OLIVINE EXPOSURES ON THE MOON: ORIGINS AND MECHANISMS OF TRANSPORT TO THE LUNAR SURFACE. L. M. Corley[1], P. J. McGovern[2], and G. Y. Kramer[2], [1]Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Mānoa, 1680 East-West Road, Honolulu, HI 96822, USA (lmc44@hawaii.edu), [2]Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston, TX 77058, USA.

Introduction: The Moon's crust and mantle crystallized from a magma ocean, with olivine crystallizing early and throughout much of the crystallization of the mantle [1, 2]. Spectral data have recently allowed for the detection of olivine located at large impact basins [3, 4]. Olivine exposures at the surface may be exposures of the mantle itself, or shallow intrusions. In either case, olivine exposures provide insight to the structural and magmatic evolution of the Moon.

Yamamoto et al. [3] used data from KAGUYA's Spectral Profiler (SP) to identify olivine located on rims and central peaks of several large impact basins. They concluded that the olivine spectra were from dunite, and thus likely originated in the upper mantle. Powell et al. [4] examined Crisium basin using Chandrayaan-1's Moon Mineralogy Mapper (M^3) spectra. They detected olivine on mare, intrusive landforms, and on crustal thickness maxima, and concluded that some olivine-bearing materials were magmatically transported. This conclusion is supported by loading models showing that areas around large basins are favorable for magma ascent via dikes [5].

Methods: We identified olivine on the Moon at Crisium, Nectaris, and Humorum basins and near the crater Roche, using M^3 data. M^3 is an imaging spectrometer that allowed us to link potential olivine spectra to geologic features. 85 bands from 460 to 2980 nm give M^3 high spectral resolution that can be used to distinguish mineral signatures. We used level 2 M^3 reflectance data, which is both thermally and photometrically corrected [6]. For our olivine investigation, we used an olivine index based on the algorithm developed for the imaging spectrometer CRISM onboard the Mars Reconnaissance Orbiter [7], but optimized for M^3 wavelengths.

Olivine spectra have three absorption features at approximately 0.85, 1.05, and 1.25 µm, which overlap and are recognized as one wide composite absorption band centered near 1 µm (Fig. 1). Pyroxene also has an absorption band centered near 1 µm and an additional absorption band centered near 2 µm, which olivine lacks. We classified our spectra with a weak 2-µm band as olivine-dominated pyroxene mixtures. Based on work by Singer [8], the spectra we classified as olivine-dominated mixtures likely had no more than 25% pyroxene. We divided the spectra that are solely olivine into two groups based on composition: Mg-dominated and Fe-dominated. Fe-dominated olivine spectra have a deeper and more asymmetric 1-µm absorption band than Mg-dominated spectra (Fig. 1) [9].

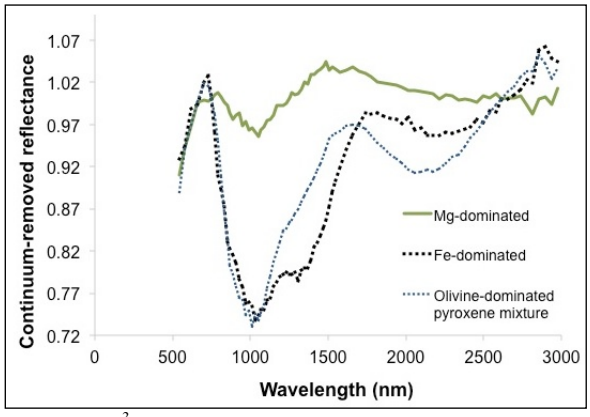

Figure 1: M^3 spectra from this study showing Mg-dominated and Fe-dominated olivines, and an olivine-dominated pyroxene mixture. Straight-line continuum removal at 750 and 2620 nm.

In an effort to constrain structural and magmatic evolution, we examined the geophysical settings of the 4 study regions using products produced from measurements of gravity by the Gravity Recovery and Interior Laboratory (GRAIL) mission. We plotted maps of Bouguer gravity and crustal thickness (Fig. 2) [10]. Maps of topography and slope were created using data from the Lunar Orbiter Laser Altimeter (LOLA) [11] onboard the Lunar Reconnaissance Orbiter (LRO). Wide Angle Camera (WAC) and Narrow Angle Camera (NAC) images from LRO allowed for further observation of geologic settings [12].

Results:

Crisium. At Crisium basin we identified 62 spectra with signatures that represent olivine or olivine-dominated mixtures. These spectra are located on the rims of small craters, on massifs at the rim of Crisium, and on mare both inside and outside of Crisium basin.

We were able to confirm many olivine locations that were detected by [3, 4], including Lacus Perseverantiae and a potential dike at Eimmart A. In addition, we report several locations where olivine was previously undiscovered, including on the main basin-filling mare of Crisium. One such discovery is located on the rim and in the ejecta of Picard crater. Crustal thickness models [10] indicate that Picard crater is large enough to have penetrated through the thin crust. In contrast, many of our olivine detections correlate

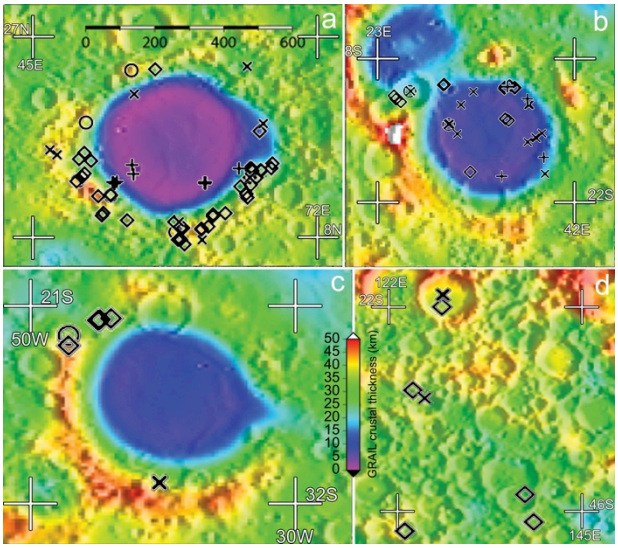

Figure 2: Locations of Fe-dominated olivine (✕), Mg-dominated olivine (◇), and olivine-dominated pyroxene mixture (+) at (a) Crisium, (b) Nectaris, (c) Humorum basins, and (d) near Roche crater from this study. Detections from [1] are shown as circles. Base maps are GRAIL crustal thickness maps with shaded topography from LOLA.

with crustal thickness maxima.

Nectaris. Nearly all of the olivine detections at Nectaris are confined to the mare. Our investigation confirmed every olivine location detected by [3]. In addition, we were able to find many more olivine locations, for a total of 45 olivine spectra. Although crustal thickness inside Nectaris basin is as low as 5 km in some areas, none of the craters where olivine is found are large enough to have penetrated through the crust.

Humorum. A total of 8 olivine spectra were detected at Humorum basin. In this investigation, only one of three olivine locations detected by [3] was confirmed. A new olivine discovery was made at Lee crater, where olivine appeared to be Fe-dominated. In addition, two Mg-dominated olivine spectra were found on a graben in northwest Humorum. All of the olivine detections at Humorum are located on its rim.

Roche. Roche crater, located on the lunar farside, had not been previously investigated for olivine using high spectral resolution data. Work by Andrews-Hanna et al. [13] identified a linear gravity anomaly near Roche using GRAIL data, which they interpreted to be an ancient dike. We identified 9 olivine spectra near Roche. Several of our detections were in close proximity to the proposed dike.

Discussion: Our findings have important implications for the origins of exposed olivines and the mechanisms of transport to the lunar surface. Possible transport mechanisms include mechanical transport of mantle or lower crustal material by basin-forming impact, or magmatic transport of cumulates or xenoliths.

There is a diversity of origins for olivines located on the mare basalts within and around Crisium. Our examination of the geophysical setting at Crisium basin suggests that olivine exposed on the main mare at Picard crater may be primary olivine from the mantle. The crust inside Crisium basin is thin enough that the 23-km diameter Picard crater likely penetrated through the crust, exposing mantle material. Olivines located at Lacus Perseverantiae were likely transported magmatically because here the crust is too thick for the craters where the olivines are detected to have penetrated to the mantle. Other olivines are located on the rim of Crisium near local crustal thickness maxima, which may indicate that mantle material was excavated by the Crisium impact and deposited at the rim [14]. However, these olivines could have been transported by magmatic processes. Consistent with [4], we identified olivine on the rim of Eimmart A where there is morphologic evidence for a potential dike.

Olivine exposures in Nectaris basin are confined to the rims of small craters (<5 km diameter). These craters are not large enough to have penetrated the estimated thickness of the mare [10]. Instead, the small craters probably exposed an olivine-rich mare basalt.

At Humorum basin, the grabens exhibiting olivine sites were likely created by extensional stresses caused by the loading of mare basalt [5, 15]. Extensional stresses would also have been favorable to the formation of dikes. Thus, we conclude that olivines detected at the graben in northwest Humorum are likely cumulates of shallow intrusions.

Due to the thicker crust on the lunar farside, material exposed near Roche crater is not likely to be impact-exposed mantle. However, the presence of olivines at this location suggests that magmatic intrusions reached the shallow subsurface and were exposed by small impacts, consistent with the presence of a dike near Roche [13].

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