GLOBAL INVESTIGATION OF OLIVINE BEARING CRATER CENTRAL PEAKS WITH M^3 IMAGES.

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Introduction: Olivine is typically the first mafic mineral to crystallize from a mafic magma and contains important records of the geologic evolution of the Moon. Olivine has been identified on the Moon through Earth-based telescopic observations [1-3], and analyses of Clementine multispectral images [4-6]. Recent detections of researches about the origin of olivine on the Moon have witnessed the use of hyperspectral data [7-10] and suggest that olivine-rich materials could originate from mantle, plutons or impact melts. Most of these studies consider the lunar mantle as the sources of olivine because olivine-rich areas are mostly associated with large impact basins or thin crust. Considering that the origin of olivine is still debated, we have conducted a systematic screening of lunar crater central peaks to determine the presence of olivine -bearing lithologies in order to shed light on the petrogenesis of olivine using the Moon Mineralogy Mapper (M^3) images.

Commonly, lunar crater central peaks originate from the lunar crust and provide an effective approach for the detection of compositional variations in the lateral and vertical dimensions of the lunar crust. In this study, we examined 167 lunar crater central peaks which were selected from 1559 lunar craters listed in the USGS crater database. The selection of these lunar craters is based on the following criteria: 1) Craters are larger than 35 km in diameter; 2) craters should exhibit obvious peak topography based on M^3 images and Lunar Orbiter Laser Altimeter (LOLA) elevation data; 3) central peaks are fully covered by M^3 L2 reflectance images; 4) central peaks should show significantly strong spectral absorption features. The application of these selection criteria assures that the examined craters have the undisturbed central peaks representing deep pristine materials from the lunar crust or upper mantle. The selected 167 craters are ~35.1 km to ~199.5 km in diameter (D), and the excavation depth (d) ranges from ~5.05 km to ~33.21 km based on $d=0.109*D^{1.08}$[11].

Dataset and Method: The datasets used in this study are M^3 L2 reflectance images at a spatial resolution of 140 m and spectral resolutions of 20-40 nm. These datasets were corrected for thermal and photometric effects and released on Dec. 8, 2011 by NASA.

M^3 L2 images for 167 craters were downloaded from the NASA PDS website. These images were geometrically corrected and smoothed for noise reduction. For geometric correction, the original reflectance images were warped based on latitude and longitude values of each pixel. For noise reduction, pixels with negative reflectance values or within shadow were eliminated. A moving window average was used to smooth spectra. After spectral smoothing, 72 bands from 540 nm to 2537 nm in which spectrally diagnostic absorptions for minerals are present were retained for further analysis.

Continuum removal was applied to each image spectrum to isolate mineral diagnostic absorption features from the spectral continuum. Olivine has broad multiple absorption features near 1050 nm and a weak or undetectable absorption around 2000 nm. These spectral characteristics were used to identify olivine -bearing central peaks with the constraint that the absorption near 1050 nm has a depth of 0.05 or larger.

Results and Discussion: Olivine has been detected in 15 out of 167 selected crater central peaks (Fig. 1).

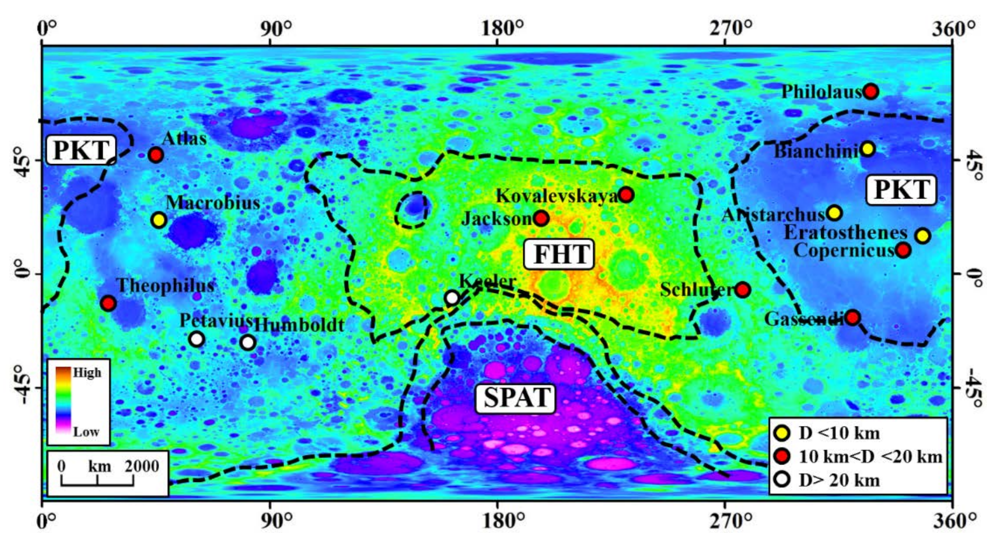

Fig. 1 Distribution of olivine - bearing crater central peaks overlaid on a LOLA DEM image of the Moon. Solid circles represent olivine - bearing central peaks identified in this study and filling colors of the circles show different excavation depth. Black dash lines describe three distinct lunar terranes.

A typical continuum removed M^3 spectrum for each olivine-bearing crater central peak shows a broad absorption band near 1050 nm (Fig. 2) but weak absorption around 2000 nm. Globally, olivine-bearing crater central peaks are sparsely distributed on the Moon, and olivine-bearing crater central peaks are not identified within SPAT. Vertically, olivine could exist in the lunar crust from ~5.48 km to ~33.21 km; most of them originated from 10 to 20 km deep; only three of olivine - bearing central peaks are from a depth larger than 20 km and four are from a depth less than 10 km. All 15 olivine-bearing craters excavated a depth above the crust-mantle interface based on the crustal thickness derived from Gravity Recovery and Interior Laboratory (GRAIL) except for Petavius and Humboldt.

Regarding the coexistence of olivine with other minerals (plagioclase, pyroxene and Mg-spinel), nine olivine-bearing central peaks contain crystalline plagioclase, and four of them show the occurrence of olivine and crystalline plagioclase without pyroxene; Eight of these nine olivine - bearing central peaks originate from lunar crust layers deeper than 10 km. Among 15 olivine - bearing central peaks 11 are detected for the presence of pyroxene. In addition, six of the olivine bearing crater central peaks are identified to contain Mg-spinel and only one of them originates from a depth less than 10 km.

Consistent with observations in [7, 8], our results clearly demonstrate that olivine - bearing locations on the Moon can be on the lunar nearside and associated with impact basins (Fig. 2). However, this study also shows that three olivine-bearing central peaks (Jackson, Kovalevskaya and Keeler) are identified in FHT on the lunar farside with the deepest excavation depth being 25.83 km. Even this depth is too shallow to reach the mantle or crust-mantle interface (The average crustal thickness of FHT is about 46 km based on recent GRAIL data [12]). Therefore, the mantle origin may not be suitable for explaining the source of olivine in FHT. Furthermore, the half of olivine - bearing central peaks are unrelated to large impact basins, and most of the olivine-bearing central peaks show the presence of crystalline plagioclase, eliminating the possibility of their mantle origin. Crystalline plagioclase, the first felsic mineral in lunar magma ocean crystallization, is the major component of the lunar upper crust. Mantle olivine and crystalline plagioclase cannot be emplaced by impacts contemporaneously unless olivine exists in relatively shallow layers. Nevertheless, the mantle origin of olivine cannot be rule out because we also found that some olivine-bearing central peaks without crystalline plagioclase are located in surrounding large basins.

The results from this analysis indicate two origins for olivine-bearing crater central peaks. One process is that the mantle olivine were first excavated by basin forming impacts and positioned to shallow layers, and they were excavated by later impact events to the surface. However, this mantle origin fails to explain the coexistence of olivine and crystalline plagioclase and the presence of olivine in the regions without large impact basins. Plutonic events in the lunar crust must be appealed as an alternative explanation. Olivine can crystallize from the pluton and be excavated by later impacts. It is concluded that the sources of olivine in lunar crater central peaks may vary with depth and the geological context. To place more accurate constraints on the origin of olivine, other regions (e.g. crater wall) need to be analyzed.

References: [1] Lucey P. G. et al. (1986) *JGR, 91*, 344-354. [2] Pieters C. M. (1982) *Science, 215*, 59-61. [3] Pinet, P. C. et al. (1993) *Science, 260*, 797-801. [4] Lucey P. G. (2004) *GRL*, 31(8). [5] Pieters C. M. et al. (2001) *JGR, 106*, 28001-28022. [6] Tompkins S. and C. M. Pieters (1999) *Meteoritics & Planet. Sci., 34*, 25-41. [7] Yamamoto R. et al. (2010) *Nat. Geosci., 3*, 533-536. [8] Isaacson P. J. et al. (2011) *JGR, 116*. [9] Mustard, J. F. et al. (2011) *JGR, 116*. [10] Powell K. E. et al. (2012) LPS *XXXXIII*, Abstract #1689. [11] Cintala M. J. and R. Grieve (1998) *Meteoritics & Planet. Sci., 33*, 889-912. [12] Wieczorek M. A. et al. (2013) *Science, 339*, 671-675.

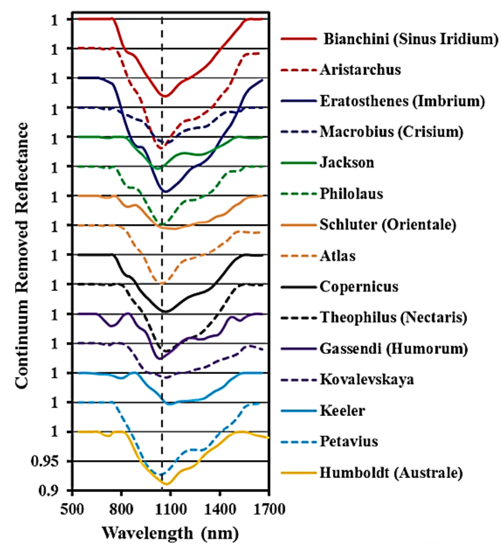

Fig. 2 Continuum removed spectra for olivine - bearing crater central peaks. This spectral plot only shows a wavelength range from 540 nm to 1650 nm to emphasize the shape and strength of olivine absorption. The crater names are ordered by increased excavation depths from top to bottom. Impact basins possibly associated with olivine-bearing locations are listed in the parentheses.