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Nonmare volcanism on the Moon: Photometric evidence for the presence of evolved silicic materials

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ABSTRACT

Images and photometric data from the Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Cameras (NACs) are used to investigate regions of the Moon inferred from previous remote sensing compositional studies to be associated with nonmare, silicic volcanics. Specifically, LROC NAC imagery, with photometry normalized to account for local slopes using NAC Digital Terrain Models (DTMs), was used to investigate the exposed areas associated with the Compton–Belkovich Volcanic Complex (CBVC), Hansteen Alpha Volcanic Complex (HAVC), Lassell Massif (LM), Gruithuisen Domes (GD), and ejecta of Aristarchus Crater (AC). Photometric studies of spacecraft landing sites, for which ground-truth compositional data exist, allow us to study the relationship between photometric properties of soils and their mineralogical and chemical compositions. The silicic regions have high reflectance and single scattering albedos that are consistent with different proportions of highly reflective minerals including alkali feldspar and quartz, and low concentrations of mafic minerals. Of the silicic sites studied, the CBVC has the highest reflectance values and single scattering albedos. Silicic pyroclastic deposits may also occur at the CBVC, and we present evidence from laboratory spectra that an addition of up to ~20 wt% glassy silicic materials to a highlands-type regolith simulant can account for the increased reflectance of these volcanic regions. Reflectance variations across and within the sites can be explained by mixing of felsic mineral components, evolved-to-intermediate silicic compositions, and/or silicic pyroclastic deposits.

1. Introduction

Remote sensing data indicate rare localities on the Moon where silicic or “felsic” rocks occur as a result of nonmare (non-basaltic) volcanic or intrusive activity. Many of these areas have been classified as “red spots” and are characterized by their high albedo and strong absorption in the UV (first recognized by Whitaker, 1972), which cause them to appear spectrally red. An example of a Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) color composite (RGB) image (Sato et al., 2014) of one of these lunar “red spots”, Hansteen Alpha, is shown in Fig. 1. Some spectrally “red” spots are inferred to be silicic in composition based on Lunar Reconnaissance Orbiter (LRO) Diviner Christiansen feature data and Lunar Prospector gamma-ray spectrometer (LP-GRS) thorium data (Lawrence et al., 2003; Glotch et al., 2010; Greenhagen et al., 2010; Jolliff et al., 2011a; Ashley et al., 2016). Lunar samples that may be products of areas of non-mare volcanism, particularly silicic volcanism, are rare and underrepresented in the Apollo, Luna, and lunar meteorite samples, so we rely on remote sensing data to help determine the composition and formation of these regions.

Many of the areas inferred to be silicic “red-spots” correspond to high-thorium (Th) anomalies, as detected by the LP-GRS (Lawrence et al., 1998, 1999, 2000, 2003), and have low FeO (<5 wt%) contents (Lucey et al., 2000). They also tend to have relatively higher reflectance than their surroundings (Gillis et al., 2002). High thorium content coupled with high reflectance and low FeO contents implicates an alkali-suite rock type (i.e., alkali anorthosite) or a silicic rock type (granite/rhyolite) based on correlations between FeO and Th observed in Apollo samples (Jolliff et al., 2011a). Lunar granitic/rhyolitic materials contain low FeO (<5–7 wt%) and high Th contents (40–60 ppm), whereas alkali anorthosites have

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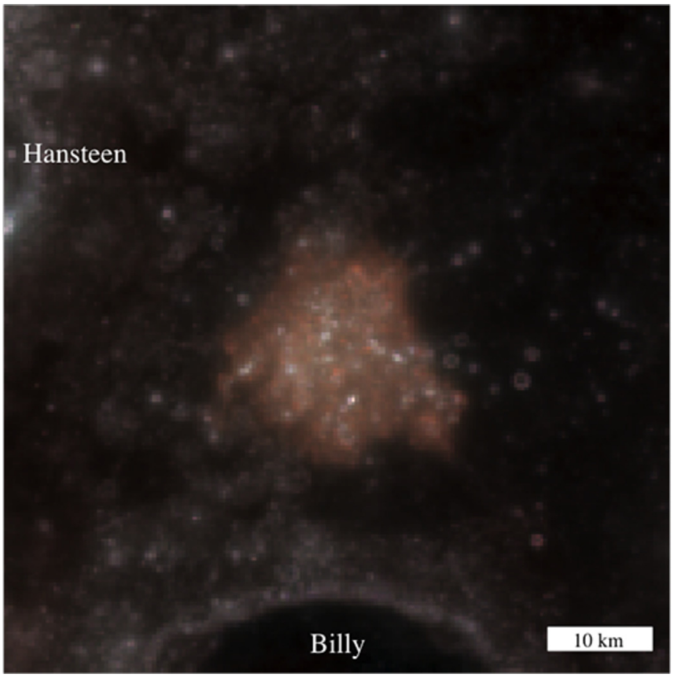

Fig. 1. WAC RGB color composite of Hansteen Alpha (R: 566 nm, G: 360 nm, B: 321 nm). Hansteen Alpha has a strong absorption in the UV and appears spectrally red, classifying it as a lunar "red spot". WAC color data compiled by Sato et al. (2014).

lower FeO (< 3 wt%) and Th (10–40 ppm) contents (Lawrence et al., 2003; Jolliff et al., 2011a). LROC Narrow Angle Camera (NAC) images show morphological features (cones, domes, etc.) that indicate these features are of volcanic origin, and data from the Diviner Lunar Radiometer show evidence for silicic compositions at these sites (Jolliff et al., 2011a; Glotch et al., 2010; Greenhagen et al., 2010; Ashley et al., 2016; Ivanov et al., 2016; Braden et al., in revision).

Both the Moon Mineralogy Mapper (M^3) and Diviner data indicate that some of the silicic areas, especially the Compton–Belkovich Volcanic Complex, may have OH/H_2O absorptions that could be attributed to the presence of pyroclastic deposits (Pieters et al., 2009; Petro et al., 2013; Bhattacharya et al., 2013). Additional modeling of the thorium data (Wilson et al., 2015) and radar data from Mini-RF onboard LRO (Nozette et al., 2010) support the occurrence of pyroclastics at the CBVC, discussed in Section 4.2. Using the various data sets discussed in this section to better understand non-mare volcanism on the Moon can help piece together the thermal history and crustal evolution of the Moon.

In this paper, we investigate how LROC NAC photometry (adjusted for topography and varying illumination conditions) can provide information about the composition and physical properties of materials at silicic sites. Factors such as composition and mineralogy, glass content, surface roughness, regolith structure, space weathering, and grain size can affect how a surface scatters light (Carrier, 1973; Hapke, 1981; Carrier et al., 1991; Hapke 2012; Hapke et al., 2012). Our goal is to determine if non-mare regions that show morphologic and photometric evidence of volcanic origin are made of granitic (rhyolitic) or felsic materials such as those that occur in Apollo samples, and to quantify compositions and abundances at the NAC scale, i.e., an outcrop scale of 1 to several meters. We quantitatively investigate the reflectance of the silicic sites at the NAC scale and use Hapke photometric modeling to compare the reflectance of areas that occur at different latitudes. We then use the Hapke photometric model to test variable parameters to determine which parameters could best account for the reflectance characteristics observed over a range of illumination conditions, as well as determine a relationship between reflectance and soil composition using data from returned Apollo and Luna soil samples. By coupling soil compositional data with photometric characteristics such as single scattering albedo and normalized reflectance, we assess variability in reflectance and composition for several highly reflective areas on the Moon (Fig. 2): the Compton–Belkovich Volcanic Complex (CBVC), the Hansteen Alpha Volcanic Complex (HAVC), Gruithuisen Domes (GD), the Lassell Massif (LM), ejecta of unusually silicic composition from Aristarchus crater (AC), and a reference area interpreted to be pure anorthosite (PAN) on the basis of hyperspectral data (Fig. 3) (Ohtake et al., 2009; Cheek et al., 2013; Donaldson et al., 2014). Finally, we present evidence from laboratory spectra that addition of glassy silicic materials to a highlands-type simulant can account for the increased reflectance at some areas within these volcanic regions (Clegg et al., 2015).

1.1. Compton–Belkovich Volcanic Complex

Lunar Prospector GRS data detected an isolated thorium anomaly centered broadly at 61°N, 100°E on the lunar farside between the craters Compton and Belkovich (Lawrence et al., 1999, 2000, 2003, 2007). Lawrence et al. (2003) calculated that the Th concentration at this feature might be as high as 40–55 ppm. A small region of elevated topography and high reflectance covering an area ~25 × 35 km lies approximately at the center of this thorium hotspot and is referred to as the Compton–Belkovich Volcanic Complex (CBVC; 61.1°N, 99.5°E; Jolliff et al., 2011a), shown in Fig. 2a.

The high reflectance of this area was first observed by Gillis et al. (2002) and is apparent in LROC NAC and WAC images. The volcanic complex is a small, isolated topographic and morphologic feature situated on the second ring of Humboldtianum basin and about 20 km east of the topographic rim of the 200 km diameter Belkovich Crater. It contains a range of volcanic features, including irregular collapse features, small domes, and several large volcanic constructs (cones or cumulo domes) (Jolliff et al., 2011a; Chauhan et al., 2015). The central part of the complex may be an irregularly shaped collapsed caldera. The central part of the elevated topographic feature rises 400–600 m above the surrounding terrain, and the elevated topography corresponds approximately, but not precisely, with the high-reflectance area (Fig. 4) (Jolliff et al., 2011a). A shallow intrusion of evolved magma may have led to the uplift of topography seen at the CBVC. Diviner Christiansen Feature (CF) data show evidence for silicic composition corresponding to the topographic and albedo feature at the CBVC, and Jolliff et al. (2011a) suggested that the CBVC likely contains compositionally evolved rock types such as granite or rhyolite. No other areas on the lunar farside have such a distinct felsic signature and very few other volcanic constructs on the Moon exhibit such a range of collapse features and domes (Jolliff et al., 2011a), making the CBVC a noteworthy and perhaps unique feature on the Moon.

Shirley et al. (2016) determined the age of the CBVC to be ~3.5 Ga, using crater size-frequency analyses (CSFD). They determined that the CBVC is younger than nearby Compton Crater, which has a well-defined CSFD of 3.6 Ga. Consideration of the largest and most degraded craters within the CBVC led to the inference that the volcanic activity occurred on a surface whose age and topography were reset at ~3.7–3.8 Ga by the formation of Belkovich Crater.

1.2. Hansteen Alpha

Hansteen Alpha (HA) is an arrowhead-shaped topographic feature centered at 12.3°S, 50.2°W in southwestern Oceanus Procellarum (Fig. 2b). It is located close to the rims of two 45 km