**OLIVINE DETECTIONS AT THE RIM OF CRISIUM BASIN WITH MOON MINERALOGY MAPPER.**
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**Introduction:** The lunar magma ocean theory proposes that 500 km of the Moon's outer layer was once molten. The lunar crust and mantle would have crystallized from this early magma ocean. Olivine was the earliest major mineral to crystallize, and became a significant component of the mantle. Finding olivine on the surface of the Moon could indicate exposure of such mantle material, which would be of interest in the study of the Moon’s interior. The location of olivine-rich rocks on the surface of the Moon may yield information about the various geologic processes that have been active throughout its history.

Using Kaguya's Spectral Profiler, *Yamamoto et al.* [1] reported detections of olivine in regions near large impact basins. Such detections were almost exclusively limited to basin rims and central peaks. They proposed that this reflects exposed mantle excavated by the impacts that formed these basins. However, analysis of stress states from lithospheric loading by mare flows [2] suggests that the areas around large impact basins are particularly favorable for magma ascent through vertical conduits, i.e., dikes. We address the origin and transport of olivine at Crisium. using spectra from the Moon Mineralogy Mapper ($M^3$) on board Chandrayaan-1. As well as images, spectra, topographic, and crustal thickness maps from Lunar Reconnaissance Orbiter (LRO), Clementine, and Kaguya.

**Methods:** $M^3$ is an imaging spectrometer, and therefore provides visual context to directly link spectra to features. This enabled a more comprehensive exploration of the Crisium region than by Kaguya's Spectral Profiler. $M^3$ has 85 bands across a range of 460 to 2980 nm, giving it high enough spectral resolution to distinguish mineral signatures. The $M^3$ data used here are “R”-calibrated and converted to apparent reflectance. These spectra are not thermally corrected, so we do not use wavelengths longer than 2300 nm as these have a significant thermal emission component. This does not diminish the efficacy of our analysis because the relevant spectral features are located below 2300 nm.

We take a conservative approach in declaring spectra to be indicative of olivine. The spectral signature of olivine has three absorptions features; at 0.85, 1.05 and 1.25 μm. These features are expected to appear in the $M^3$ data as a wide band centered near 1μm. This signature must be distinguished from the pyroxenes; which display a 1 μm band and also a wide band near 2 μm. Often our spectra show a weak 2 μm band, indicating that the rocks may be a mixture of olivine and pyroxene instead of a pure olivine.

The search for olivine with $M^3$ spectra was assisted by an olivine index based on the algorithm developed for CRISM [3]. Although Clementine spectra lack the spectral resolution for unambiguous olivine identification, from this data set we were able to create an optical maturity index [9] and $TiO_2$ [10] and FeO [11] abundance maps, providing us with additional information about the different compositional units in the region. We mapped the major geologic units in and around Mare Crisium. We assessed the geophysical setting of the Crisium basin with products derived from altimetry and gravity observations. We referenced LOLA topography [6] to the lunar geoid [7] and used a model of crustal thickness derived from Kaguya gravity and topography data (Fig. 1) [8].

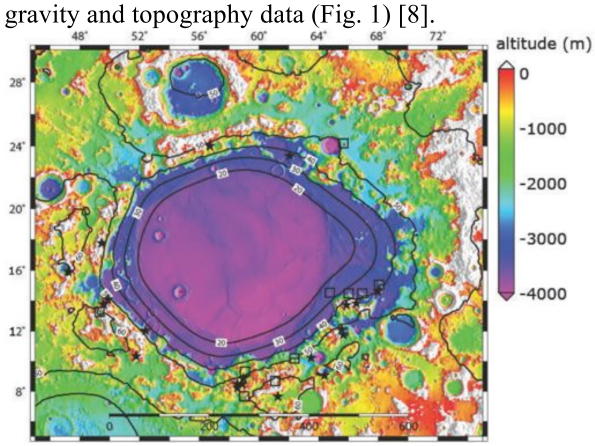


**Figure 1** **Topographic map of Mare Crisium from LOLA, with crustal thickness contours from Kaguya. Symbols are olivine detections from this work; stars represent single areas of finite dimension, boxes represent larger areas with several non- contiguous detections.**

**Results:** We report detections of olivine in 30 locations around the rim of Crisium (Fig. 1), several of which are new areas of discovery. They exist in varied geological and geophysical settings including the rims of small impact craters, massifs at the rim of Crisium, and in maria beyond the main mare-filled basin. Only one of these detections is located within the basin-filling mare. In many instances we were able to confirm the findings of [1]. For example, many detections occur in an area south of Crisium, on the southeast rim of Crisium near Promontorium Agarum, and on the rim of Glaisher crater - all areas where multiple detections were reported by [1]. However, in several areas where they reported olivine detections, our findings were inconclusive.

<u>*Eimmart A*</u>*:* One notable detection of olivine not reported by [1] occurs in the very fresh 7-km crater Eimmart A (24.08°N, 65.64°E). It is located on the rim of the 45-km crater Eimmart and likely samples both the wall of that crater and the surrounding terrain.

Eimmart in turn is located outside the mare on the northeast rim of Crisium, where it would have sampled overturned material from the impact.

Blewett et al. [4] reported a mixture of olivine and pyroxene in Eimmart A as part of a regional survey of Crisium using Clementine spectra. The CRISM olivine index identifies three locations for candidate olivine exposures within and near the rim of Eimmart A. One spectrum from the northern rim of the crater shows a strong olivine signature, while other spectra suggest olivine involvement. We find isolated exposures of olivine only within Eimmart A, not around it. The diagnostic olivine spectral features are identifiable only in the upper crater walls, although can be briefly traced in streaks down the inside of the crater until the signature is swamped by the spectrally dominating pyroxene.

Inspection of LRO NAC imagery of Eimmart A reveals an outcrop on the southern rim of the crater, extending northward from the edge of the rim, not radial to the center of the crater. Nearby terrain consists of larger blocks than the northern rim. This potential dike may have been made of mechanically stronger material than its surroundings and thus a piece of it survived the impact that formed Eimmart A.

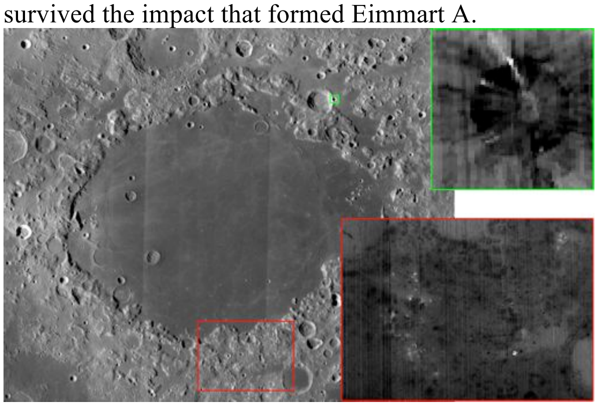

**Figure 2 LROC WAC imagery of Crisium. Insets: Olivine index derived from M3 spectra; potential olivine in white.**

<u>*Lacus Perseverantiae:*</u> This irregularly-shaped volcanic flow south of the rim of Crisium (center: 7.78°N, 61.91°E) is penetrated by several small (<5 km) impacts, one of which exposes olivine. The lacus is clearly a mare flow based on its irregular shape, dark visual appearance, and FeO and $TiO_2$ abundances. The source of the flow is uncertain. The olivine spectrum appears in the crater that has the largest diameter and thus should be exposing material from the greatest depth.

<u>*Inner southeast rim of Crisium:*</u> Many olivine detections were found on the inner southeast rim of Crisium on and around Promontorium Agarum, some of which were previously reported by [1]. This area has rough rim terrain and a strong gradation in elevation over a relatively small region. In contrast to several other areas of olivine detection, this southeast rim is far from a local crustal thickness maximum.

**Discussion:** Our findings have important implications for both the origins of the lunar olivines and the mechanisms by which they were transported to the lunar surface. There are two broad categories for possible transport of olivine to the near-surface: mechanical transport by basin-forming impact of deep material from either the lower crust or mantle, or magmatic transport of melts, cumulates, or xenoliths through intrusive networks. The transport mechanism is distinct from the ultimate origin of the materials themselves. Yamamoto et al. [1] favored a scenario of olivine-bearing mantle rocks transported to the surface by the impact that formed Crisium. They also considered an alternative origin as lower crustal magnesium-rich plutons.

While some of our olivine detections may reflect deep material uplifted by the basin-forming impact, other exposures appear to be transported magmatically. The association of prominent olivine exposures with mare basalt units (e.g., Lacus Perseverantiae) and intrusive landforms (e.g., the proposed Eimmart A dike) strongly indicates magmatic transport. Further, olivine detections at Crisium often correlate with local crustal thickness maxima (Fig. 1). If olivine here were indicative of a substantial amount of exposed mantle material, we would not expect it to be observed where the crust is thickest: thus, magmatic transport is more likely. This finding contrasts with the argument that *low* crustal thickness (in a *global* rather than local sense) at Crisium favors impact transport [1]. In addition, loading from emplacement of initial mare units creates a stress state very favorable to magma ascent at basin margins [2], right where the Crisium olivines are located. Again, such magmatically transported material may itself have a magmatic origin (e.g., cumulates in mid-crustal magma chambers) or may comprise peridotitic mantle xenoliths entrained by rapidly ascending magma. Nonetheless, many of our new detections are in regions where impact transport is plausible, including the rugged inner southeast rim of Crisium, far from the crustal thickness maximum and near several earlier olivine detections [1].

**References:** [1] Yamamoto et al. 2010. *Nat. Geos. Lett.,* 3 (7) pp. 1-4. [2] McGovern and Litherland, 2011. *LPSC 42*, abstract 2587. [3] Pelkey, at al. 2007. *JGR.* 112, E08S14. [4] Blewett et al. 1995. *Geophys. Res. Lett.* 22, No. 22, 3059-3062. [5] Pieters, C. M., M. I. Staid, E. M. Fischer, S. Tompkins, and G. He 1994.. *Science*, 266, 1844–1848. [6] Smith, D. E. et al., 2010. *Geophys. Res. Lett.*, 37, L18204. [7] Matsumoto, K., et al., 2010. *JGR*. [8] Ishihara, Y., et al., 2009. *Geophys. Res. Lett.*, 36, L19202. [9] Lucey, P., D. Blewett, and B. Hawke 2000. *JGR.,* 105(E8), 20,297-20,305. [10] Lucey et. al. 2000b. *JGR.,* 105(E8), 20,377- 20,386. [11] Wilcox, B., P. Lucey, and J. Gillis 2005. *JGR.*