COMPARATIVE SPECTRAL ANALYSIS OF THREE DISTINCT LUNAR BASINS. Jordan M. Bretzfelder[1,2] (Bretzfel@usc.edu), Rachel L. Klima[1], Benjamin T. Greenhagen[1], Debra L. Buczkowski[1], Samuel F. A. Cartwright[1], Daniel P. Moriarty[3], 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 20771, USA.

Introduction: Basin-forming impacts provide an opportunity to gaze into the interior of the Moon from orbit, as they can excavate and expose material from depth. 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]. Previous work examined the materials around the Imbrium basin using combined near- and mid-infrared analyses, and concluded that most mafic minerals were mixed with substantial amounts of plagioclase, except in the southeast portion where some ultramafic pyroxenite is exposed [3]. In order to better understand the origin of compositional differences around Imbrium and their relationship to the structure of the upper crust and mantle, we have performed similar analyses on the Moscoviense and Apollo Basins. Prior studies have identified ultramafic exposures around the Moscoviense basin [4] and the differences in crustal thickness and geologic setting of the three basins allow for analysis of a spectrum of scenarios.

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 these basins. As part of an expanded 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 basins in order to identify exposed mantle, and to characterize the diversity of lithologies excavated in different portions of the lunar surface.

Diviner and Mid-IR Measurements: Analysis began with mapping features associated with the basins; massifs which formed due to material being ejected or uplifted by the impacts. Compositional maps of the basins were created by compiling M^3 spectral images, and Diviner data was compiled for ten target sites in the Imbrium Basin, while full coverage was possible for both the Apollo and Moscoviense basins. The data from the Diviner instrument, in particular the Christiansen feature (CF) values, 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 visible (VIS) and near-infrared (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 examining regions shown to be olivine-rich in NIR data [5] using Diviner data have not identified any materials that are consistent with olivine-dominated ultramafic material [e.g., 6-8]. In a previous investigation of the massifs around the Imbrium basin, in particular in the Montes Alpes region [9], materials which appear potentially ultramafic 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. Using this fact we are able to differentiate between potential sources for the early-crystalizing minerals observed.

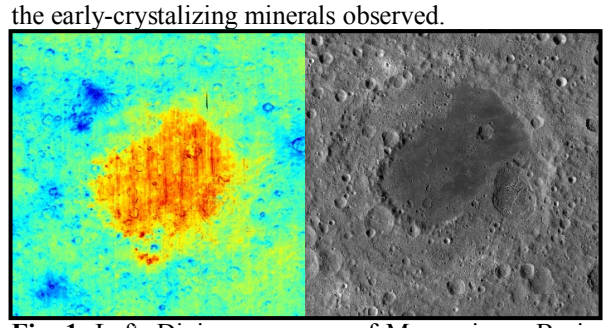

Fig. 1. Left: Diviner coverage of Moscoviense Basin. Low CF values, consistent with anorthosite-dominated lithologies, appear as blues, while higher CF values (reds) are found among the mare deposits. Right: LROC VIS image of the Moscoviense Basin.

Mare Imbrium: Using the excavation depth estimates of Spudis [10] and the revised crustal thickness derived from the GRAIL mission [11], as much as 30% of the material excavated by the Imbrium impact may have been mantle-derived. As the basin is located on the near side, on thin crust which was part of the Procellarum KREEP Terrane (PKT), further study was needed to determine whether the previously observed [5] olivine exposures were in fact examples of exposed mantle. Though the impact should have excavated between 60-85 km [e.g., 10], a recent experimental study suggested that the basin may have been formed during an oblique impact with a proto-planet traveling on a northwest-southeast trajectory [12]. The direction of the impact contributes greatly to the distribution of ejecta, and thus the varying mineralogy observed 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. The ultramafic materials in the southeastern portion, near Wolff Mons (Fig. 2) may be also be sourced from deeper layers of magmatic intrusions, or potentially the upper mantle.

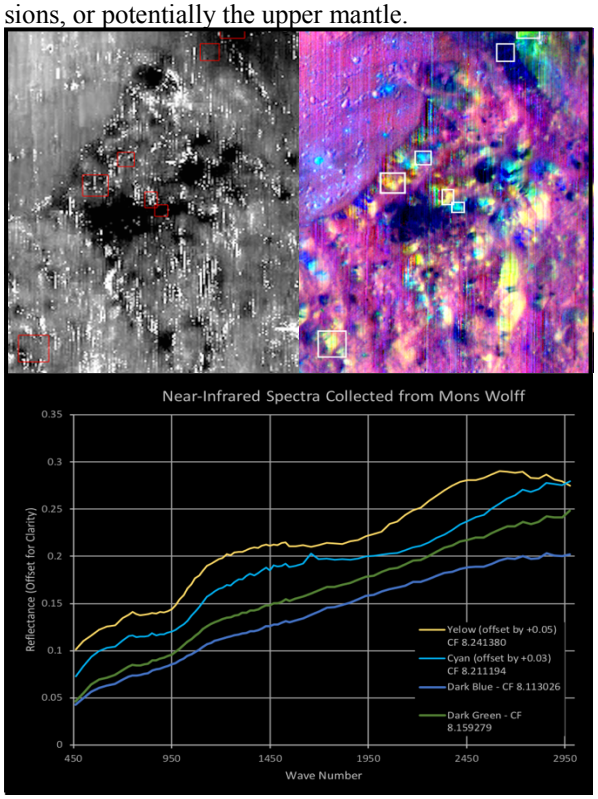

Fig. 2. Wolff Mons - Located at the SE edge of the mare (seen here as the 'flat' region in the upper left of the images). Top left: Diviner data used for CF value sampling. Darker areas have higher CF values. Top right: M^3 spectral data with R- BD 1900nm, G- IBD 2000nm, B- IBD 1000nm. Bottom: Spectra collected from areas marked with boxes. Image centered at (6.91ºW, 16.64ºN).

Moscoviense Basin: The Moscoviense basin is nestled in the highlands material on the far side, where the lunar crust remains thick (approximately 45-55 km deep). However, as seen with GRAIL data, the floor of the basin has some of the thinnest crust anywhere on the Lunar surface [11]. Based on the preliminary analysis of NIR spectra and CF data, the composition of some materials excavated in the SW portion of the basin may be sourced from deeper than those found elsewhere. Observations made were consistent with prior studies which identified mafic materials and spinel [4]. Further analysis of existing impact models and consideration of the geologic setting will allow for better understanding the observed distribution of materials.

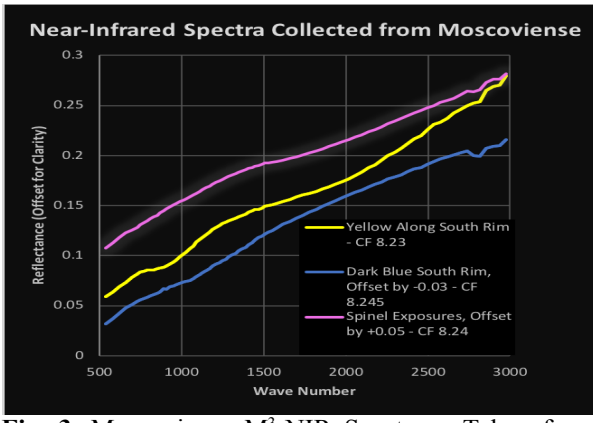

Fig. 3. Moscoviense M^3 NIR Spectra – Taken from massifs with apparent mafic signatures along the SW edge of the mare. CF values for the regions sampled are provided in the legend.

Apollo Basin: The Apollo basin is another example of a unique geologic setting, as it is superposed on the massive South Pole-Aitken (SPA), and sits above some of the thinnest crust on the Moon [11]. High-Mg orthopyroxenes lie along inner ring of Apollo [13]. Given the thin nature of the crust at Apollo, and the positioning of the high-Mg detections on the inner ring of the basin, it is possible that Apollo excavated deeper primary crustal (or mantle) material than is exposed elsewhere in SPA. However, preliminary Diviner analyses suggest that significant plagioclase is also present in the inner ring, as was found in the Montes Alpes region of Imbrium [9].

Initial Conclusions: Coupled NIR and Mid-IR analyses continue to suggest that large blocks of mantle (or even ultramafic lower crustal) material are rare, if present, on the lunar surface. However, some ultramafic material is excavated on the nearside in the SE of Imbrium, and on the far side around Moscoviense. We will present a comparative analysis of the mineralogical compositions of these materials as well as those excavated around the Apollo basin, to explore the compositional variations as a function of geological setting.

References: [1] Shearer, C. K. et al., (2015), *MAPS* 50, 1449-67. [2] Schmitt, H. H. (2016), *LPSC 47*, Abstract #2339. [3] Bretzfelder et al., (2018), *LPSC 49*, Abstract #1675. [4] Pieters et al. (2011), *JGR*, 116, E6. [5] Yamamoto S. et al. (2012) *GRL* 39, L13201. [6] Greenhagen, B. T. et al. (2010) *Science* 329, 1507. [7] Song, E., et al. (2013) *JGR* 118, 689. [8] Arnold, J. A., et al. (2016) *JGR* 121, 1342. [9] Klima, R. L. et al., (2017) *LPSC 48*, Abstract #2502. [10] Spudis, P., et al., (1988), *LPSC XVIII*, 15568. [11] Wieczorek et al. (2013), *Science* 339, 671. [12] Schultz. P. H. and Crawford, D. (2016), *Nature* 535, 391. [13] Klima et al. (2011) *JGR*, 116.

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