model for the basin-forming process and the depth of excavation and sampling; in an iterative manner, an improved understanding of the basin-forming process and the mineralogy of the rings and basin deposits can be used to probe the stratigraphy of the crust and test models for crustal formation and evolution. In this study we focus on an overview of the geomorphology and mineralogy of the Orientale basin rim and interior; we use a mosaic of images at 2.9 µm (reflected light and thermal emission) and spectra from the Moon Mineralogy Mapper (M3) experiment flown onboard Chandrayaan-1 [6] to define and characterize the array of rings and deposits in the Orientale region, and test models for basin structure and crustal stratigraphy.

Background. Recognition that several eastern massifs of the Inner Rook Mountains are composed of shocked plagioclase was established with earth-based 4-20 km telescopic measurements [7-9]. Galileo multispectral data [4,10] showed that the Hevelius Formation is homogeneous and spectrally similar to Apollo 16 mature soils, suggesting an upper crustal source. Located between the Cordillera and Outer Rook rings, the Montes Rook Formation showed a slightly stronger mafic absorption, and was interpreted to be the deepest crustal material excavated. The centrally located Maunder Formation is distinct from stratigraphically younger mare basalts and comparable to the Hevelius in its spectral properties, supporting a basin-related impact melt origin [1,4]. Clementine data generally supported these interpretations [11]. More recently, near-infrared spectroscopic data from KAGUYA (SELENE) discovered crystalline plagioclase in the central peaks of several large highland craters [12] and in Orientale [13] based on a diagnostic absorption near 1.3 µm [e.g., 14].

The crystal-field basis for near-infrared spectral properties of lunar materials is documented extensively in the literature [15]. Note that before KAGUYA, the diagnostic features of crystalline Fe-bearing anorthosites had only been seen in the laboratory. Anorthosite was previously identified remotely by high albedo and *lack* of Fe^{2+} absorptions [8,15] since plagioclase is the only mineral known to become sufficiently disordered with shock to lose its absorption bands.

M3 Mineralogy. Mineralogy across Orientale (Fig. 1) is derived through combined spectral and spatial information [16-17]. *Hevelius Formation* (**HF**: exterior): Feldspathic breccias with minor noritic mafic component; relatively homogeneous and well-mixed at M3 scale (no distinctive blocks or mountains). *Cordillera Mountains* (**CM**: outer ring): Outcrop exposures of unweathered feldspathic breccias similar to HF. *Montes Rook Formation* (**MRF;** between CM and ORM rings): Blocky and *not* well-mixed at M3 scale; feldspathic breccias with some shocked anorthosite blocks. *Outer Rook Mountains* (**ORM** ring North and South): Distinctively more crystalline blocks of noritic anorthosite and anorthosite. Not well mixed at M3 scale. All anorthosite blocks are the shocked form. *Inner Rook/Peak Ring* (**IR/PR**: inner ring). All massifs bordering Lacus Veris are pure anorthosite including discrete zones of the unshocked crystalline form; a few massifs toward the basin interior contain blocks with zones of mafic minerals. *Maunder Formation*: This unit occurs within the Outer Rook Ring of the Orientale basin, and has been interpreted as impact melt [1-4], a hypothesis consistent with multispectral image data [4] but as yet unconfirmed by direct measurement of mineralogical relations. Rough, bright, hilly, and mountainous topography in the Maunder Formation was interpreted to be underlying coherent basin floor debris protruding through the impact melt [1]. Single pixel spectra from the Maunder [16-17] show the dominance of anorthositic lithologies with very little mafic component across all the Maunder Formation. However, no significant crystalline anorthosite is observed. Only rare exposures of mafic bearing materials are found within the Maunder Formation. Thus, since the crystalline basement and ejecta debris of Orientale are observed to be highly feldspathic, the Maunder Formation units are consistent with an impact melt origin for this deposit. Nevertheless, it is apparent that in this region the Maunder Formation overlies and is mixed with large blocks of impact debris that is essentially anorthosite with minor noritic components.

Discussion and Conclusions: The overall regional crustal stratigraphy sampled by the basin forming event and the correspondingly varied shock history as inferred from Orientale mineralogy observed by M3 is (bottom to top): 1. Crystalline mafic-bearing anorthositic rocks (largely noritic) as seen as large blocks in the ORM, a remnant of the excavation cavity; 2. Pure anorthosite (all or some of which is Fe-bearing) as seen in the IR/PR, formed by late-stage lateral movement and uplift; 3. Megaregolith of unknown thickness (removed, laterally transported and mixed). The two lower units (1&2) are consistent with the stratigraphy proposed by [8]. The MRF represents a large-scale mixture of the excavated column including melt, and the HV represents a more fine-grained and intimately mixed version. The Maunder Formation is highly feldspathic and represents an impact melted homogenization of the upper units [16-17]. Discovery of crystalline Fe-bearing anorthosite within the IR/PR and its contiguous relations to inferred shocked plagioclase validates the near-infrared identification of plagioclase. Furthermore, the steeper continuum slope of shocked plagioclase suggests trace FeO in the crystalline form may be transformed to npFe° during shock. These data favor the interpretation that the Orientale basin sampling depth was largely confined to the upper crust; the mineralogy of the central peaks of the post-Orientale 55 km diameter Maunder crater, located in the basin interior depression inward of the IR, are somewhat enriched in low-Ca pyroxene and may have sampled noritic lower crust, but apparently not mantle. Most importantly, M3 data reveal that the mountains of the innermost mountain ring (Inner Rook) consist of pure anorthosite, including outcrops of the unshocked crystalline form. This massive exposure of anorthosite across the entire mountain range helps to validate the Lunar Magma Ocean hypothesis (plagioclase flotation in the crystallizing lunar magma ocean).

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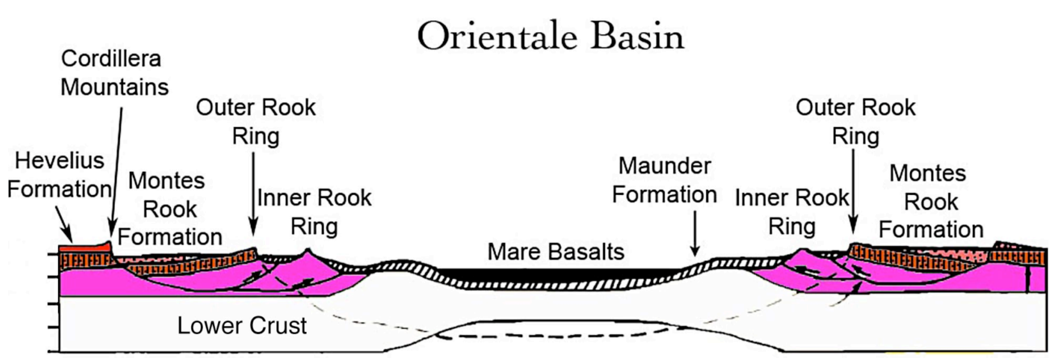

Fig. 1. Schematic cross section of the Orientale basin illustrating the relation of the Inner Rook Ring to the basin deposits of the exterior [4].