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Comparison of lunar red spots including the crater copernicus

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ABSTRACT

The lunar red spots, Helmet, Hansteen Alpha, and the NW quadrant of the crater Copernicus, were selected for a complex comparative investigation of their characteristics measured by the spacecraft Clementine, LRO, and Chandrayaan-1. For the analysis we used the following parameters: the reflectance A(750 nm), color-ratio A(750 nm)/A(415 nm), parameter of optical micro-roughness (LRO WAC), parameters deduced from LRO Diviner data, optical maturity *OMAT*, abundance of FeO and TiO_2 (Clementine UVVIS and LRO WAC data), oxygen content determined using Lunar Prospector data, and parameters characterizing the 0.95-μm and 2.2-μm bands of Fe^{2+} ions (crystal field bands), and 2.8-μm band of H_2O/OH and/or Fe^{2+} ions. The red spots Helmet and Hansteen Alpha are considered to be extrusions of rhyolite composition, which can be attributed to the Nectarian period; we did not find contradictions of this assumption. As for the Copernicus red spot, this, perhaps, is a similar formation that has been destroyed by the impact. We demonstrate that the material of the Copernicus red spot probably has the same composition as the classical red spots Helmet and Hansteen Alpha. The distributions of the parameter of optical micro-roughness and optical maturity *OMAT* show that the Copernicus red anomaly was not formed during the long evolution of the lunar surface, but results from crater formation. We find several confirmations of the hypothesis that the Copernicus red spot can be a residual of a red material (possibly rhyolite) extrusion that was involved in the impact process. The red material could have been partially melted, crushed, and ejected to the crater's north-western vicinity. The described red asymmetry of the Copernicus ejecta can be related to the eccentricity, relative to the extrusion, of the impact and/or to the inclination of the impactor trajectory. The latter also is confirmed by an analysis of the region, which is based on the geological map shown in this paper.

1. Introduction

The lunar surface reveals pronounced chemical and mineral diversity that manifests itself in the regional variations of optical characteristics, such as albedo and different color-ratios. There are, in particular, regions having intermediate albedo A, but a significant excess of the color-ratio in the visible spectral range, A_{red}/A_{blue}. Several such red spots were found many years ago with Whitaker's color-ratio images (Whitaker, 1966, 1972). Red spots occur mostly on the western nearside of the Moon, in Oceanus Procellarum. These red formations are considered to be pre-mare materials of evolved composition (Malin, 1974; Head and McCord, 1978; Bruno et al., 1991; Raitala et al., 1999; Chevrel et al., 1999; Bondarenko and Shkuratov, 2000). These unusual formations occur within the predominantly basaltic terrain of the lunar surface. The red color of the areas is due to low titanium abundance (e.g., Burns, 1993) and partially can be related to the presence of nanophase metallic iron $npFe^0$ in regolith particles (e.g., Hapke, 2001; Tompkins and Pieters, 2010, Noble et al., 2007).

Examples of red spots are the formations Helmet, Hansteen Alpha, Gruithuisen Domes, Riffaeus Montes, and others (see Fig. 1). Using Lunar Prospector data, it was found that the lunar red spots poorly correlate with Th abundances. For example, Hagerty et al. (2006) have shown that Hansteen Alpha, the Gruithuisen Domes, and the Lassell massif all have Th abundances that are consistent with the presence of lunar granites (rhyolites). On the other hand,

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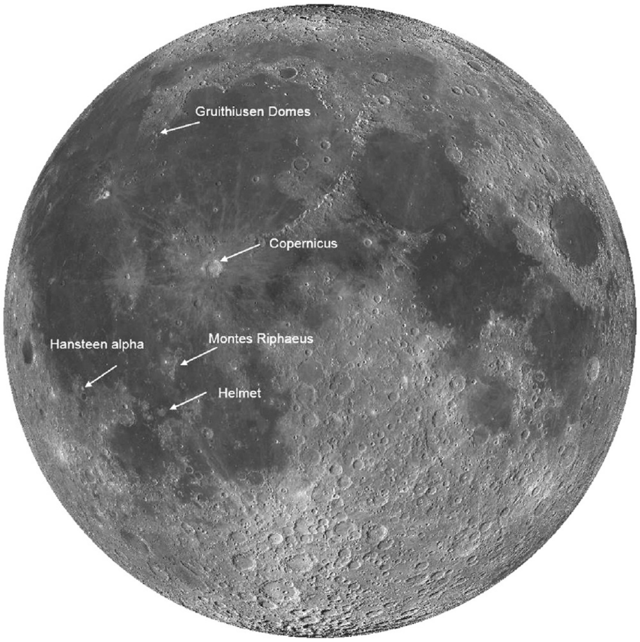

Fig. 1. The locations of several red spots on the lunar disk.

the formations Helmet and Montes Riffaeus do not have high Th content.

The LRO Diviner radiometer allowed measurements of the location of the Christiansen feature (CF) in spectra near 8 μm. The feature is related to the fundamental vibrational bands of silicates. The Christiansen frequency corresponds to the case when the real part of the refractive index of a material approaches 1. The feature position depends strongly on the mineral composition and allows one to remotely determine landforms rich in silica. It has shown that some lunar red spots exhibit Christiansen frequency locations consistent with high silica content (e.g., Glotch et al., 2010; Jolliff et al., 2011).

Recently, water and/or hydroxyl anomalies have been detected at several red spots (Bhattacharya et al., 2013; Pathak et al., 2015). This result is based on Chandrayaan-1 Moon Mineralogy Mapper (M^3) measurements. This may be related to endogenic/magmatic origin of the formations. Moreover, Bhattacharya et al. (2013) also have reported the presence of the prominent spinel feature in the Hansteen Alpha formation that somewhat contradicts the hypothesis about rhyolite composition of the formation materials. Using M^3 data, Pieters at al. (2014) also have found Mg-spinel at a few areas of hypothesized non-mare volcanism, in particular, in Hansteen Alpha (see also the discussion by Prissel et al., 2014).

Among the red spots, there is a red feature associated with the crater Copernicus, which is centered approximately at latitude +10.2°, longitude –20.9°; it is not usually considered in the common context of the red spots. It is interesting to compare optical properties of the Copernicus feature with other red spots in order to include it or not in the class of regular lunar red spots (Shkuratov et al., 2015).

We selected three areas for different comparative studies: the northwestern quadrant of the crater Copernicus, the formation Helmet that is located at the northern edge of the Humorum basin (latitude = –16.8°, longitude = –31.5°), and the polygonally shaped feature Hansteen Alpha that is centered at the latitude = –12.2° and the longitude = –50.1°. The formations Helmet and Hansteen Alpha are isolated domes 35 and 13 km in average diameter, respectively, which elevate over the surrounding mare surface. Their material appears to be brighter and more fresh-looking than that of nearby highland areas (Raitala et al., 1999). Hawke et al. (2002, 2003), Wilson and Head (2003), Hagerty et al. (2006), Wagner et al. (2010), and Glotch et al. (2010) considered that both these formations, perhaps, are rhyolite extrusions.

The crater Copernicus, 96 km in size, is located on the lunar near side. It is a bright, young crater, ~779 m.y. (Heisinger et al., 2012). Fig. 2a shows a portion of the LROC WAC mosaics (Korokhin et al., 2015; 2016) at $\lambda = 750$ nm around the crater. This region is optically and, hence, compositionally heterogeneous (e.g., Pinet et al., 1993; Dhingra et al., 2013, 2015). In particular, Dhingra et al. (2015) have discussed multiple origins for olivine-bearing lithologies at Copernicus crater.

Fig. 2b shows a color-ratio A(750 nm)/A(415 nm) image obtained with the LROC WAC mosaics (Korokhin et al., 2015, 2016). As one can see, there is an amazing feature in the left upper quadrant of the crater, which is very well detected in this color ratio. This color anomaly results from a spectrum characterized by strong ultraviolet absorption. A question arises: do the Copernicus red spot and the red extrusions (Helmet and Hansteen Alpha) have commonalities besides their color characteristics? We show here that the Copernicus feature can be related to the formations.

2. The parameters studied and source data

For the comparative investigation of the three areas, we used the following 12 parameters: the reflectance (albedo) A(750 nm), color-ratio A(750 nm)/A(415 nm), shaded topography images, parameter of optical micro-roughness, LRO Diviner rock abundance, parameter of optical maturity *OMAT*, abundance of FeO and TiO_2, oxygen content determined using Lunar Prospector data, and the parameters bend1, bend2, bend3 that characterize, respectively, the 0.95-μm and 2.2-μm bands of Fe^{2+} ions (crystal field bands), and 2.8-μm band of H_2O/OH and/or Fe^{2+} ions. We characterize the bands with the band bends calculated from Chandrayaan-1 M^3 spectral data. The bend1$= A_{750}A_{1109}/(A_{950})^2$, bend2 $= A_{1548}A_{2537}/(A_{2218})^2$, and bend3 $= \overline{A_3}\cdot\overline{A_1}/(\overline{A_2})^2$, where $\overline{A_1} = (A_{2657}+A_{2697}+A_{2737})/3$, $\overline{A_2} = (A_{2777}+A_{2817}+A_{2856})/3$, and $\overline{A_3} = (A_{2896}+A_{2936}+A_{2976})/3$; the albedo indices are the wavelengths given in nanometers. The first bend has been used, in particular, for the detection of lunar red spots (Raitala et al., 1999).

The Clementine 100-m mosaics (McEwen and Robinson, 1997), Lunar Prospector gamma-ray spectrometer (GRS) measurements (e.g., Lawrence et al., 2002; Elphic et al., 2002), Chandrayaan-1 M^3 IR spectrometer measurements (Pieters et al., 2009), and LROC WAC images (Robinson et al., 2010) were used as source data for the analysis. The 12 characteristics were calculated as described below. They are not independent of each other and the reliability of their determination is different, but it is sufficient for semi-quantitative assessments.

Using the LRO WAC data and Clementine mosaics we apply Lucey's method (Lucey et al. 1995, 2000) for the assessment of TiO_2, FeO abundance and the parameter of optical maturity *OMAT* with the following expressions:

$$\mathrm{FeO}[\%] = -17.43\left\{\arctan\left[\frac{A(950\ \mathrm{nm})/A(750\ \mathrm{nm}) - y}{A(750\ \mathrm{nm}) - x}\right]\right\} - 7.56, \quad (1)$$

$$\mathrm{TiO_2}[\%] = 3.71\left\{\arctan\left[\frac{A(415\ \mathrm{nm})/A(750\ \mathrm{nm}) - z}{A(750\ \mathrm{nm})}\right]\right\}^{5.98}, \quad (2)$$