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Multiple origins for olivine at Copernicus crater

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ABSTRACT

Multiple origins for olivine-bearing lithologies at Copernicus crater are recognized based on integrated analysis of data from Chandrayaan-1 Moon Mineralogy Mapper (M^3), Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) and Kaguya Terrain Camera (TC). We report the diverse morphological and spectral character of previously known olivine-bearing exposures as well as the new olivine occurrences identified in this study. Prominent albedo differences exist between olivine-bearing exposures in the central peaks and a northern wall unit (the latter being ~40% darker). The low-albedo wall unit occurs as a linear mantling deposit and is interpreted to be of impact melt origin, in contrast with the largely unmodified nature of olivine-bearing peaks. Small and localized occurrences of olivine-bearing lithology have also been identified on the impact melt-rich floor, representing a third geologic setting (apart from crater wall and peaks). Recent remote sensing missions have identified olivine-bearing exposures around lunar basins (e.g. Yamamoto et al., 2010; Pieters et al., 2011; Kramer et al., 2013) and at other craters (e.g. Sun and Li, 2014), renewing strong interest in its origin and provenance. A direct mantle exposure has commonly been suggested in this regard. Our detailed observations of the morphological and spectral diversity in the olivine-bearing exposures at Copernicus have provided critical constraints on their origin and source regions, emphasizing multiple formation mechanisms. These findings directly impact the interpretation of olivine exposures elsewhere on the Moon. Olivine can occur in diverse environments including an impact melt origin, and therefore it is unlikely for all olivine exposures to be direct mantle occurrences as has generally been suggested.

1. Introduction

Olivine is commonly the first crystallizing solid during magmatic differentiation and resides largely in the mantle of differentiated planetary bodies such as the Earth and the Moon (e.g. Snyder et al., 1992). Near-surface occurrences of olivine dominated lithologies are therefore unusual unless produced through secondary processes like volcanism or plutonism. In the case of the Moon, mantle overturn has been suggested to have brought early cumulates (including olivine) to shallower depths and subsequently led to the formation of Mg-suite rocks (including olivine-bearing lithologies such as troctolites) by interaction with crustal rocks (e.g. Hess, 1994; Elkins-Tanton et al., 2002; Elardo et al., 2011). Knowledge gaps still exist for both the mantle overturn and formation of Mg-suites rocks but their existence on the lunar surface (and in our sample collection) suggests some mechanism for their relatively shallow origin. In addition to internal evolutionary processes, impact craters can excavate and relocate subsurface minerals from various depths leading to their exposure at the surface, with larger craters excavating relatively deeper than smaller craters. Central peaks of impact craters represent some of the deepest material sampled within a crater. Their steep slopes minimize soil retention and aid in the identification of constituent mineralogy, revealing compositions from depth (e.g. Tompkins and Pieters, 1999; Cahill et al., 2009).

Olivine on the lunar surface was first discovered remotely in the central peaks of Copernicus crater (Pieters, 1982) and interpreted to be sourced from the mantle or a buried pluton (e.g. Pieters and Wilhelms, 1985). Later studies suggested a relatively shallow source region (e.g. Lucey et al., 1991) based on potential olivine-bearing locations in the northern crater wall and the assumption that olivine in the wall and the peak had a common origin. Several additional olivine-bearing exposures have been detected using recent datasets (e.g. Pieters et al., 2011; Kramer et al., 2013). A variety of geological scenarios have been proposed to invoke a mantle origin for olivine exposures on the Moon, including excavation through a thin crust (e.g. Yamamoto et al., 2010), multiple impacts in a given region (allowing access to deeper material) (e.g. Pieters and Wilhelms, 1985), and a single giant impact

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event (e.g. Yamamoto et al., 2010). Diverse origins of olivine continue to be proposed (e.g. Powell et al., 2012; Corley et al., 2014; Sun and Li, 2014). Here, we analyze the olivine-bearing exposures at Copernicus crater (previously known occurrences as well as some new ones) and highlight their different geological settings and origins. The critical implications of these findings for olivine occurrences elsewhere on the Moon are also discussed.

2. Data and methods

In this study, we have integrated a variety of remote sensing data, from multiple lunar missions. The spectral and spatial data used here are archived and available in public domain. Chandrayaan-1 M^3 (e.g. Pieters et al., 2009; Goswami and Annadurai, 2009), LRO NAC (e.g. Chin et al., 2007; Robinson et al., 2010) and Lunar Orbiter Laser Altimeter (LOLA) (e.g. Smith et al., 2010) datasets are available on the Planetary Data System (PDS) (http://pds.nasa.gov) while Kaguya TC data (e.g. Haruyama et al., 2008) are available on the SELENE Data Archive (http://l2db.selene.darts.isas.jaxa.jp/).

M^3 data were acquired in various phases known as optical periods and which represent various imaging conditions (Boardman et al., 2011). In this study, we used data from optical periods Op2c1 and Op2a. Mosaics were created for each optical period using imaging strips covering the area of study. The choice of the optical period was guided by the areal coverage, illumination conditions and spatial resolution. In this context, Op2c1 data was used because of its better viewing geometry which minimized shadows and facilitated detection of albedo differences. Op2a data was helpful due to its better data quality which could be used to identify small scale compositional differences. We used the Level 2 data for both optical periods which is publicly available and has all major corrections (viz. photometric, thermal) applied to it (e.g. Green et al., 2011).

The reflectance data from M^3 was initially used to derive various spectral parameters that allow general mapping of compositional differences in a spatial context. The M^3 parameters used in this study are described in supplementary information (Table 1). Subsequently, representative spectra from the study region were extracted to highlight the observed character of olivine lithologies. The spectra are presented as general reflectance variations and in a continuum-removed form, the latter highlighting fine-scale compositional differences. A linear continuum was estimated (for each spectrum) based on the spectral slope between 750 nm–1618 nm. The spectrum was then divided by the estimated continuum to evaluate diagnostic features.

3. New observations and insights

We have carried out detailed spectral and morphological analyses at Copernicus crater (9.62°, 339.92°; 96 km) on the lunar near side. It is a young, well-developed complex crater with a raised rim, well-formed terraces, extensive melt-covered floor and central peaks. Prominent occurrence of olivine throughout the central peaks and a well-defined olivine-bearing exposure in the northern wall (both outlined in red in Fig. 1b) are readily recognized in M^3 spectra. We report several new observations about these known olivine occurrences and discuss additional olivine-bearing exposures identified in this study.

3.1. Major albedo differences in olivine-bearing lithologies

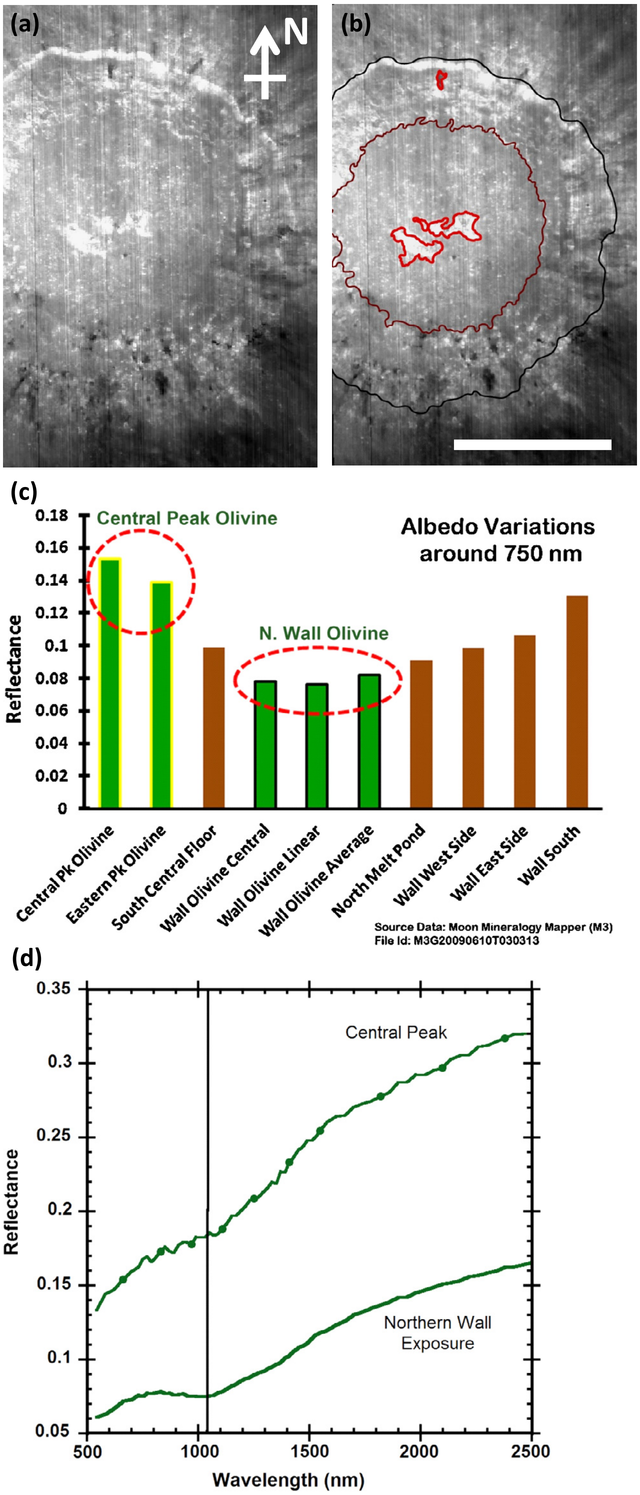

Fig. 1. Observed albedo differences between olivine-bearing central peaks and the northern wall exposure. (a) M^3 Op2c1 image highlighting bright central peaks and the relatively dark olivine-bearing northern wall. (b) The same image with the two locations outlined in red. Image Id: M3G20090610T030313. The phase angle for the acquired data was about 13°. Scale bar, 48 km. (c) M^3 Op2c1 reflectance values measured at 750 nm for the olivine bearing central peaks (light green bars), northern wall (dark green bars) and nearby locations (brown bars). (d) M^3 Op2a spectra illustrating the differences between olivine exposures in the low-albedo northern wall and the central peaks.

Photometrically-corrected high sun (low-phase angle) observations minimize shadows and maximize the ability to identify mineralogical and brightness differences. In this context, we note that the northern wall olivine-bearing exposure exhibits a dramatically lower albedo compared to the olivine-bearing lithology in the peaks. A comparison of albedo around 750 nm for various locations