Compositional variability of the Marius Hills volcanic complex from the Moon Mineralogy Mapper (M3)

S. Besse,1 J. M. Sunshine,1 M. I. Staid,2 N. E. Petro,3 J. W. Boardman,4 R. O. Green,5 J. W. Head,6 P. J. Isaacson,6 J. F. Mustard,6 and C. M. Pieters6

Received 30 August 2010; revised 25 December 2010; accepted 21 February 2011; published 12 May 2011.

[1] Using the Moon Mineralogy Mapper(M3), we examine the Marius Hills volcanic complex for the first time from 0.46 to 2.97 μm. The integrated band depth at 1 μm separates the mare basalts on the plateau in two units: (1) a strong 1 μm band unit of localized lava flows within the plateau that has similar olivine-rich signatures to those of the nearby Oceanus Procellarum and (2) a weaker 1 μm band unit that characterizes most of the basalts of the plateau, which is interpreted as having a high-calcium pyroxene signature. Domes and cones within the complex belong to the high-calcium pyroxene plateau unit and are associated with the weakest 1 μm band observed on the plateau. This difference could be the result of higher silica content, more opaque minerals, and/or a weaker olivine content of the magma. Finally, the floor of Marius crater has one of the strongest olivine-rich signatures of the entire Marius Hills complex. These compositional differences are indicative of the long and complex volcanic history of the region. The first episode started before the emplacement of the surrounding basalts of the plateau and produced the high-calcium pyroxene flows present on the plateau and their associated domes and cones. The second episode occurred concurrently or slightly after the emplacement of the adjacent Procellarum basalts and produced the olivine-rich basalts seen within the plateau, outside the plateau, and in Marius crater. If the olivine content of the lava flows increases with time, the olivine-rich region on the floor of Marius crater may represent one of the latest episodes of volcanism exposed on the Marius Hills complex.


1. Introduction

[2] The Marius Hills volcanic complex (MHC) is one of the largest volcanic complexes on the Moon. The diversity of the geologic features (e.g., cones, domes, rilles, lava flows) indicates that volcanic activity was very important and very complex in this area. The MHC is a 35,000 km2 plateau located in central Oceanus Procellarum at 13.3N/306.8E and rising 100–200 m from the surrounding plains [Head and Gifford, 1980; Whitford-Stark and Head, 1977]. A Moon Mineralogy Mapper (M3) mosaic of the MHC including the volcanic edifices and Marius crater is presented in Figure 1 at a resolution of 280 m/pixel (m/pix). Observations of the MHC with the Lunar Orbiter Laser Altimeter (LOLA) [Smith et al., 2010] are presented in Figure 2. To understand the different volcanic episodes that built the MHC, it is necessary to study the domes, cones and lava flows of the MHC as well as to compare deposits them with the surrounding mare basalts of Oceanus Procellarum. The surface of the Moon is dominated by mafic minerals (e.g., olivine, pyroxenes) and plagioclase. These minerals present specific spectroscopic signatures and in particular absorption bands in the 1 μm region of the electromagnetic spectrum as described in Figure 3. The M3 spectrometer onboard the Chandrayaan-1 spacecraft is a unique opportunity to examine in details the MHC with a high spectral resolution.

[3] The MHC has the highest concentration of volcanic features in Oceanus Procellarum [Whitford-Stark and Head, 1977]. A detailed study of 200 volcanic domes on the nearside by Head and Gifford [1980] demonstrated the Marius Hills domes are a unique class with irregular shapes, complex surface details, and a few summit craters or cones on top of some domes. The MHC contains 262 domes divided in two types, low domes and steep domes [Whitford-Stark and Head, 1977]. Low domes have a diameter up to 25 km and are 50–200 m high. Steep domes have a diameter of

---

1Department of Astronomy, University of Maryland, College Park, Maryland, USA.
2Planetary Science Institute, Tucson, Arizona, USA.
3NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
4Analytical Imaging and Geophysics LLC, Boulder, Colorado, USA.
5Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.
6Department of Geological Sciences, Brown University, Providence, Rhode Island, USA.

Copyright 2011 by the American Geophysical Union. 0148-0227/11/2010JE003725
2–15 km, an elevation of 200–500 m and many are located on the top of low domes.

4 The MHC also contains 59 cones with a maximum diameter of 3 km and an elevation up to 300 m above the plateau surface [Whitford-Stark and Head, 1977]. The cones of the MHC commonly display a horseshoe appearance resulting from the breaching of one side of the cone by lava flows. The cones are not only located on top of the domes, but can also be found on ridges and plains materials, most commonly between other edifices. Many of these isolated cones are not breached. Whitford-Stark and Head [1977] interpreted the cones to be composed of pyroclastic materials. The cones formed on the Moon are broader and lower than those formed on Earth because of the low gravity and lack of atmosphere [Wilson and Head, 1981]. Finally, at least one cone has been identified as the source of one of the Marius Hills rilles [Greeley, 1971].

5 There are 20 sinuous rilles located predominantly in the western region of the MHC [Whitford-Stark and Head, 1977]. Recent observations by the Lunar Reconnaissance Orbiter (LRO) spacecraft allow the production of a local Digital Terrain Model (DTM) for at least one of them [Lawrence et al., 2010]. The average relative depth along sinuous rille A [after Greeley, 1971] is 250 m, with layers formed by lava flows and large boulders exposed in the walls [Lawrence et al., 2010]. This rille is indicated by the A in Figure 1.

6 Although the MHC was determined to be composed of different volcanic edifices and lava flows on the basis of photogeologic analyses, the first identification of different compositional units was made by Sunshine et al. [1994] using the Galileo multispectral images at a scale >1 km. Two units were identified based on the brightness differences and ratios in the visible and near infrared (0.76/0.99 μm, a simplified 1 μm band strength). Later observations of the MHC with Clementine multispectral data allowed Weitz and Head [1999] to identify two units with mixed boundaries: a high-titanium basalt unit and a low-titanium basalt unit. Heather et al. [2003] use a technique detailed by Heather [2000] to map lava flows of the MHC. Six main units were mapped according to the UV/VIS slope, the strength of the 1 μm band and the estimated TiO₂ content.

7 These studies made using the Clementine data provide constraints for all the volcanic features of the MHC. The domes are distributed on all types of lava flows and are spectrally identical to the surrounding mare, both high-titanium and low-titanium mare [Heather et al., 2003; Weitz and Head, 1999]. No spectral differences were identified between the different type of domes (e.g., low/step domes). The domes are embayed by the basalts of the plateau that represent a later phase of highly effusive activity. These basalts are varied in composition and dominated by a high-titanium basalt unit [Heather et al., 2003]. Weitz and Head [1999] proposed a complex formed by numerous dikes of
various composition to explain the diversity of the domes and lava flows composing the MHC. Heather et al. [2003] proposed the same explanation but noted that a single source is possible if a long period of time is allowed for the titanium content of the magma to evolve. The formation of the domes may have occurred with a low effusion rate, a low temperature, and a crystallization of the magma [Heather et al., 2003; Weitz and Head, 1999]. In Clementine multispectral images, the cones are spectrally different from the surrounding mare (and thus the domes), with lower reflectance and weaker mafic absorptions [Heather et al., 2003; Weitz and Head, 1999]. Both authors suggest a fine-grained crystallization of the glassy lavas to explain the spectral properties of the cones. Campbell et al. [2009] studied the domes with Earth-based radar observations at 12.6 and 70 cm. The high circular polarization ratio of the domes was interpreted to result from blocky lavas that composed the domes beneath, at most, a few meters of regolith. The cones are not evident in the radar observations (likely due to the low spatial resolution of the observations of Campbell et al. [2009]).

The spatial resolution has so far been limited to approximately 200 m/pix for spectral observations of the MHC. In the case of Marius Hills, this resolution allows the distinction of cones and domes. The MHC has been observed during the LRO and Kaguya missions, LROC and the HDTV camera provide very high spatial images but with no spectral information. Previous mineralogic interpretations of the MHC were mainly limited by the spectral resolution of available data. Galileo multispectral data and Clementine contain few channels and extend only to 1 μm. Ratios in the ultraviolet, visible and near infrared were used to distinguish cones from their surroundings and to map the different units of the plateau. However, a complete study of the 1 μm

Figure 2. Topographic map of the Marius Hills volcanic complex using the Lunar Orbiter Laser Altimeter (LOLA) on board the Lunar Reconnaissance Orbiter mission (LRO). The along-track spatial resolution is about 20 m, and the cross-track resolution is approximately 1.6 km. The highest altitude of the plateau is localized in the central eastern part of the plateau that has been observed by M3 only during OP2C (see section 2.2 for details). Figure 2 covers a wider area than Figure 1, especially toward the western part of the plateau. The arrow points to the dome discussed at the end of section 3.

Figure 3. Reflectance spectra of the most common mafic minerals of lunar samples measured in Earth-based laboratory. Low-calcium pyroxene is the solid line, and high-calcium pyroxene the dashed line. The M3 channels for the lower-resolution global mode (85 bands) are shown along the top.
basalts on the MHC and the spatial variability of the different mineralogical units. Ultimately, the better spectral resolution of M$^3$ will define new mare units and areas that will be different to those proposed by Heather et al. [2003]. A better understanding of the composition (i.e., olivine and pyroxenes) and distribution of the mare units will give us a better understanding of the MHC history and facilitate their integration into the context of Oceanus Procellarum as a whole. In this study, we will examine the MHC at spatial resolutions of 140 and 280 m/pix using M$^3$ images with spectral resolutions of 20 and 40 nm between 0.43 and 3 $\mu$m. Spectral signatures of lunar terrains are strongly impacted by space weathering and maturity. Therefore, we compare units that have similar maturity and carefully select the spectra to avoid maturity effect.

2. Instrument, Data, and Calibration

2.1. The Moon Mineralogy Mapper (M$^3$) on Board the Chandrayaan-1 Spacecraft

[9] M$^3$, a guest instrument aboard India’s Chandrayaan-1 mission to the Moon, is a 0.43 to 2.97 $\mu$m imaging spectrometer. The spacecraft was launched 22 October 2008 and M$^3$ started to acquire data on 19 November. After more than nine months of lunar observations, the spacecraft stopped sending radio signals on 29 August 2009. During the Chandrayaan-1 mission, M$^3$ mapped more than 95% of the Moon [Boardman et al., 2011] with resolutions of 140 and 280 m/pix with 85 spectral channels in global mode.

[10] The large spectral range and the performance of M$^3$ has already led the team to new discoveries on the surface of the Moon [Pieters et al., 2009, 2011; Sunshine et al., 2010] and emphasizes the importance of extending the spectral range of observations of the Moon.

2.2. Data Used in This Study

[11] The MHC was observed at three different times during the mission resulting in three different coverages, observation conditions, and resolutions. The different times of observation are referred to as Optical Periods (OP). There are five different sets of observations: OP1A, OP1B, OP2A, OP2B and OP2C as discussed by Boardman et al. [2011]. Most of the time, the detector was above its nominal operating temperature, which degrades the signal-to-noise ratio and contributes to vertical stripes visible in the images presented in this paper (see section 2.2 for details). These 750 nm images are vertically aligned with respect to OP2C.

[12] A summary of all the observations of the MHC is presented in Figure 4. Initial coverage of the MHC during OP1B and OP2A was incomplete, with a resolution of 140 m/pix and a phase angle of 45°–62° for OP1B, and 44°–68° for OP2A. The midwest part of the plateau was observed during OP1B. The mosaic of these observations was produced from five individual strips. The coverage with OP2A was less extensive to the west, but the central part of the plateau was better covered and the eastern part of Marius crater was available. The mosaic of these observations consists of seven individual strips. The coverage with OP2A was less extensive to the west, but the central part of the plateau was better covered and the eastern part of Marius crater was available. The mosaic of these observations consists of seven individual strips. During OP2C, the altitude of the spacecraft was raised from 100 to 200 km due to thermal and other technical issues with the spacecraft. Consequently, the entire plateau was observed at a degraded resolution of 280 m/pix. The phase angle was also much lower in OP2C, between 11° and 19°. The mosaic of OP2C observations...
contains 6 individual strips; the black gap on the right of Figure 4 (bottom) is the only area of the MHC not covered by OP2C observations. [13] Data from OP2C observations are used in this paper to discuss the spectral properties of the entire plateau and of Marius crater, which is incomplete or absent from other periods. Data from OP1B and OP2A observations are used to discuss the spectral properties of the domes and cones, as the resolution is two times better than OP2C.

2.3. Data Calibration

2.3.1. M3 Calibration

[14] The calibration of M3 is presented in detail by R. O. Green et al. (The Moon Mineralogy Mapper (M3) imaging spectrometer for lunar science: Instrument, calibration, and on–orbit measurement performance, submitted to Journal of Geophysical Research, 2011). All data presented in this paper have been processed through the M3 standard calibration pipeline to produce radiance with flat field, dark current, solar, and geometric corrections. All data presented here are based on the K version of the radiance calibrations of M3. There are some known issues in this version of the calibration that have been addressed in subsequent versions, specifically a scattered light component below 1 \( \mu \)m and an electronic panel residual (Green et al., submitted manuscript, 2011).

[15] To obtain apparent reflectance, we use the following simple equation:

\[
ARFL = \frac{RAD \times \pi}{F^* \cos(i)}
\]

where \( RAD \) is the measured radiance, \( F \) is the solar flux, and \( i \) the solar incidence angle during acquisition. A thermal correction [Clark et al., 2011] and a photometric correction [Hicks et al., 2011] are under development but were not applied for this analysis. Consequently, we limit our study to 2.2 \( \mu \)m where thermal effects are minimal.

2.3.2. Selenolocation of OP2C Data

[16] The initial spacecraft pointing was poorly known for OP2C data, often resulting in inaccurate spatial location on the surface and orbit-to-orbit offsets between M3 data strips. Typically, offsets can be on the order of a few kilometers and sometimes more than 20 km in the worst cases. Systematic corrections are being applied to data for delivery to PDS. However, orbits of the data analyzed and presented here have been manually corrected and mosaiced. These corrections were made by choosing tie points between adjacent strips (mainly craters) and shifting them so that the volcanic domes present on two strips match. Because we used the overlap of adjacent M3 observations to correct the orbit-to-orbit errors, the mosaic produced specifically for this study is not tied to any base map. The shift applied to the strips was also applied to the geometric parameters to produce an estimated parameters used to derive the apparent reflectance.

2.4. Spectral Parameters

[17] The wide spectral range of M3 enables analysis of both the 1 \( \mu \)m and the 2 \( \mu \)m regions, which are important wavelengths for the study of mafic minerals such as those on the surface of the Moon. Because we did not correct thermal effects, we focus on the 1 \( \mu \)m region and, occasionally, describe the shape of the 2 \( \mu \)m region below 2.2 \( \mu \)m. The shape and the depth of the absorption bands give us crucial information about the composition of the surface. In order to characterize the depth of the 1 \( \mu \)m absorption band, we use an integrated band depth (IBD) parameter for the 1 \( \mu \)m region (IBD1000 hereafter). This IBD calculates the area of the absorption band region using

\[
IBD1000 = \sum_{n=0}^{26} \left(1 - \left(\frac{R(789 + 20n)}{R_C(789 + 20n)}\right)^{\frac{1}{5}}\right)
\]

\( R_C \) is the 1 \( \mu \)m continuum reflectance at the given wavelength. Band depth is calculated between 789 and 1308 nm for the 1 \( \mu \)m band (26 bands spaced at 20 nm each).

[18] The IBD1000 can vary due to the abundance of mafic minerals, which will affect the strength of the absorption band or due to mineral composition, which will affect the shape of the band. Consequently, this parameter must be used cautiously as two different compositions can give the same results. An olivine composition will increase the band depth toward longer wavelengths. However, the IBD1000 can be the same for a stronger low calcium-pyroxene composition because the absence of absorption at longer wavelengths is compensated by a stronger absorption at short wavelengths. The IBD1000 is useful for mapping different units as done in preliminary analyses of the MHC [Besse et al., 2010]. However, the interpretation of the units cannot be made without an analysis of the complete spectrum.

[19] In order to characterize the 1 \( \mu \)m band, we use a continuum removal method that enhances the characteristic of the 1 \( \mu \)m absorption band and more accurately shows the position of the center of the band. We used a straight line between 0.73 and 1.60 \( \mu \)m as defined by Pieters et al. [1993]. This is modified slightly for M3 data, we fit a straight line between 0.73 and 1.62 to remove the continuum.

3. Spectral Signatures of the MHC Mare Basalts

[20] The MHC is composed of various volcanic features and basalt units with different composition. These different units were identified based on brightness differences and ratios in Galileo data [Sunshine et al., 1994], and ratios between the few spectral channels of the Clementine UVVIS camera (e.g., 750, 900, 950, and 1000 nm) [Weitz and Head, 1999; Heather et al., 2003]. These channels were chosen because they allow the discrimination between pyroxene types (high Ca versus low Ca), but they are not optimum for distinguishing olivine. The youngest basalts of Oceanus Procellarum are located close to the Aristarchus and the Marius Hills plateaus [Hiesinger et al., 2003]. These young basalts have been interpreted to be richer in olivine [Staid et al., 2011; Staid and Pieters, 2001; Pieters et al., 1980]. The spectral range of M3 allows the investigation of the entire 1 \( \mu \)m band, as well as the discrimination of different mafic minerals that contribute to the 1 \( \mu \)m band, especially pyroxenes and olivine.

[21] Figure 5 presents an image of the IBD1000 parameter for the MHC. In Figure 5, the different greyscale correspond to the strength of the 1 \( \mu \)m band depth; darker areas have a weaker 1 \( \mu \)m band depth. The vertical stripes, and in general the noise of these data, are largely a result of a preliminary calibration. The noise and striping make parameter maps such as that shown in Figure 5 unfavorable for using the mapping.
techniques developed by Heather et al. [2003] to distinguish among mare units. However, the MHC can be easily separated in two mare units that exhibits different characteristic of the 1 \( \mu m \) band. The distinction of two flows on the MHC follows previous observations made by Galileo where Sunshine et al. [1994] distinguish two units based on the strength of the 1 \( \mu m \) band with a degraded spatial and spectral resolution than M³ observations.

[22] The MHC can be distinguished from its surroundings by a weaker 1 \( \mu m \) band depth. In addition different maria, some with common boundaries with those previously mapped [Heather et al., 2003], can be distinguished within the plateau. Figure 5 is a map of the maria based on the IBD1000. These maria are defined by differences in contrast and mainly point out the difference in the 1 \( \mu m \) band strength. The numbers on the map do not distinguished mare basalt units, but rather specific locations whose spectra are presented later on (Figure 7). These numbers help the discussion and describe areas of the stronger and weaker 1 \( \mu m \) units.

[23] The identification of the maria based only on the IBD1000 has some similarities with those previously mapped; however, most of the boundaries are different and lead to different interpretations of the MHC flows. Areas 6 and 7 in Figure 5 have the same eastern boundaries as unit m15 from Heather et al. [2003]. However, our analysis suggests that these two maria are connected to the basalts outside the MHC. We can also find some common boundaries between our area 2 and m10 from Heather et al. [2003]. Area 9 was not mapped by Heather et al. [2003].

[24] Figure 6 is a color composite of the MHC using continuum-removed band depths at 950, 1050, and 1250 nm. The maria boundaries of the plateau we have just described are still visible in Figure 6. In addition, we also see differences between maria that have similar IBD1000. In Figure 6, more blue means a stronger absorption at 1250 nm, which is likely the result of a more olivine-rich composition. Marius crater, 41 km in diameter, has an intense blue hue that suggests an olivine-rich floor composition as discussed in section 5. Mare basalts outside the plateau have green/yellow/blue that suggest a 1 \( \mu m \) band that is slightly shifted beyond 1 \( \mu m \). A 1 \( \mu m \) band center beyond 1 \( \mu m \) suggests the presence of some olivine. However, the olivine content of these mare basalts is less than seen in Marius crater. Areas 6, 7, and 8 of Figure 5 are mare basalts with olivine-rich compositions.

[25] The weak IBD1000 unit discussed previously with areas 1 to 5 is mainly red/purple, suggesting the 1 \( \mu m \) band is slightly shifted to wavelengths below 1 \( \mu m \). If the 1 \( \mu m \) band is centered at shorter wavelengths, the basalts are likely to have a pyroxene-rich composition with less olivine (a low-calcium pyroxene will have a center of band close to 0.9 \( \mu m \)).
while a high-calcium pyroxene will have a center of band close to 1 μm). The domes and cones belong to this unit. The domes are outlined in white in Figure 6. Some domes and cones are embayed by the olivine-rich unit. However, the volcanic features still exhibit a lower olivine content and a red/purple compared to the green/blue of the more olivine-rich unit. In Figure 5, area 9 has a strong IBD1000 and seems to be spectrally related to areas 6, 7, and 8. However, in Figure 6, area 9 appears to have a pale red that links it to the one containing the domes and cones. These differences emphasize the characteristics described in section 2.4; IBD1000 (Figure 5) gives the overall strength of the 1 μm band, and Figure 6 gives the band position and an estimation of the mineralogy of the maria.

Figures 7a and 7b present the spectra of the two different mare units within the MHC. We have collected spectra from fresh craters and averaged 5 × 5 pixels. Figures 7a and 7b are the same spectra; Figure 7b has had the continuum removed to help locate the center of the band and emphasize the differences between the spectra. Spectra have been divided in three groups: (1) the red lines correspond to areas 1 to 5 of Figure 5, (2) the green lines correspond to areas 6 to 8 and (3) areas 5 and 9 are represented differently (dashed red and purple, respectively) because of their unique signatures. Spectra of the high-calcium pyroxene units have different absorption strengths at 1 μm and do not have an absorption at 1.3 μm characteristic of an olivine-rich composition. Spectra from the olivine-rich areas (e.g., areas 6, 7, and 8) have a stronger 1 μm absorption and a different shape at 1.3 μm. As described in Figure 5, these regions have a band center shifted toward the longer wavelengths and display a stronger absorption at 1.3 μm, characteristic of an olivine-rich composition. Absolute albedos and band strengths cannot be reliably compared due to potential differences in the optical maturity of the craters sampled and the lack of a reliable photometric correction. However, area 5 has a very weak absorption at 1 μm that is confirmed by the very low IBD1000 parameter (darker in Figure 5).

From the different maps and spectra presented here, it appears that the MHC is composed of two main mare units that may represent different volcanic episodes of the MHC: (1) a high-calcium pyroxene mare unit that covers a large portion of the plateau and has a weaker IBD1000 compared to the other mare unit and (2) an olivine-rich mare unit that is more localized and has a strong IBD1000. Several ideas can be proposed to explain the differences between these two
units (i.e., composition and band strength): (1) variation in olivine content, (2) variation in plagioclase content, (3) variation in weathering, and (4) variation in opaque minerals such as ilmenite. It is possible that all of these options have occurred on the MHC. Compared to the thicker domes of the high-calcium pyroxene unit, the effusive thin olivine-rich flows would require a decrease in the silica content of the lavas. The spectra are consistent with this explanation. The origin of the cones as pyroclastic deposits [Weitz and Head, 1999; Heather et al., 2003] is consistent with the presence of opaque minerals that could decrease the absorption band of the high-calcium pyroxene unit. In many cases, Lunar Orbiter images show that the domes and cones are embayed by lava flows [Whitford-Stark and Head, 1977]. Using M3 data, it appears that the mare unit that embayed the domes and cones is the olivine-rich unit. Therefore, we can assume that the olivine-rich unit is younger than the high-calcium pyroxene unit. However, since both units are relatively old, there are unlikely to be differences in optical maturity over large areas because soils have had adequate time to optically mature. Area 9 of Figure 5 shows a different IBD1000 than its surrounding flows. The spectral properties of this region is emphasized in Figure 6 and in the spectra of Figure 7 that present the signature of a high-calcium pyroxene with deeper and shorter wavelength absorption than other regions with weaker IBD1000s. The first release of LOLA data from the LRO spacecraft located the highest point of the plateau very close to area 9 (see Figure 2). We investigated the Kaguya HDTV images and it seems that in the central eastern part of the plateau, domes were formed on top of older domes. The large dome that covers the area 9 might represent one of the latest domes on the MHC because it is built on top of older domes. If we assume a single source for the origin of the MHC [Heather et al., 2003], the evolution of the magma (e.g., decrease of the silica content or decrease of opaques) could explain the stronger absorption band of area 9.

4. Properties of the Volcanic Domes and Cones

[28] The volcanic domes and cones of the MHC are identified in the M3 images based on the description of Whitford-Stark and Head [1977] and the morphology in the inherently
registered 2976 nm image. This wavelength includes both reflected and thermal components and is thus sensitive to slopes. This is helpful in identifying the domes and cones. The location of the domes is presented on Figure 6; each is outlined by a thin white line.

4.1. Domes and Cone of Marius Hills

The spectrum of the dome located in Figure 6 (black box D) is presented in Figure 8. This dome corresponds to Figure 5 of Weitz and Head [1999] as observed by Lunar Orbiter. One spectrum corresponds to the low dome; the others are two steeper domes. The spectra have been offset for clarity. There are no apparent spectral differences between the two type of dome. A cone (Figure 6 northern black box) is also shown but does not appear to be significantly different from the domes.

4.2. Variation of the Spectral Signature With the Phase Angle

As described previously (Figure 3), the MHC was observed during different periods of the mission resulting in different observation conditions (55° for the phase angle of OP1B, approximately 15° for OP2C). Figure 9 presents the observations of the MHC under different illumination conditions. On the left is a 2018 nm M3 image of the MHC for OP2C; OP1B is on the right. The OP2C image reveals numerous small dark spots all over the plateau. These pixels have a lower reflectance and are not seen in OP1B (some dark spots with OP1B are related to shadows because of the larger phase angle). The dark spots seen in OP2C data are consistent with those previously seen in Clementine data by Weitz and Head [1999] and Heather et al. [2003]. These authors described the dark spots as mainly associated with cones, but identified cones without dark spots and dark spots without cones. In the case of M3 observations, we report these dark spots as being associated with cones and domes. Dark spots on the domes may represent the location of ancient vents and/or small impact craters. Investigation of the LROC and Kaguya images shows a correlation of the presence of these dark spots with dark material that appears to have a different texture. The dark spots are low in albedo across all wavelengths, although the relative difference in albedo with the surrounding materials is larger with increasing wavelength.

It is unlikely that these dark spots are related to shadows. A first approximation of the shadows is calculate for OP2C using the maximum altitude of the domes and cones from Whitford-Stark and Head [1977] and the phase angle of the M3 data. The shadow should not exceed 180 m of extension from the center of the domes. That distance is lower than the resolution of one M3 pixel for OP2C observations (240 m/pix) and should consequently be limited to one M3 pixel. In many places, the dark spots extend to several pixels. Investigation of Kaguya images do not show any unusual local topography that could produce a localized shadow (it is possible that because of the small phase angle we are looking inside the vent of the cone, which would be invisible at higher phase angles). Consequently, we think that dark spots are produced by the properties of the surface itself and are not shadow effects.

The characteristics of two different cones and one dome are presented in Figure 10. Five images are displayed for each: an albedo image (2976 nm) from OP2C (Figures 10a, 10e, and 10i); an albedo image from OP1B (Figures 10b, 10f, and 10j); a false color image (R = 1010 nm, G = 2018 nm, B = 1520 nm) from OP2C (Figures 10c, 10g, and 10k); a false color image from OP1B (Figures 10d, 10h, and 10l); and a Kaguya image of one portion of the presented M3 images (Figures 10m–10o). We can see that Figures 10c, 10g, and 10k have a relatively low reflectance. The dark color of these pixels indicates that all three bands used in Figures 10c, 10g, and 10k have a relatively low reflectance.

The effect of thermally emitted radiation is expected to be small near 2000 nm, if we use the band at 2018 nm we should avoid the thermal effects. It is, however, possible that temperature can still play a role in the decrease of the albedo. The M3 albedo image at 2976 nm of the first dome also contains rille A [Greeley, 1971] (Figure 10a). The southern
Figure 9. M^3 2018 nm band of the Marius Hills volcanic complex for (left) OP2C (at a resolution of 280 m/pix) and (right) OP1B (at a resolution of 140 m/pix). Dashed black box on Figure 9 (left) corresponds to the location of OP1B observations on Figure 9 (right). Dark spots are observed in several places in the OP2C observations that are correlated with the location of domes and cones. These dark spots are not observed with OP1B.

Figure 10. Observations of two cones and a dome with different phase angles. (a, b, e, f, i, and j) M^3 2976 nm images sensitive to topography. (c, d, g, h, k, and l) Color images (R = 1008 nm, G = 2018 nm, B = 1500 nm) of the same area. Figures 10a, 10c, 10e, 10g, 10i, and 10k correspond to OP2C; Figures 10b, 10d, 10f, 10h, 10j, and 10l correspond to OP1B at twice the spatial resolution. (m, n, and o) High-resolution Kaguya images of the dome and cones as outlined in Figures 10b, 10f, and 10j. The phase angle in the case of OP2C is smaller than OP1B (see text for values). The phase angle is around 70° for Kaguya images and a resolution of 10 m/pix. In all cases, the localized portion of the domes and cones are darker than the surrounding area in the color image. This effect is visible on the OP2C image. Dark spots on OP1B are mainly shadows. The darker areas are related to a lower reflectance.
rim of the rille is darker than the northern, but this is mainly an effect of temperature. The sun is coming from the southwest and, given the inclination of the rims, the temperature of the south rim is lower than the north and thus explains the dark and bright sides of the rille in the albedo image at 2976 nm. The northern part of the dome (Figure 10a) appears darker in that image, which is also a temperature effect (as shadow can contribute to only half a M° pixel maximum). When we look at Figure 10c, both rims of the rille have the same color, confirming that temperature effect is removed when we use wavelengths lower than 2.2 µm (the same effect can be seen with craters). However, part of the domes and cones still appear dark in Figures 10g, 10c, and 10k.

[36] Weitz and Head [1999] and Heather et al. [2003] have proposed glassy particles coming from explosive eruptions of the cones as the particles responsible for the dark signature. As described previously, the presence of these particles agrees with the lower absorption band of these features in the IBD1000 and thus can explain the lower albedo when we come close to the source of the cones. In our analysis, using a larger spectral range, we see that the dark spots are correlated with the presence of cones and domes. The mechanism responsible for these dark spots might be more complicated and the variations with phase angle are puzzling. It is possible that the grain size could be partially responsible for these changes in reflectance. The behavior of opaque minerals may also produce these dark spots. In order to assess the properties of the dark spots, thermal and photometric corrections are needed. Because the phenomenon is associated with volcanic features and localized topography, both corrections are required at a pixel level with a topographic model for the photometric correction to insure that we adequately correct for any thermal effect. These corrections are an ongoing process that will allow us in the future to evaluate the properties of these dark spots.

5. Spectral Analysis of Marius Crater
5.1. Distinctive Composition From the Rest of the MHC

[37] We have briefly described in section 3 the unusual nature of Marius crater. Based only on the IBD1000 parameter presented in Figure 5, the crater does not appear to be particularly different from the rest of the plateau. Its strength in the 1 µm region seems to be intermediate between the two mare units (i.e., strong and weaker IBD1000). In Figure 11, ejecta blankets can be seen around the crater. In Figures 5 and 6, these ejecta blankets have a spectral signature that is consistent with the weaker IBD1000 mare units.

[38] Figure 6 addresses the compositional differences of the 1 µm absorption by separating the olivine-rich compositions (more blue) and the high-calcium pyroxene-rich compositions (more red). Figure 6 clearly addresses the uniqueness of Marius crater, which exhibits the strongest olivine-rich composition on the MHC, similar to deposits located northeast of the plateau and south of the crater. These other blue areas are located at the edge of the MHC and may reflect the composition of the surrounding maria. This olivine-rich composition appears to be far more olivine-rich than the strong IBD1000 of the MHC mare units described in section 3. In their mapping of the mare units, Heather et al. [2003] defined the m20 Flamsteed basalt unit that contains Marius crater. This unit extends to the south part of the crater and the central part of the plateau. However, the characteristics of Marius crater are so different that the present analysis suggests that this region should be unique. The spectral characteristics of the floor of Marius crater are presented in Figures 7c and 7d. The purple curve that sampled the floor of the crater exhibits the characteristic olivine signature; the presence of the absorption at 1.3 µm and the center of the band shifted to longer wavelengths (greater than 1 µm) is typical of an olivine-rich composition. These results suggest that either the olivine is abundant relative to pyroxene or that factors such as grain size and mineral associations within the basalts allow light to reflect more easily within the olivine-rich component.

[39] The modeling of band positions of basalts containing both olivine and pyroxene is a complex problem. An attempt at modeling the Marius olivine is presented by Isaacson et al. [2011]. However, the spectrum of Marius crater does not represent pure olivine and includes substantial pyroxene. In addition, as described previously, thermal and photometric corrections have not been applied and it is thus not possible to use the 2 µm band to constrain modeling. Therefore, a more detailed compositional modeling is not possible at this time.

[40] Images from Lunar Orbiter suggest that the rim of Marius has not been breeched (Figure 11). Therefore, the floor of Marius crater was likely filled from the bottom with the magma likely reaching the surface through the numerous fractures and faults created by the impact.

5.2. Comparison With Surrounding Basalts

[41] Figures 7c and 7d present the spectra of Marius crater and characteristic spectra of previously described mare units. These spectra are good examples of the diversity of the lava flows and volcanic episodes that occurred on the MHC. The floor of Marius clearly has the strongest olivine shoulder at 1.3 µm and the weakest 2 µm band. The blue crosses of Figure 7 correspond to basalts of Oceanus Procellarum outside of the plateau and exhibit similar characteristic with Marius crater (e.g., position of the 1 µm band, weaker absorption at 2 µm and stronger absorption at 1.3 µm).

[42] Absolute albedos and band strengths cannot be reliably compared due to potential differences in the optical maturity of the craters sampled and the lack of a reliable photometric correction. However, the craters selected for these spectra were carefully chosen following these criteria: (1) approximately the same size, (2) no ejecta rays, and (3) as close to the same albedo as possible, suggesting relatively similar maturity levels. We then can argue that the band depth can be compared between the different regions of the MHC. These relative band strengths suggest a greater olivine content for the basalts in Marius crater. However, the relative difference in strength between the olivine-rich unit and the high-calcium pyroxene unit is very slight for the 2 µm band. The full characterization of the 2 µm band can only be made by studying that part of the absorption that is potentially contaminated by thermal emission, which requires a thermal correction of the spectrum. The red diamonds of Figures 7c and 7d correspond to the mare unit with a weaker IBD1000. After continuum removal, the 1 µm absorption band appears
weaker than in the other flows and particularly different from Marius crater’s basalt.

6. Integrated History of the Marius Hills Complex

[43] We have presented the diversity of the spectral signatures found on the MHC and the surrounding Oceanus Procellarum basalts. These different signatures are related to different volcanic episodes and changes in the mafic mineralogy of the magma. The $M^3$ spectral data, combined with the morphological data of previous Lunar Orbiter mission and the recent Kaguya mission, allow us to propose a stratigraphy of the plateau with different volcanic episodes.

[44] 1. The first volcanic episode of the MHC took place before the emplacement of the youngest basalts of Oceanus Procellarum. This first eruptive phase built the plateau of the MHC. These basalts have a weaker IBD1000 signature and an absorption band that is slightly shifted before 1 $\mu$m. The position of the band strongly suggests a high-calcium pyroxene signature. The weaker 1 $\mu$m absorption could be the result of a silica-rich composition, an increased abundance of opaque minerals, and/or a low olivine content. Along with the eruptions on surface, the liquid content of the magma diminished allowing changes in the magma composition. It is possible that area 9’s different spectral properties (e.g., stronger mafic absorption) are an expression of the variation of the magma with time. Finally, the characteristic high-calcium pyroxene signature of the domes and cones indicates that they also belong to this first volcanic episode.

Figure 11. Lunar Orbiter image of Marius crater. No part of the rim appears to be breached.

**Figure 11.** Lunar Orbiter image of Marius crater. No part of the rim appears to be breached.

**Figure 12.** Sketch that summarizes the stratigraphy of the plateau based on the constraints provided by the $M^3$ observations. Age decreases from left to right; time is not to scale. The content of the different elements is expressed as high (plus) or low (minus); the arrows give the evolution of the content at any given time.
[45] 2. The second volcanic episode of the plateau might be contemporary to the basalts of Oceanus Procellarum. This episode is represented on the MHC by the olivine-rich mare unit. Figure 6 links the flows of areas 6 and 7 with those surrounding the plateau. Because of the altitude of the plateau, it is impossible that lava flows from Oceanus Procellarum flowed onto the plateau and produced the olivine-rich mare unit. It is more likely that these basalts erupted on the MHC, followed the slopes of the plateau and flowed to the surrounding plains. On the map displayed in Figure 5, it appears that areas 6 and 7 are connected through a channel to the mare units of Procellarum. Rille B (see Figure 1) lies exactly on the path of that channel and could be the source of the eruption in that volcanic episode. However, rille A,
just to the south, belongs to the high-calcium pyroxene mare unit. It is possible, that rille B was reactivated during the second volcanic episode. The other volcanic episode that has occurred on the plateau is the filling of Marius crater with a basalt that has an olivine-rich signature. As the olivine content of the western basalts of Oceanus Procellarum increases for younger basalts [Staid and Pieters, 2001], we proposed that the floor filling of Marius crater is the result of the latest volcanic episode of the MHC. The event is much younger than the high-calcium pyroxene unit and probably dates from the end of the olivine-rich mare unit emplacement. The filling of Marius may also be separated in time from the emplacement of the Oceanus Procellarum basalts. It is possible that the impact occurred slightly after the emplacement of the Oceanus Procellarum basalts and could have created a number of fractures that may have triggered a final eruption with an olivine-rich composition. However, it is most likely that the crater formation occurred in the early history of the MHC because the spectral signature of the ejecta blankets are consistent with the weaker IBD1000. If the event had occurred later, the ejecta blanket would probably present an intermediate spectral signature between the weaker IBD1000 and the nearby Oceanus Procellarum basalts. This is not the case.

7. Conclusion

[46] The Marius Hills Complex is a localized area that expresses complex episodes of volcanism through time. The different volcanic episodes identified using the M^3 spectral data and the possible evolution of the magma they represent are summarized in Figure 12. The variation in olivine content of all the flows of the MHC agree with studies at a regional scale done by Staid and Pieters [2001] and Staid et al. [2011] using Clementine and M^3 data. The companion study by Staid et al. [2011] shows that mapping of the flows of Oceanus Procellarum basalted mainly on the mafic absorptions (1 µm and 2 µm) displays a similar trend, an increase of the olivine content for younger basalts. The spectral characteristic of the MHC within the Oceanus Procellarum context is presented in Figure 13. The olivine-rich basalts appear red, highlands rich in plagioclase appear blue, and high/low-calcium pyroxenes appear green and yellow. The MHC is mainly dominated by greens with some red units that correspond to the unit that has a higher content in olivine. Marius crater stands out from the rest of the MHC, with a strong red olivine-rich signature similar to the surrounding mare basalts of Oceanus Procellarum.

[47] Integration with recent high resolved images returned by the Kaguya and LRO missions will be helpful in defining the ages of the mare units described in this paper and to develop a more accurate stratigraphy of the plateau. In the future, the thermal and photometric corrections applied to the M^3 data at a pixel level will help define the properties of the dark spots of the plateau and to use the full 2 µm absorption band to characterize the MHC deposits.

[48] Acknowledgments. The M^3 instrument was funded as a mission of opportunity through the NASA Discovery program. M^3 science validation is supported through NASA contract NNM05AB26C. The M^3 team is grateful to ISRO for the opportunity to fly as a guest instrument on Chandrayaan-1. We acknowledge two anonymous reviewers for helpful comments that improved the quality and clarity of the manuscript. We thank A. Raugh for reading the manuscript and correcting the grammar.

References


S. Besse and J. M. Sunshine, Department of Astronomy, University of Maryland, College Park, MD 20742-2421, USA. (sbesse@astro.umd.edu)
J. W. Boardman, Analytical Imaging and Geophysics LLC, 4450 Arapahoe Ave., Ste. 100, Boulder, CO 80305, USA.

R. O. Green, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., MS 306-438, Pasadena, CA 91109-8099, USA.
J. W. Head, P. J. Isaacson, J. M. Mustard, and C. M. Pieters, Department of Geological Sciences, Brown University, Box 1846, Providence, RI 02912, USA.
N. E. Petro, NASA Goddard Space Flight Center, Code 698, Greenbelt, MD 20771, USA.
M. Staid, Planetary Science Institute, 1700 E. Fort Lowell, Ste. 106, Tucson, AZ 85719, USA.