DIVINING THE LUNAR MANTLE: SPECTRAL ANALYSIS OF THE IMBRIUM BASIN. Jordan M. Bretzfelder[1, 2] (Bretzfel@usc.edu), Rachel L. Klima[1], Benjamin T. Greenhagen[1], Debra L. Buczkowski[1], Carolyn M. Ernst[1], and Noah E. Petro[3]. [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA., [2]University of Southern California, Los Angeles, CA 90007, USA., [3]NASA/Goddard Space Flight Center, Greenbelt, MD, USA.

Introduction: Larger lunar basins, which are concentrated on the near side, provide an opportunity to gaze into the interior of the Moon from orbit. Given the number and size of these basins and the extensive regolith mixing since the formation of the lunar crust, one would expect to find exposed mantle; either in samples on Earth from Apollo, Luna, and meteorites, or detected remotely on the surface of the Moon. However, no samples of the lunar mantle have been unambiguously identified [1], though there may be some small fragments in the Apollo 17 collection [2]. The impact that formed the Imbrium Basin excavated to depths of 60–85 km, and should have reached the mantle [e.g., 3]. The presence of olivine around the basin, identified based on visible (VIS)–near infrared (NIR) data from the Spectral Profiler (SP) on the Kaguya mission [4], has been attributed to pieces of exposed mantle. By identifying the relative abundance of plagioclase in massifs bearing early-crystallizing minerals (such as olivine and orthopyroxene) we strive to determine the origin of the olivine and orthopyroxene rich deposits around the basin. As part of a new analysis which integrates hyperspectral data from the Moon Mineralogy Mapper (M^3), Lunar Reconnaissance Orbiter Camera (LROC) imaging data and Diviner Lunar Radiometer (Diviner) thermal infrared data we map and characterize the mineralogy of the basin in order to identify exposed mantle, and to characterize the diversity of lithologies excavated in different portions of the basin.

Diviner and Mid-IR Measurements: Analysis began with mapping features associated with the basin; massifs which formed due to material being ejected or uplifted by the impact. A compositional map of the basin was created by compiling M^3 spectral images, and ten sites around the basin were chosen for analysis using Diviner data based on (1) their compositions as seen in with M^3, (2) their geomorphology, (3) and their location relative to the mare (Fig. 1). Sites on the inner and outer rings were selected, allowing for regional differences in composition to be observed. The data from the Diviner instrument, in particular the Christiansen feature values (CF) allows for the classification of materials by differentiating based the relative abundances of plagioclase present. Olivine and orthopyroxene bearing massifs can be misleading; very small amounts of these minerals can produce strong, distinctive, absorption bands in VIS and NIR, even when the bulk mineralogy is dominated by plagioclase. Thus, it is extremely challenging to reliably distinguish ultramafic deposits from orbit using VIS - NIR data alone. Previous global investigations using Diviner data have not identified any materials that are consistent with olivine-dominated ultramafic material [e.g., 5-7]. In an initial investigation of the massifs around the Imbrium basin, in particular in the Montes Alpes region [8], materials which appear potentially ultra mafic in the M^3 spectra are consistently found to be largely anorthositic when the Diviner data is taken into account. If these orthopyroxene and olivine bearing massifs had originated in the mantle, one would expect little to no plagioclase present in the materials.

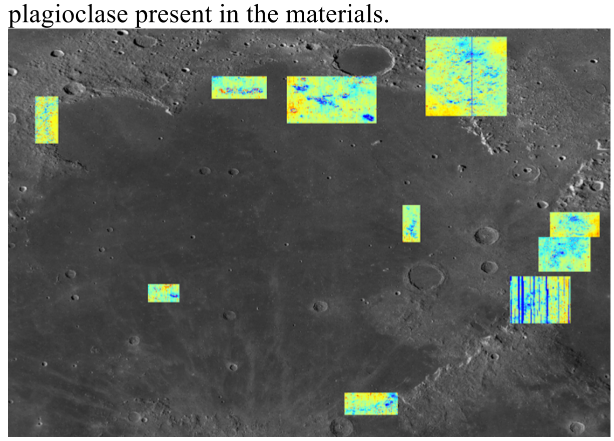

Fig. 1. Diviner sites analyzed around Mare Imbrium. Low CF values, consistent with anorthosite-dominated lithologies, appear as blues, while higher CF values (reds) are found among the mare deposits.

Rings of Mare Imbrium: Using the excavation depth estimates of Spudis [3] and the revised crustal thickness derived from the GRAIL mission [9], as much as 30% of the material excavated by the Imbrium impact may have been mantle-derived. However, a recent experimental study suggests that the basin may have been formed during an oblique impact with a proto-planet approximately 250 km in diameter on a northwest-southeast trajectory [10]. The direction of the impact contributes greatly to the distribution of ejecta, and thus the varying mineralogies in different areas of the basin. The oblique angle of impact may have decreased the depth of excavation in most of the basin (northwestern and northern areas); possibly explaining the lack of identifiable mantle material located. This motivates the suggestion that the "mantle" materials observed on the surface originated from either the excavation of magmatic intrusions into the lower crust, or as ejecta that mixed significant amounts of crust with mantle material. In both scenarios, the higher ratios of plagioclase in the massifs is explained by the shallower origin of the minerals.

Inner ring. Shown in Fig. 2 is an example of one of the massifs mapped as part of the innermost ring of the basin, which rises out of the mare in a broken circle. Using a color composite that distinguishes high-Mg orthopyroxene as yellow and more Ca- and Fe-rich pyroxenes as cyan, these massifs are all consistently dark green, purple, and blue in the M^3 spectra, revealing an extremely low abundance of pyroxenes overall. In conjuction with the CF data, the green regions have been identified as anorthositic materials containing small amounts of orthopyroxene while the blue and purple regions are mostly normal anorthositic with potentially a small amount of olivine. The cyan material, both on and off the massif, appears in the NIR to be typical basaltic material. The spectral similarity of the mare crater and the cyan material on the massif suggests that the material on the massif may be mare debris, rather than distinctive gabbroic material.

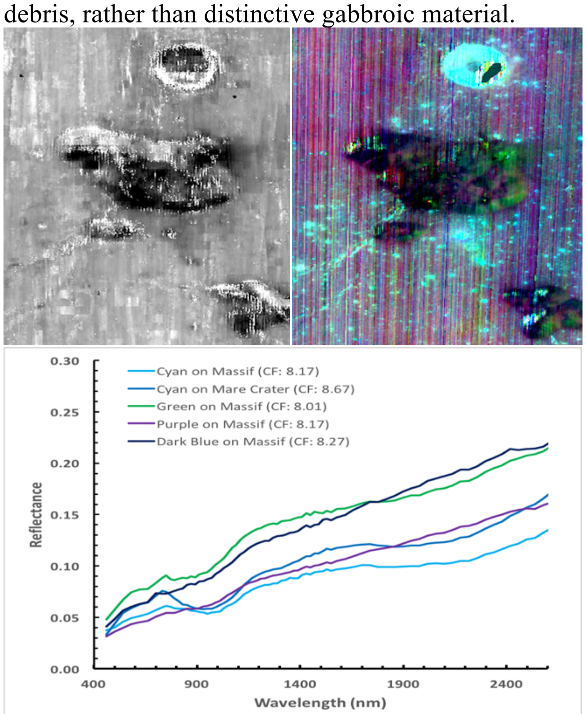

Fig. 2. Massif of the inner ring centered at (-14.85ºE, 48.86ºN). Crater in image is Plato D. Top left: Diviner data used for CF value sampling. Top right: M3 spectral data with R- BD 1900nm, G- IBD 2000nm, B- IBD 1000nm. Bottom: Spectra collected from both the massif and the crater in the mare seen in the images.

Outer ring. As the distance from the center of the mare increases, more diverse mineralogies are observed. At Wolff Mons, located on the south-by-south-east portion of the outer ring, a variety of mafic minerals were identified (Fig. 3). Orthopyroxene-rich material, east of the mare stands out as a bright yellow in the M^3 spectra. Unlike the Mg-rich orthopyroxenes identified in the Montes Alpes region, which exhibit a CF value of around 8.0 µm, the higher (~8.15 µm) CF values of these exposures suggest that these as more likely candidates for pyroxenite or very pyroxene-rich norite.

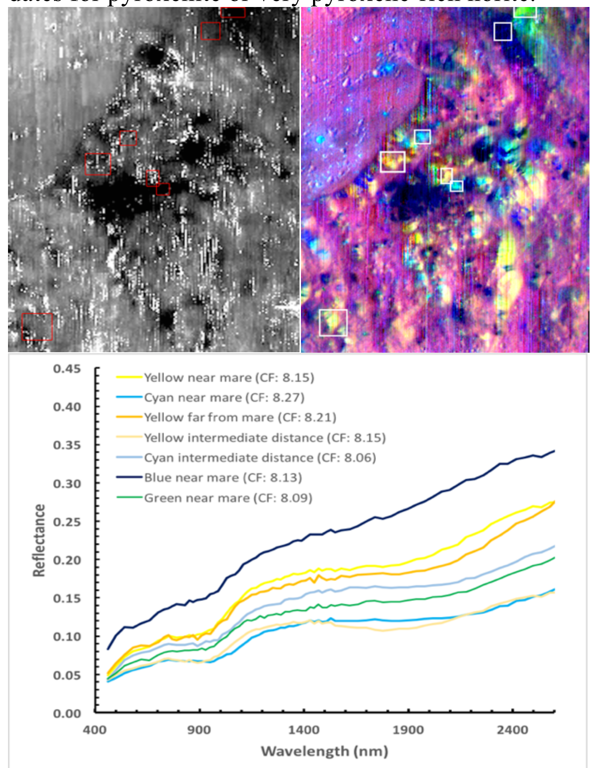

Fig. 3. Wolff Mons - Located at the SE edge of the mare (seen here as the 'flat' region in the upper left of the images). Top left: Diviner data used for CF value sampling. Top right: M3 spectral data with R- BD 1900nm, G- IBD 2000nm, B- IBD 1000nm. Bottom: Spectra collected from areas marked with boxes. Image centered at (-6.91ºE, 16.64ºN).

Initial Conclusions: Based on this preliminary analysis of Diviner data, the composition of materials excavated in the SE portion of Imbrium may be sourced from deeper than those found elsewhere around the basin. However, definite mantle samples remain elusive. Further analysis, using new sites and with improved corrections on the Diviner data will seek to clarify the origin of the mafic materials observed.

References: [1] Shearer, C. K. et al., (2015), *MAPS* 50, 1449-67. [2] Schmitt, H. H. (2016), *LPSC 47*, Abstract #2339. [3] Spudis, P., et al., (1988), *LPSC XVIII*, 15568. [4] Yamamoto S. et al. (2012) *GRL* 39, L13201. [5] Greenhagen, B. T. et al. (2010) *Science* 329, 1507-09. [6] Song, E., et al. (2013) *JGR* 118, 689-707. [7] Arnold, J. A., et al. (2016) *JGR* 121, 1342–61. [8] Klima, R. L. et al., (2017) LPSC, Abstract #2502. [9] Wieczorek et al. (2013), *Science* 339, 671-4. [10] Schultz. P. H. and Crawford, D. (2016), *Nature* 535, 391-4.

Acknowledgements: We are grateful to the NASA LDAP program for supporting this work under grant # NNX16AN50G.