Planetary and Space Science 106 (2015) 67–81

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Lunar cryptomaria: Mineralogy and composition of ancient volcanic deposits

Jennifer Whitten [a,*], James W. Head [b]

[a] Smithsonian Institution, Center for Earth and Planetary Studies, MRC 315, PO Box 37012, Washington, DC 20013-7012, USA
[b] Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912, USA

ARTICLE INFO

Article history:
Received 17 June 2014
Received in revised form
23 October 2014
Accepted 27 November 2014
Available online 6 December 2014

Keywords:
Moon
Volcanism
Cryptomaria
Moon Mineralogy Mapper
Visible to near infrared
Spectroscopy
Modified Gaussian Model (MGM)

ABSTRACT

Ancient lunar volcanic deposits, known as cryptomaria, have been detected by remote telescopic and orbital measurements since the 1970s. Cryptomaria are most easily identified by the presence of dark-halo impact craters and are associated with a mare basalt mineralogy, which is indicated by two pyroxene spectral absorption features near 1 μm and 2 μm in the visible to near-infrared (VNIR) wavelengths. However, there are many early igneous lithologies that have been identified in the Apollo sample collection that have a similar VNIR spectral signal, implying a pyroxene-dominant mineralogy. In this study we use high resolution Moon Mineralogy Mapper (M^3) VNIR spectral data and the Modified Gaussian Model (MGM) to determine cryptomare mineralogy as well as Lunar Prospector gamma-ray spectrometer (LP GRS) FeO and Th compositional measurements to evaluate which ancient igneous rocks (e.g., low-Ti mare basalt, high-Ti mare basalt, Mg-suite rocks, dunite, high-Al mare basalt, KREEP basalt) are consistent with our mineralogical observations. In addition, spectra from different M^3 optical periods were compared to determine how the MGM-derived absorption band centers vary between datasets. Band center differences between optical periods are on the order of $\sim 6 \pm 4$ nm and $\sim 25 \pm 10$ nm for the 1 μm and 2 μm features, respectively. Cryptomare mineralogies are dominated by clinopyroxene and are consistent with measurements from locally exposed mare basalts. LP GRS measurements support a mare basalt rock type when regolith mixing is taken into account.

1. Introduction and background

Ancient lunar volcanic deposits, known as cryptomaria (Head and Wilson, 1992), have been identified beneath basin ejecta deposits (e.g., Schultz and Spudis, 1979, 1983; Hawke and Spudis, 1980; Hawke and Bell, 1981; Bell and Hawke, 1984; Hawke et al., 1993, 2002, 2005, 2013; Head et al., 1993; Antonenko et al., 1995; Blewett et al., 1995; Mustard and Head, 1996; Antonenko, 1999; Giguere et al., 2003; Campbell and Hawke, 2005; Lawrence et al., 2008). The name assigned to these ancient volcanic deposits, cryptomaria, implies that these ancient volcanic deposits are mare basalts. However, mare basalts are not the only ancient igneous lithology that was produced on the Moon during its earliest geologic history. Samples returned from the Apollo missions indicate that a diverse suite of ancient rock types, including ferroan anorthosites, KREEP basalts, high-Al mare basalts, and Mg-suite rocks such as troctolites, dunites, norites, and gabbros (e.g., Warren and Wasson, 1977) formed during the final stages of the lunar magma ocean crystallization and shortly thereafter. The primary lunar crust is dominated by ferroan anorthosites (Smith et al., 1970; Wood et al., 1970), while extrusive KREEP basalts and intrusive Mg-suite rocks are derived from melts of the lunar mantle (Warren and Wasson, 1977). The few dated samples of Mg-suite rocks and KREEP basalts indicate ancient ages >3.8 Ga, immediately after the Imbrium formation event (Nyquist et al., 1975; Papanastassiou and Wasserburg, 1976; Ryder and Spudis, 1980; Nyquist and Shih, 1992; Stöffler et al., 2006). There is no indication that these lithologies continued to be produced after 3.8 Ga. The paucity of Mg-suite and KREEP basalt rocks in the sample collection could be due to a preservation effect, since much of the lunar nearside has been resurfaced by mare basalts over the last 3.8 Ga (Hiesinger et al., 2011), or it could be due to a cessation of their formation process. Whatever the cause of the paucity of the Mg-suite and KREEP basalts, mare basalts became the dominant igneous rock type for the remainder of the Moon's volcanic history.

Deconvolving the composition of ancient volcanic materials has important implications for the thermal history of the Moon. Analyses of mare basalt ages and their distribution provide information about mantle dynamics, including the timing of magma ocean overturn and the formation of mare basalt source regions in the mantle. Cryptomaria composition is also important

---

* Corresponding author. Tel.: +1 202 633 1585.
E-mail address: WhittenJ@si.edu (J. Whitten).

http://dx.doi.org/10.1016/j.pss.2014.11.027
0032-0633/© 2014 Elsevier Ltd. All rights reserved.

for determining the composition of magmas melting within and being erupted from the mantle. For instance, Mg-rich mantle melts may have been produced early in lunar history, intruding into the anorthositic crust, and it is only after mantle overturn (e.g., Hess and Parmentier, 1995) that the mare basalt source regions were established and able to melt. The frequency distribution of mare basalt crater retention ages (Hiesinger et al., 2011) shows a peak in the flux of volcanic activity around ~3.6 Ga. Returned samples tell the story of a much more compositionally and temporally diverse volcanic history compared to the mare basalt deposits. During the first ~500 My, the Moon was simultaneously producing mare basalts, KREEP basalts, and Mg-suite rocks (Ryder and Spudis, 1980; Taylor et al., 1983; Nyquist and Shih, 1992; Stöffler et al., 2006; Terada et al., 2007). Soon afterwards, around 3.8 Ga, there was either a substantial increase in the eruption of mare basalts or a decrease in the production of parental melts for KREEP basalts and Mg-suite rocks, or both processes occurred simultaneously.

Cryptomaria were first identified by the presence of dark-halo impact craters (DHCs) (Schultz and Spudis, 1979, 1983), which are small impact craters, <10 km in diameter, that excavate low albedo material from beneath higher-albedo surface material; these are not to be confused with other dark-halo craters interpreted as volcanic vents (e.g., Shoemaker, 1962; Head and Wilson, 1979). Initially, the DHC compositions were reported as basaltic, with some deposits being enriched in magnesium and KREEP (Schultz and Spudis, 1979). Geochemical analyses of cryptomaria utilized measurements of elemental ratios, such as Mg/Al and Mg/Si, and elemental abundances (thorium and iron) from gamma-ray and x-ray spectrometer data (Hawke and Spudis, 1980; Maxwell and Andre, 1981; Lawrence et al., 2008). Measurements of elemental abundances over regions of the lunar surface with a high concentration of DHCs were compared with mare basalts and KREEP-rich basalts in order to ascertain the composition of the buried volcanic material. These geochemical surface measurements of DHCs resulted in a variety of interpretations, including the presence of Mg-rich basalts, mare basalts, and KREEP-rich basalts (e.g., Schultz and Spudis, 1979; Hawke and Spudis, 1980; Lawrence et al., 2008).

Further geochemical and visible to near-infrared (VNIR) spectral analyses suggested that the compositions of DHCs were consistent with mare basalt material (Maxwell and Andre, 1981; Hawke and Spudis, 1980; Hawke and Bell, 1981; Bell and Hawke, 1984; Blewett et al., 1995; Giguere et al., 2003; Hawke et al., 2005; Lawrence et al., 2008). DHC VNIR spectral measurements are dominated by two pyroxene absorption features centered near 1 μm and 2 μm. At VNIR wavelengths, the center wavelength of the different absorption bands provides information about the composition of the pyroxene; longer wavelength 1 μm and 2 μm absorption features are associated with Fe- and Ca-rich pyroxenes (Adams, 1974; Cloutis and Gaffey, 1991) and are consistent with mare basalts. As a result of the systematic change in band center with mineral composition, many spectral studies of DHCs have focused on measuring the position of the pyroxene absorption band centers and comparing those values to the composition of known lunar samples (e.g., Bell and Hawke, 1984) or exposed mare basalt deposits from the same image scene (Blewett et al., 1995; Giguere et al., 2003; Hawke et al., 2005).

The mineralogy and composition of identified ancient volcanic deposits is important for understanding the early volcanic history of the Moon and the petrologic relationship between the different ancient igneous lithologies. Therefore, we have undertaken a study of the mineralogy of DHCs identified in Whitten and Head (2015) using Moon Mineralogy Mapper (M^3) VNIR spectral data, as well as an analysis of LP GRS elemental data. The purpose of this investigation is to: (1) determine the mineralogy of mapped cryptomaria to ascertain if some or all of the deposits are mare basalts, (2) investigate the mineralogical variations both within a cryptomare region and also between cryptomare regions, (3) measure the compositional characteristics (Th and FeO) of all identified cryptomaria to further characterize and constrain their compositions, and (4) understand how calculated cryptomaria mineralogies compare with ancient volcanic lithologies from the Apollo sample collection. Despite the fact that the Mg-suite is interpreted as intrusive, the Mg-suite lithologies (e.g., troctolite, norite) are included in this analysis in order to make the fewest number of assumptions about the mineralogy and composition of cryptomaria; at some time during early lunar history conditions may have been such that the eruption of Mg-suite parental magmas was possible (Prissel et al., 2013).

2. Methods

2.1. Collection of VNIR spectra

All of the VNIR spectra used in this study were collected from the Moon Mineralogy Mapper (M^3) dataset (Boardman et al., 2011; Clark et al., 2011; Green et al., 2011; Besse et al., 2013). M^3 was a VNIR imaging spectrometer aboard the Chandrayaan-1 spacecraft that collected mineralogic information about the Moon's surface in 85 bands, from approximately 0.4–3.0 μm, at a spatial resolution of 140–280 m/pixel, depending on the spacecraft altitude (Pieters et al., 2009; Green et al., 2011). All spectra examined in this study were collected from M^3 mosaics composed of individual data strips (Table S3) and have a spatial resolution of 140 m/pixel. A total of 1020 reflectance spectra (3×3 pixel averages) were collected from individual DHCs located within 20 mapped cryptomare locations and any associated exposed mare basalt deposits (Figs. 1a and S1; Tables S1 and S2) (Whitten and Head, 2015). Each region of mapped cryptomare contains between 1 and 40 individual volcanic ponds (Fig. S1) and between one and three DHCs were sampled from each volcanic pond (Table S4). All DHC spectra within an individual volcanic pond were investigated and only those with the strongest absorptions were sampled for analysis. These individual DHC spectra were then averaged together to produce a single diagnostic spectrum for each volcanic pond within a given cryptomare region. The 1020 individual cryptomare and mare spectra were thus reduced to a total of 414 diagnostic spectra; each cryptomare region has multiple spectral measurements, one for each individual volcanic pond (Tables S1, S2 and S4).

A ground truth correction derived from laboratory spectra of feldspathic lunar soils was applied to the sampled M^3 spectra. This correction improves the accuracy of the position of the M^3 1 μm absorption feature and is especially relevant for spectral analyses involving highland soils (Isaacson et al., 2013). The spectral data used in this study were collected from multiple M^3 optical periods, including 1b, 2c1, and 2c2. The shape of spectra collected during different M^3 optical periods varies depending on the detector temperature; spectra collected during “hot” optical periods where temperatures exceeded ~160 K (2c1 and May 20–July 9, 2009 of 2c2) required a different ground truth correction (Isaacson et al., 2013) compared with spectral data from “cold” optical periods (1b and July 12–August 16, 2009 of 2c2) (Green et al., 2011). In order to quantify the spectral differences between optical periods, we compared the Modified Gaussian Model (MGM)-derived 1 μm and 2 μm absorption band centers from the same sample location in two different optical periods. Australe, Dewar, Langemak, Lomonosov–Fleming and Van de Graaff spectra were used for the optical period 2c2–2c1 comparisons while spectra from Cleomedes, Frigoris, Mendel–Rydberg, Schiller–Schickard, Taruntius, West Humorum, and