Spectral properties of the Marius Hills volcanic complex and implications for the formation of lunar domes and cones

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Abstract. We have used multispectral data from the Clementine UV-visible camera to study the volcanic features of the Marius Hills complex and their comparison to other lunar domes and cones. There are several mare units identified in the complex, each with a unique Ti content, as indicated by their 415/750 nm value. The domes in Marius Hills are spectrally identical to the mare plains of the complex, supporting similar compositions. In contrast, most of the volcanic cones of the complex are lower in reflectance, bluer in color, and have weaker mafic absorptions than the mare and domes. The spectral characteristics of the cones can best be explained by fine-grained crystallization in the spatter that compose the cones. Other lunar cones, such as Mons Esam in northern Tranquillitatis, have spectral properties similar to those at Marius Hills. The Rima Parry cones and their associated dark mantle deposit appear redder with a stronger mafic absorption than the Marius Hills cones. The cones Isis and Osiris in southern Mare Serenitatis, the domes of Rumker Hills, and several domes in northern Mare Tranquilitatis are spectrally similar to adjacent mare units. The Mairan and Gruntihusen domes in northern Oceanus Procellarum have a feldspathic signature characteristic of highland material although they are redder and brighter than adjacent highland soils. They appear to represent highland material that resembles domes rather than actual mare domes, like those at Marius and Rumker Hills. The diversity of lunar volcanic features can best be explained by differences in accumulation rates and cooling of ejected clasts from various eruption styles. Mare domes may have formed at lower effusion rates, thereby allowing lava to construct small shields with slopes <3°. The steeper domes at Marius Hills require higher viscosities resulting from even lower effusion rates and enhanced crystallization in the magmas during the terminal stages of earlier eruptions that emplaced the mare. Cones like Mons Esam, Rima Parry, Isis, and Osiris are aligned along linear rilles and are interpreted to result from degassing of near-surface dikes. In contrast, the cones of Marius Hills show no linear alignment and may result from Stromboliian eruptions at the terminal stages of earlier effusive eruptions that emplaced the domes and mare in the complex.

1. Introduction

The Marius Hills volcanic complex is situated on a 100-200 m high plateau located in central Oceanus Procellarum (Figure 1). Volcanic activity in the complex is thought to span from the Imbrium to the Eratosthenian periods [McCrea, 1968; Whitford-Stark and Head, 1977, 1980]. The 35,000 km² complex consists of several hundreds of volcanic features, including sinuous rilles, low- and steep-sided domes, and cones [Greeley, 1971; Guest, 1971; Head and Gifford, 1980; McCrea, 1968; Whitford-Stark and Head, 1977, 1980]. In this paper, we refer to cones as smaller, concal-shaped features, while domes appear flatter, broader, and more irregular in shape. Other regions on the Moon have cones and domes, but the Marius Hills complex is unique in the high concentration of these features. An examination of over 200 domes on the Moon by Head and Gifford [1980] showed that the Marius Hills domes represent a unique class that has irregular outlines, complex surface details, and few summit craters. Because of the potential to sample more evolved lavas at Marius Hills, the area was proposed as a potential Apollo landing site [McCrea, 1969]. However, it is also possible that the morphologic variations seen in the volcanic features of Marius Hills could be due to changes in the effusion rates, rather than reflecting compositional variations [Whitford-Stark and Head, 1977, Gillis and Spudis, 1995]. Other domes on the Moon resemble shield volcanoes in Iceland [Head and Gifford, 1980], supporting the interpretation that lower effusion rates were capable of producing some classes of lunar domes.

The presence of lunar pyroclastic constructs implies that gas was released from the erupted magma, causing disruption of the magma and subsequent dispersal of the clasts. On the Moon, the lower gravity and lack of an atmosphere produced cones that are broader and lower than terrestrial cones [McGetchin and Head, 1973; Wilson and Head, 1981]. On Earth, cones result from centralized eruptions above a magma chamber or in association with fissure eruptions, such as those in the Snake River Plain, Idaho [Kunz et al., 1994].
Theoretical work by Wilson and Head [1981] suggests that during strombolian activity on the Moon, coarse clasts would have accumulated within 10 to 20 m of the vent and formed a spatter cone. Cinder cones result from the accumulation of cinder and ash around a vent, in association with strombolian, Hawaiian, or vulcanian eruptions. Strombolian and vulcanian activity consist of intermittent, discrete explosive bursts, whereas Hawaiian type fountaining results from a continuous eruption of coarse clasts. Lava flows may be produced simultaneously with cone formation if clasts accumulate rapidly and remain hot after landing, thereby coalescing to form flows. If the eruption is effusive, then little explosive activity will occur and predominantly lava flows will be emplaced. The majority of eruptions on the Moon were almost certainly effusive because of the paucity of constructs and the very low viscosity (1 Pa s) of lunar magmas [Murase and McBirney, 1970].

Subaerial domes on Earth, such as those of Inyo Crater in Long Valley, California, often form by the eruption of very silicic lavas [Bailey et al., 1976]. Domes and cones indicate the presence of shallow neutral buoyancy zones where magma stalled and evolved, eventually erupting in relatively small volumes and durations. Because of the low-density crust on the Moon, shallow neutral buoyancy zones were unlikely to form; instead, most eruptions were at high effusion rates that produced mare rather than smaller, low effusion rate eruptions that emplaced cones and domes [Head and Wilson, 1991]. In addition, the lithosphere was probably thicker than the crust at the time of mare formation [Head and Wilson, 1992; Hess and Parmentier, 1999], which means that large dike were required to transport melts from >200 km depths and the resulting eruptions were likely at high effusion rates. Cones at Rima Parry V were interpreted as having formed by degassing of a near-surface dike [Head and Wilson, 1993], indicating that under certain circumstances, it was possible to produce only cones and no associated mare on the Moon.

Studies of lunar domes and cones have been restricted to high-resolution Lunar Orbiter (LO) and Apollo photographic images because of the small size of these features. Galileo spectral data of the Marius Hills region indicated complex variations in volcanic activity, including variability in the composition of the basalts and pyroclastic deposits [Sunshine et al., 1994]. The resolution of the Galileo data was only 1.5-2 km, making it difficult to study the spectral properties of the smaller domes and cones. Only now do we have Clementine multispectral data with resolutions below 200 m to resolve these features and show their spectral characteristics. In this paper, we have used Clementine UV-visible (UVVIS) data to examine the various volcanic features of the Marius Hills region. We have also studied volcanic domes and cones from other regions of the Moon for comparison, including (1) the cones Isis and Osiris in southeastern Marc Sertennitatis; (2) Rima Parry V cones in Fra Mauro crater; (3) the cones Mons Esam and domes Grace and Diana in northern Tranquillitatis; (4) the domes of Rumker Hills in northern Oceanus Procellarum; and (5) Mairan and Grithuisen domes in northeastern Oceanus Procellarum. Our goal was to use the spectral properties of the lunar cones and domes in order to determine if they were spectrally distinct from the mare and whether these differences could be used to learn more about the volcanic activity that emplaced the features.

2. Clementine Calibration and Spectral Properties of Lunar Mare

The Clementine UVVIS data consist of five spectral channels: 415, 750, 900, 950, and 1000 nm. The data were calibrated by removing electronic offset and correcting for an added signal that accumulated after exposure as the frame was being transferred to the buffer. The nonuniformity of sensitivity across the detector was corrected pixel by pixel by a scalar correction using flat fields derived for each channel from in-flight data. A photometric correction to account for differences in viewing geometry from scene to scene adjusted the measured signal, acquired at one geometry, to the equivalent signal at the standard geometry of 30° phase (i = 30°, e = 0°). This approximation does not account for the wavelength dependency of the geometric corrections, however, which causes lunar soils to be redder at larger phase angles. Finally, the images were calibrated to reflectance using laboratory measurements of an Apollo 16 soil sample as described by Pieters et al. [1996]. Even after applying these corrections, some calibration errors still exist at the level of about 3%, particularly from scattered light [A. McEwen, personal communication, 1999]. After the images were calibrated, the five spectral channels were coregistered in order to extract reflectance spectra and create color ratio images.

We have taken spectra only from the long-exposure, higher-phase angle orbits for Marius Hills (orbits 54-57 at 21°-26° phase angle). The lower-phase angle orbits (orbits 187-189 at 10°-18° phase angle) suffered from compression noise and higher calibration errors because of the low (<15°) phase angles. Therefore we used only these lower-phase angle orbits to produce the mosaics and color ratio images. When spectra were taken from other areas of the Moon, we listed the phase angle, and for the spectral ratios, we applied this wavelength correction to a standard 30° phase angle [McEwen, 1996]. All spectra were taken using 4x4 pixel boxes, and those that appeared to suffer from large errors and poor data quality were rejected. Several individual Clementine frames were mosaiced together both along and across orbits to cover the Marius Hills region and the other mare domes and cones. Because each Marius Hill’s mosaic combines orbits taken at different phase angles, there are subtle color variations that can be seen across the mosaics because of variations in the photometric correction as a function of wavelength. In contrast, all color differences seen along each orbit are more indicative of compositional variations rather than calibration errors. The color ratio images are simply a way to show relative compositional differences between the various geologic units. Quantitative differences are identified in the spectra for these units.

Color ratio images were produced and used to assist in identifying various geologic units. Each color ratio consists of (1) 750/415 nm ratio in the red channel; (2) 750/950 nm in the green channel; and (3) 415/750 nm in the blue channel. The 415/750 value, or UVVIS slope, is a measure of both the color and the maturity level for lunar soils. An important characteristic of lunar soils is their maturation over time due to space weathering. Maturation causes the strength of the 1000 nm absorption and the overall reflectance to decrease while the continuum slope (i.e., 750/415 ratio) increases [Pieters et al., 1993a; Fischer and Pieters, 1994]. Space weathering produces
this optical alteration by the development of a regolith containing <1 mm size agglutinates, which are individual glassy particles coated with single domain iron, Fe, and produced by micrometeoroids, solar and galactic irradiation, and solar wind implantation. Even though the <25 μm finest particles constitute a minor mass fraction of lunar soils, they dominate the optical properties of the bulk soil [Pieters et al., 1993a]. Although the spectral properties of lunar surfaces have been altered by soil formation, it is still possible to classify mature soils using their reflectance properties.

In the case of mature mare soils, an empirical relationship was noted between UVVIS and TiO₂ content [Charette et al., 1974/4]. All the mare spectra in this paper were selected away from fresh craters and are therefore considered to be equally mature [Pieters et al., 1985]. Consequently, variations in the UVVIS ratio should reflect diversity only in Ti contents between the mare units assuming all basalts have a similar FeO content [Pieters, 1978]. In general, a lower TiO₂ content in the mare corresponds to a lower 415/750 ratio [Pieters, 1978; Pieters et al., 1993b]. In the color ratio images, these low-Ti mare units appear red. Mare soils with higher TiO₂ contents have higher 415/750 values and appear blue in the ratio images. In contrast, lunar volcanic glasses, such as the orange glasses collected on the Apollo 17 site [Heiken et al., 1974], show the opposite correlation between color and Ti content. For volcanic glasses, those with high Ti and Fe contents have a low 415/750 ratio [Bell et al., 1976]. In the case of the volcanic glasses, the relationship between Ti content and UVVIS ratio has been derived only for pristine, immature glasses; hence it is not clear if the same relationship applies to the mature lunar soils which contain these glasses.

The 750/950 or 750/900 values indicate the abundance of Fe²⁺-bearing minerals and the maturity level of the surface. Higher ratios reflect stronger mafic absorptions due to fresher soils while weaker absorptions imply more mature mare. Fresh impact craters in the mare will have a strong absorption band around 1000 nm because of exposure of high-Ca pyroxene. If the mafic absorption band is stronger for a mare surface, perhaps because the soil is younger owing to a recent impact crater, then the ratio value should be higher than for more mature mare soils. The anorthositic highlands have a much weaker mafic band and hence a lower ratio value. If a mare soil has mixed with highland material, then it should have lower 750/950 and 750/900 values compared to unmixed mare.

On the basis of these relationships, we can interpret the colors seen in the color ratio images in terms of their composition and maturity. A red color indicates a low 415/750 value, while a blue color indicates the opposite. Because we assume that the mare soils are equally mature, a red color for a mare unit implies a relatively low TiO₂ content while a blue color indicates a relatively high TiO₂ content. The actual TiO₂ content cannot be ascertained precisely because the colors in each ratio image are partially determined by a stretch which takes into account all the other units in the scene. In other words, a unit that appears very red in one color ratio image may appear less red in another image, depending upon the TiO₂ contents of the other units that it is being compared and contrasted with as part of the stretch. A better way to estimate relative TiO₂ contents in the mare units is to look at their 415/750 values after they have been converted to the same 30° phase angle.

Highland units in any scene will appear blue in the color ratio images if they have relatively fresh surfaces and red if they have mature surfaces. Plagioclase feldspar, the most abundant mineral in lunar highland rocks, is spectrally characterized by a continuous upward slope from the 415 to the 900 nm channel and then shows a decrease in reflectance between 900 and 1000 nm because of an absorption band at 1300 nm [Tomkins and Pieters, 1999]. Fresh highlands appear blue because they have a higher 415/750 value, which is the ratio displayed in the blue channel, compared to mature highlands soils. Low-Ca pyroxene, which may be intermixed with the anorthositic in highlands rocks, should have an absorption at around 900 nm, slightly shorter than the high-Ca pyroxene absorption at 1000 nm [Tomkins and Pieters, 1999].

3. Marius Hills Geologic Units

3.1 Mare Units

The Clementine data show several mare units in the area, but two main units can be identified in the color ratio images (Plate 1a and 1b): (1) a unit that appears as various shades of green in Plate 1a and blue in Plate 1b and (2) a mare that appears red in color in both images. Plate 1a has the 750 nm in the blue channel, making albedo differences more visible, while Plate 1b has the 415/750 ratio in the blue channel to emphasize Ti differences in the mare units. There are several intermediate mare units that cannot be classified into one of these units because they appear an equal mixture of red and either blue or green. The boundary of the complex is shown in the sketch map of Plate 1b. It is visible in the north of the color ratio images, but to the east and west, there is no corresponding color difference in the mare units that marks the boundary. Because the complex boundary is not very distinct and many of the flows can be traced across this boundary, mare volcanism in the complex must have been concurrent with the eruption of mare in Oceanus Procellarum. This observation

Plate 1. (Plate 1a) Color ratio image of the Marius Hills volcanic complex. The color ratio consists of the 750/415 nm ratio in the red channel, the 750/950 nm ratio in the green channel, and the 750 nm in the blue channel. Green color indicates the Ti contents in mature mare soils and the maturity level of fresh volcanic features, such as craters and rille walls. Red color indicates lower Ti contents in the mare. The large crater is Marius (40 km diameter). The blue feature in the south is part of the Reiner Gamma formation [Bell and Hawke, 1981]. (Plate 1b) Same image as Plate 1a except the 415/750 nm ratio is in the blue channel to emphasize titanium variations in the mare units. Blue mare indicates higher Ti contents compared to the red mare units. The sketch map shows locations of sinuous rilles, domes, and cones (black dots). Also shown are locations of spectra for mare and domes. The three crossed areas represent large depressions discussed in the text. The dashed line is the approximate plateau boundary identified by Whitford-Stark and Head [1977].
contrasts to that seen at Aristarchus Plateau to the north, which is completely embayed by Oceanus Procellarum mare and has a pronounced topographic gradient associated with the plateau boundary [Zisk et al., 1977]. In the north of Marius Hills, the bright red mare unit (Plate 1b, R2) has a sharp contact with a more intermediate color mare unit, marking the boundary between the complex and the adjacent mare. In both the Lunar Orbiter (Figure 2) and Clementine 750 nm images, this boundary is very difficult to identify. In fact, most of the mare unit boundaries are quite difficult to distinguish in the albedo images but are strikingly visible in the color ratio images.

Representative spectra for several of the mare units are shown in Figure 3 and were taken at 22°-28° phase angle. The location for each mare unit spectra is shown in the sketch map superimposed on the color ratio image in Plate 1b. We took spectra from multiple locations across the complex and some spectra probably represent the same flow units but at different localities within the units. Those mare units that appear blue in Plate 1b are identified by “B,” those that appear red are identified by “R,” and those that appear intermediate in color begin with the letter “I.” For instance, B5 indicates the fifth spectra taken from a blue mare unit. Many of the spectra have an unusual inflection between the 900 and 1000 nm channels, which is a common calibration error found in the Clementine data that is not yet understood [Tompkins and Pieters, 1999]. The spectrum taken from B2 has the lowest reflectance at all five channels, and other spectra taken from blue mare units also have low reflectances, most likely because of their higher Ti contents. Unit R8 has the highest reflectance of all the mare units on the plateau. The intermediate units that appear equal mixtures of red and blue in Plate 1b appear spectrally to be more similar to the red units by their higher reflectances and steeper UV/VIS slopes, yet they have stronger mafic absorptions than both the red and blue units.

To better compare the different mare units, we have plotted the 415/750 and 750/900 nm values for several mare spectra (Figure 4). The plot symbols correspond to locations shown in Plate 1b. MS low-Ti represents the spectrum for the red mare of Serenitatis, located at 21.5°N, 28.9° E, about 60 km northwest of the Apollo 17 landing site. MS high-Ti is a spectrum in the high-Ti mare of Serenitatis, located 20 km north of the MS low-Ti location. The 415/750 nm values for the Marius Hills mare units range from 0.62 to 0.68, while the 750/900 nm values vary between 0.96 and 0.98. Some of the variations may reflect phase angle differences, but most are too large and must result from unique compositions in the maria. The mare unit R2, which has the reddest color in Plate 1, has the lowest 415/750 value, 0.957, and indicates the lowest Ti content mare in the area. Units R4, R8, and R9 are also quite red, while a cluster of moderately red mare units have 415/750 values from 0.65 to 0.66. Units that appear green in Plate 1a and blue in Plate 1b have 415/730 values above 0.66, although there is no sharp distinction between their ratio values, but rather a gradual increase in the 415/750 value. The blue mare units have a wider range of values in the 750/900 ratio. B9 has the highest 415/750 ratio and therefore appears the bluest color in Plate 1b. Unit B5 has a relatively strong mafic absorption compared to the other blue units. The range of values for the 750/900 ratio may result from differences in
Figure 3. Spectra of selected Marius Hills mare units. Symbols refer to locations shown in Plate 1b and indicate the color seen in Plate 1b, with "B" meaning blue color, "R" indicating red color, and "I" meaning intermediate color. The blue mare units have the lowest reflectances and flattest slopes between 415 and 750 nm, while the red units are brighter and have steeper slopes. The intermediate units have the same reflectance and slope as the red mare units but with much steeper mafic absorptions between 900 and 1000 nm.

Figure 4. Ratio values for selected Marius Hills mare units. The red units have lower 415/750 values, but there is no sharp distinction between the red and blue units. The 750/950 values indicate a wide range of mafic absorptions, especially for the blue units. The MS symbols correspond to the low- and high-Ti mare units in southeastern Mare Serenitatis (see text for details). The mare of Marius Hills are relatively higher in Ti compared to these two nearside mares.
Fe content, calibration errors in the Clementine data, and mixing effects, as has been shown for units in Mare Tranquillitatis [Staid et al., 1996]. In summary, there is a broad range of Ti contents and mafic absorptions in the Marius Hills mare units, indicating that there are at least several distinct units in the complex.

Galileo solid state imaging (SSI) multispectral data of the Marius Hills plateau showed low 760/990 nm values compared to the surroundings, indicating a weaker FeO absorption than other mare plains outside of the plateau [Sunshine et al., 1994]. However, more recent analyses of the Galileo data suggest that scattered light affected the 1000 nm region [Gaddis et al., 1995]. Removal of scattered light from the Galileo spectra produced a stronger mafic absorption in several limb and far side regions, comparable to near side basalts [Gaddis et al., 1995]. Hence the weaker mafic absorptions measured for Marius Hills units by Sunshine et al. [1994] may have suffered from this scattered light effect. This is supported by Clementine data which indicate that the spectra for Marius Hills mare units have relatively stronger mafic absorptions compared to Mare Serenitatis on the nearside (Figure 4). Additionally, Clementine FeO maps of Marius Hills suggest very high FeO contents in all the Ti mare units compared to the surrounding region and to near side mare [Dunkin and Heather, 1999].

Clementine spectra of units B5, B4, R4, and R5 all lie outside the plateau boundary identified by Whitford-Stark and Head [1977]. Units B5 and R4 have stronger mafic absorptions than all the mare units on the plateau, while units B4 and R5 have similar, though relatively strong, absorptions. Two high-Ti mare units were identified in the Galileo data of Marius Hills: (1) one with a strong 1000 nm absorption similar to that of the nearby mare not on the plateau and (2) a mare with a weaker absorption than the nearby mare [Sunshine et al., 1994]. The Clementine data show a much broader range of mare types on the basis of both the 750/900 and 415/750 ratios. Compared to the low-1) mare of Serenitatis, the Marius Hills mare units have higher 415/750 nm ratios, supporting the interpretation by Sunshine et al. [1994] that the mare units for Marius Hills are relatively higher in titanium compared to other lunar mare. Only the R2 unit has a slightly lower value than the low-Ti Mare Serenitatis unit, suggesting a similar or slightly lower titanium content. Global TiO2 and FeO maps produced from Clementine data [Lucy et al., 1998] indicate that the Marius Hills region has between 8 and 11 wt% TiO2, and 17-30 wt% FeO, similar to values in the surrounding Oceanus Procellarum mare. However, higher-resolution FeO maps of Marius Hills suggest that the mare units have higher FeO contents than the surrounding Procellarum units [Dunkin and Heather, 1999].

Numerous sinuous rilles are visible in the various mare units (Figure 2) and are shown in Plate 1b. Those rilles that are large enough to be resolved in Clementine data have a strong green color in the ratio images and strong high-Ca pyroxene absorptions, indicating exposure of fresh mare along their walls. Only the Aristarchus Plateau has a higher concentration of sinuous rilles on the Moon [Guest and Murray, 1976; Whitford-Stark and Head, 1977]. Sinuous rilles are thought to form from turbulent flows in high effusion rate eruptions of long duration [Hulme, 1973; Wilson and Head, 1981]. For one of the rilles in Marius Hills, Hulme [1973] calculated an effusion rate of 4x10^12 m^3 s^-1 for a year, producing a volume of 1200 km^3. The presence of numerous rilles in the Marius Hills region argues for high effusion rates producing the mare here.

Some rilles show structural control, like the two in the west that both have 90° junctions. The more northern of these two rilles also has an unusual elongate source depression compared to the other rilles, which tend to have circular sources. Several of the rilles in the west have been partially buried beneath younger mare, indicating that they formed concurrently with the mare in the complex. A portion of a sinuous rille is visible on the southern ejecta of Marius crater (Figure 2). The oval source head is located just at the crater rim, and then the rille disappears where younger mare has embayed the crater ejecta. None of the sinuous rilles appears to be associated with either domes or cones. Unlike the rilles at Aristarchus Plateau, which have evidence for associated pyroclastic deposits [Zisk et al., 1977; Lucey et al., 1986; McEwen et al., 1994; Weitz et al., 1998], those in Marius Hills appear to have erupted only mare. The rilles occur in both the low- and high-Ti mare units and appear to span the entire range of volcanic activity in the region.

### 3.2 Volcanic Constructs

While the mare plains volumetrically dominate the Marius Hills complex, volcanic domes and cones are also very numerous, especially compared to other areas on the Moon.

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**Figure 5.** Medium-resolution LO V-211 photo showing a horseshoe-shaped cone (white arrow) and a volcanic dome (black arrow). The dome has a two-part sequence with a smooth, flat base and two rougher, steeper flows superimposed. Location shown in Figure 2 and North is at the top.
Figure 6. High-resolution LO V-216 photo illustrating several types of cone morphologies. A horseshoe-shaped cone to the south (black-white arrow) has been breached to the southwest, and it has visible layering along the flanks. A larger cone to the right (white arrow) has been breached in both the north and south where a channel can be seen emerging from each direction. The cone in the north (black arrow) has an irregular shape, and it too has been breached. Location shown in Figure 2 and North is at the top.

Plate 1b shows the location of 121 domes and 46 cones in the region. Topographic data show that the low domes are 25 km in diameter and 50-200 m high, while the steeper domes are 2-15 km in diameter and 200-500 m in height [Whitford-Stark and Head, 1977]. Figure 5 shows a high-resolution LO V image of several domes. The large dome at the top (black arrow) has a flatter, smoother surface below and two rougher, steeper domes superimposed. Other domes show a similar two-part sequence with a smooth, broad dome beneath rougher, steeper domes. In the Clementine data, the domes are spectrally indistinguishable from the surrounding mare. Domes are visible in both the red and blue mare units shown in Plate 1b. Many of the domes have sharp, truncated boundaries with the adjacent mare plains, indicating that the domes have been embayed by younger mare and therefore represent a relatively older stage of volcanism in the region.

The volcanic cones in the complex are <3 km in diameter and <300 m in height [Whitford-Stark and Head, 1977]. High-resolution LO V images of portions of the Marius Hills region show that many of the cones have a horseshoe appearance (Figure 6). Morphologically, these cones are very similar to terrestrial cinder cones, such as those in Hawaii and the Snake River Plain. The horseshoe appearance indicates that the cones were breached on one side where lava flowed out. Cones are located both on the mare and superimposed on domes. Figure 6 shows three cones located to the west on the plateau. The largest cone (white arrow) is situated on a dome, and it has been breached both to the north and south, where a channel can be seen emerging from each breach. A smaller cone located to the south (black-white arrow) has a horseshoe appearance and possible layering inside the cone. The third cone (black arrow) has a very irregular shape and also shows breaching where a channel can be seen emerging to the north.

The volcanic cones are readily visible as black spots in Plate 1a, and they are located in both the red and blue mare units of Plate 1b. There are numerous dark spots in the color
ratio images that have not been identified as cones by previous investigators, perhaps because a significant amount of the cone has been destroyed. Although there may be other cones in the complex, in Plate 1b we show only the cones identified by previous investigators on the basis of LO photos. In a few cases, the dark spots are surrounded by red circles in the color ratio images. In the LO images, the dark spots correspond to the interior of the cones, while the red circles represent the cone flanks. Figure 7 shows a plot of 415/750 versus 750/900 nm for some of the volcanic cones and mare units. The dark spots associated with the volcanic cones have the bluest color and weakest mafic band of all the units, while the red spots have the strongest mafic absorption and a 415/750 ratio similar to the reddest mare units. An interpretation of the volcanic cones spectra is discussed in section 4.6 when they are compared to other lunar cones.

3.3 Other Features

Marius crater has a bright blue color along its walls where fresh mare has been exposed (Plate 1b). The crater is 40 km in diameter and, using crater excavation estimates for this size craters [Melosh, 1989, Cinatula and Grieve, 1994], the crater should have excavated down to 4-6 km depth. Therefore the mare must be at least several kilometers thick in this area since the ejecta is spectrally characteristic of the basalt units. Because the crater has been embayed by younger mare, its stratigraphy indicates that a significant amount of volcanism occurred both before and after crater formation. At the center of Marius is a small crater (~2 km diameter) that appears relatively blue in Plate 1a compared to other craters, which appear green. Spectra for the crater walls indicate a weak mafic absorption but a high reflectance comparable to the other fresh craters. Therefore we suggest that the crater may have penetrated through the mare to the central peak of Marius and exposed a mixture of mare and feldspathic highland material. Small dark spots can be seen along the wall of Marius, one in the southwest and another in the northwest (Figure 8). Both have low reflectances and spectra with flatter slopes between the 415 and 750 nm channels compared to the mare soils. A plausible explanation for these dark spots is that they represent localized dark mantle deposits produced from volcanic eruptions, similar to dark spots seen on the floor of the crater Alphonsus [Head and Wilson, 1979; Coombs et al., 1990].

Several large depressions are visible in the Marius Hills region and are shown in Plate 1b (cross-hatched areas). The depressions located to the north of Marius crater have upraised rims and oval shapes. They are also aligned along wrinkle ridges in the mare and are partially visible in Plate 1A by their bright green color along the walls. We suggest that these features formed during lava migration and drainage or from magma withdrawal at depth which caused collapse at the surface. One final feature of interest in the region is a streak in the south that appears blue in Plate 1a. The streak is a portion of the Reiner Gamma Formation located to the south. It has been proposed as a crater ray from Cavalierius although its unusual shape and magnetic properties suggest other possibilities, including recent gas emissions [McCausley, 1967]. Telescopic multispectral images of Reiner Gamma by Bell and Hawke [1981] showed a deep 0.95 μm pyroxene absorption and no red continuum characteristic of mature soils. From spectral mixing models, Bell and Hawke [1981] suggested that the bright areas were dominated by major amounts of very fresh mare basalt fragments with minor amounts of fresh highland rocks. A study of the Formation using Clementine data showed a high soil iron content (14%) compared to the surrounding
mare and the presence of extremely immature mare soils [Pinet et al., 1997]. Our Clementine results indicate a high albedo, low 750/415 ratio, and a moderate 750/950 value compared to the adjacent plains units. Reiner Gamma does not have the same strong mafic absorption band as fresh impact craters, which is why it appears blue in Plate 1a rather than green. Therefore we agree with the previous work by Bell and Hawke [1981] and Pinet et al. [1997] that this portion of the Reiner Gamma Formation can best be explained as a mixture of fresh mare and highland debris.

4. Other Lunar Volcanic Cones

We have also studied cones and domes from five other locations on the Moon (Figure 1) to assist in our interpretation of the Marius Hills spectra: (1) the cones Isis and Osiris in southeastern Mare Serenitatis; (2) cones associated with the rille Rima Parry V in Fra Mauro crater; (3) the cones of Mons Esam and the domes Grace and Diana in northern Tranquilitatis; (4) the domes of Rumker Hills in northwestern Oceanus Procellarum; and (5) Mairan and Gruthuisen domes in northern Oceanus Procellarum.

4.1 Isis and Osiris

Isis and Osiris are the largest of five cones aligned along a linear rille in southeastern Mare Serenitatis (Figure 9) [Scott, 1973]. The rille is recognizable to the south of the cones, but, beginning with Osiris and extending north to Isis, it becomes less visible in the Apollo 17 photographs. Isis and Osiris are located at the edge of the basin, so it is possible that other cones once existed farther inside the basin but became completely buried as the basin filled up with younger mare. We have used topographic maps derived from Apollo 17 stereo images to determine the heights and slopes of Isis and Osiris. Figure 10 shows profiles across each of the cones. Osiris has a symmetrical shape perpendicular to the rille, while along the rille it is higher to the south. It has a height of 90 m and a width of 2.5 km on the basis of the E-W transect, with a slope of 7.0°. For comparison, the cones of Marius Hills have heights <300 m and widths <3 km [Whitford-Stark and Head, 1977]. Slopes for terrestrial cones can be up to 33° because of the angle of repose for clinders, but the greater dispersal of clasts on the Moon favors lower slopes [McGetchin and Head, 1973; Wilson and Head, 1981]. Isis has a more asymmetric shape than Osiris, both along and perpendicular to the rille. Apollo 17 photographs show that the northwestern rim is breached, and a channel can be seen emerging from the cone. Isis is about 70 m high and 2 km in diameter on the basis of the transect perpendicular to the rille (SW-NE), with a slope of 7.1°. The other cones along the rille are too small to be resolved in the topography.

In the Clementine data, the cones are only a few pixels across because of their small size and resolution of the data. The cones are just visible in the 750 nm images because their flanks are slightly higher in reflectance than the adjacent mare. Spectrally, the cones appear to be similar to the adjacent mare, unlike the cones at Marius Hills, which have lower reflectances and weaker mafic absorptions than the neighboring mare soils.

4.2 Rima Parry V Cones

The 50 km long linear rille Rima Parry V is located in southern Fra Mauro crater (Figure 11). Just offset from the rille is a row of volcanic cones to the west (black arrow) and two cones to the east [Wilhelms, 1987; Head and Wilson, 1993]. Head and Wilson [1993] suggested that the cones were
composed of spatter and produced from strombolian eruptions from a near-surface dike. On the basis of the horizontal extension of the graben, the top of the dike is estimated to be at 650 m depth with a width of about 150 m [Head and Wilson, 1993]. Spectra of the cones and other geologic units are shown in Figure 12. Using representative spectra for highland rocks taken by Tompkins and Pieters [1999, Figure 7], we interpret the H2 spectrum to represent anorthosite exposed by a fresh crater on the southern rim of the crater Parry (Plate 2a). H1 shows a larger crater on the rim of Parry-Bonpland (Plate 2a) that could represent a mixture of gabbro and anorthosite. A fresh crater on the smooth plains (Plate 2a, FC) has a shape similar to H1 but much lower reflectance, suggesting that it is more mature. The smooth plains that cover the region have an anorthositic signature although it is relatively low in reflectance, suggesting that it is composed of mature soils from an impact melt origin. A fresh highland signature is observed only where there has been mass wasting or exposure by younger craters. Compared to the smooth plains, the cones have a lower reflectance, a slightly larger 415/750 value, and a similar 750/950 value. There is no indication in the spectra of any mare plains in the area that may have been eroded in association with the formation of the cones.

In addition to the cones identified on the floor of Fra Mauro crater, there is a large cone on the floor of the crater Bonpland, about 10 km offset to the east of the Rima Parry V rille (Figure 11, large white arrow). LO V images show an unusual feature here, but it has not yet been documented as volcanic. In the Clementine data, the cone has the spectral shape and low reflectance characteristic of the Rima Parry V cones to the north. The cone appears in morphology to be broader and flatter, though, than those to the north. An unusual depression to the west of the rille (small white arrow) is morphologically similar to pit craters produced by magma withdrawal at depth.

In the color ratio image (Plate 2a), the cones are indistinguishable from the surrounding terrain. Fresh impact craters appear blue and green, indicating the presence of highland material. Surrounding the Rima Parry V cones is a dark veneer of debris that is visible in the 750 nm image and the LO photograph. The debris has the same spectrum as the cones. The Alphonsus dark mantle deposits (Figure 1) are thought to form from volcanic eruptions when a caprock in the conduit caused gas build-up until enough overpressurization permitted an eruption that emplaced a localized dark mantle deposit [Head and Wilson, 1979; Hawke et al., 1989; Cummins et al., 1990]. There are no volcanic cones associated with the Alphonsus deposits; instead, they have central pits aligned on linear rilles. Therefore, while the Alphonsus eruptions emplaced only a dark mantle deposit from volcanic activity, the Rima Parry eruptions appear to be strombolian style activity that produced both dark mantle deposits and spatter cones. A further discussion of the types of eruptions is discussed in section 5.

4.3 Cones and Domes in Northern Tranquillitatis

There are numerous mare domes located in northeastern Tranquillitatis basin. Most of the domes are found within the high-Ti mare, but a few are also in the older low-Ti mare farther north [Staud et al., 1996]. Because there exists topographic
Figure 10. Topographic profiles derived from Apollo 17 stereo images (42C3S1 and 42C3S2) for Issis and Osiris. Osiris is symmetrical perpendicular to the graben (BB') but slightly irregular parallel to it (AA'). Isis is more irregular in shape and is breached in the northwest, as seen in profile DD'.

Figure 11. Apollo 16 P-5425 photo of Rima Parry V rille and associated volcanic cones (black arrow). The bright highlands correspond to the rims of the craters Fra Mauro (top) and Doupland (bottom). The large white arrow shows another cone located farther to the south. The small white arrow indicates an unusual depression that resembles pit craters seen on Earth.

data derived from Apollo 15 photography for the more northern domes, we have focused on them. These domes include Grace, Diana, and an unnamed dome (Figure 13). In addition to the domes, Mons Esam represents overlapping cones aligned linearly, similar to the Rima Parry V cones. Topographic profiles for the domes Grace and Diana and the cones of Mons Esam are shown in Figure 14. Grace is about 160 m high and 8 km across, with a slope of 2.0°. Its central pit is 1 km wide and 80 m deep. Diana is shorter than Grace, but it has a much deeper central pit. It is 45 m high and 5 km wide, with a slope of 2.6°. Its unusually deep central pit compared to its small height could be attributed to embayment of the cone by other mare (perhaps from Grace), thereby reducing its height. Mons Esam is only 4 km across but over

Plate 2. Color ratio images and 750 nm frames of lunar domes and cones studied in this paper. The ratios represent the 750/415 in red, 750/950 in green, and 415/750 in blue. (Plate 2a) The cones associated with the rille Rima Parry V are shown by blue arrows. The cones and associated dark mantle deposits have a low albedo in the 750 nm mosaic. In the color ratio image, the blue represents fresh highlands, while the red and orange colors show more mature highland soils. No mare units can be identified. H1, H2, and FC represent spectra locations shown in Figure 12. (Plate 2b) The domes Grace (G), Diana (D), and an unnamed dome (U) along with the cones Mons Esam (ME) are shown by arrows in the 750 nm image. Mons Esam has a much lower albedo than the domes, a characteristic seen at Marius Hills as well. (Plate 2c) Outlined in yellow on the 750 nm image are the locations of 11 domes, while the Rumker Hills boundary is shown in white. The domes have the same red color as the mare on the Rumker Hills. Surrounding the Rumker Hills are other mare units with higher Ti contents. (Plate 2d) Two of the three Marius domes are shown in the 750 nm image by yellow arrows. The domes have a red color similar to the adjacent highlands. (Plate 2e) All three Gruithuisen domes are shown in these images. The domes appear slightly redder than the surrounding highlands in the color ratio image.
260 m high, with a slope of 11.0°, making it comparable to the cones of Marius Hills and Isis and Osiris. Central pits are visible along the structure, although they are too small and shallow to be resolved in the topography data.

The color ratio image (Plate 2b) shows a red, low Ti mare and a blue, high-Ti mare. Spectra shown in Figure 15 reveal that Mons Esam is similar to the high-Ti mare but with a slightly flatter UV/VIS slope (i.e., higher 415/750 value). Mons Esam has the lowest reflectance in the image, similar to the low reflectance of the Rima Parry V and Marius Hills cones.

The high-Ti mare has a lower reflectance than the low-Ti mare. Another unnamed dome located farther to the west (Plate 2b, U) in the low-Ti mare has a large pit crater. Grace is spectrally similar to this unnamed dome except that it has a slightly stronger mafic absorption. Diana has a spectrum that is intermediate in reflectance and shape between the high-Ti mare and the unnamed dome. Therefore it appears that Grace and the unnamed dome erupted as part of the low-Ti mare eruptions followed by emplacement of younger high-Ti mare and the Mons Esam cones. Diana appears to represent an intermediate-

**Figure 12.** Spectra for Rima Parry V cones and other geologic units. The cones have a low reflectance and a weak mafic absorption that may be due to volcanic glasses or glassy spatter. The other spectra are characteristic of anorthositic breccia and noritic signatures commonly found in highland rocks [Tompkins and Pieters, 1999].

**Figure 13.** Apollo 17 frame M-305 showing the domes Grace (black arrow) and Diana (black-white arrow) in northern Mare Tranquillitatis. The cones of Mons Esam are to the northeast and another unnamed dome (white arrow) is to the west.
Ti unit or a spectral mixture of the low-Ti and high-Ti mare units.

4.4 Domes of the Rumker Hills

Over 30 domes may be concentrated on the 80 km diameter Rumker Hills in northern Oceanus Procellarum [Smith, 1974]. Plate 2c shows the Clementine color ratio image with the 11 largest domes outlined on the 750 nm mosaic. Smith [1974] divided the domes into three types, each related to a different eruption period. All the domes appear relatively flat compared to those of Marius Hills, with a smooth, circular appearance and some with possible summit pit craters [Whitford-Stark and Head, 1977]. In the color ratio image, Rumker Hills has a bright red color. To the west are younger red mare, and to the east are blue mare units. Several of the northern craters on the Hills have a blue color, indicating the presence of either highland materials or low-Ti mare.

Spectra for the various geologic units in the image are shown in Figure 16. One of the domes is spectrally identical to the mare on the Rumker Hills, suggesting that it was produced from the same eruption that emplaced the low-Ti mare. The purple mare unit in Plate 2c just west of the Rumker Hills has the lowest reflectance, even lower than the high-Ti mare to the east. The orange unit located to the southwest is spectrally similar to the mare on the Hills but has a weaker UV/VIS slope. Because the domes are spectrally identical to the mare on the Hills, it supports Whitford-Stark and Head's [1977] interpretation that the domes were produced by low effusion rates, perhaps at the terminal stages of the eruptions that emplaced the mare on the Hills. We do not believe that the domes represent stratovolcanoes, as suggested by Smith [1974], because on Earth stratovolcanoes form above subduction zones by multiple eruptions of lava flows and pyroclastic deposits and we see no evidence of this at Rumker Hills. The blue craters seen in the north of Rumker Hills have a spectrum (Figure 16, Crater Wall) characteristic of highland material. We propose that the highland material was either carried in by secondary craters or exposed beneath the low Ti mare in the north.

4.5 Maian and Grubhuisen Domes

The Maian and Grubhuisen domes are distinguished by their red color in the infrared, their high topography, and their morphological similarity to volcanic domes [Head and McCord, 1979]. Their morphology and texture have been interpreted to be due to more silicic compositions compared to
mare domes [Head and McCord, 1978]. Head and McCord [1978] observed that their strong ultraviolet absorption distinguished them from the highlands and could indicate a lower content of iron or titanium. Plate 2d shows the color ratio image and 750 nm frame for two of the Mairan domes, while Plate 2e illustrates the color ratio and 750 nm mosaic for all three Gruithuisen domes. The Mairan domes appear as a red color, similar to the adjacent highlands. The Gruithuisen domes also appear red compared to the bluish-red highland soils.

Figures 17 and 18 show the spectra for the various domes and geologic units. The domes all have spectra characteristic

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**Figure 15.** The spectrum of Grace and an unnamed dome are similar except Grace has a slightly stronger mafic absorption. Both are similar to the low-Ti mare but with lower reflectances. Diana is intermediate between the high- and low-Ti units. Mons Esam is similar to the high-Ti mare although slightly lower in reflectance.

**Figure 16.** Spectra of the Rumker Hills and surrounding mare units. The domes are spectrally indistinguishable from the mare on the Rumker Hills. The other mare units vary in their UV/VIS slopes and mafic absorptions but all have flatter UV/VIS slopes compared to the Rumker Hills. The Crater Wall spectra refers to the blue secondary craters in the north that indicate the presence of highland material.
of feldspathic material, which is also seen in the highland rocks. The highest albedo and lowest 415/750 value corresponds to fresh impact craters on the domes (Figure 18, Highland Crater), as noted previously in telescopic data [Chevrel et al., 1993]. These fresh craters appear dark blue on the γ dome in Plate 2c, and their spectra ressemble that of anorthosite [Tompkins and Pieters, 1999]. Although the domes do have smaller 415/750 values and higher albedos compared to the surrounding highlands, their overall spectral character is more similar to highland material than to mare. Their brighter appearance can be explained by steeper slopes causing more mass wasting and exposure of fresher surfaces. Their lower 415/750 ratios are more consistent with a mature soil, however. In summary, the Mairan and Gruithuisen domes represent nonmare material with an unusually high UV/VIS slope, perhaps due to lower titanium contents. However, it is

Figure 17. The three Mairan domes have higher reflectances and steeper UV/VIS slopes than the highland soils, but their shape is characteristic of highland-like feldspathic material rather than mare.

Figure 18. The three Gruithuisen domes also have higher reflectances and steeper UV/VIS slopes than the highland soils. The Highland Crater spectrum was taken from a fresh crater on the δ dome.
clear that these domes could not be formed by the same eruption styles that emplaced the other mare domes studied in this paper. Previous studies by Head and McCord [1978], Head et al. [1978], and Malin [1974] show that the features are morphologically and spectrally distinct from the highlands, suggesting that they cannot simply be remnant highland islands but also require an explanation for their spectral signature. Chevrel et al. [1999] outline evidence that there may be adjacent non-mare regions associated with this volcanic style as well.

4.6 Spectral Comparison of Lunar Cones and Domes

In order to spectrally compare all the cones and domes in this study, we have listed representative spectral ratios and reflectance values for these features (Table 1). All the ratio values have been corrected to 30° phase angle to remove any differences caused by phase angle variations [McEwen, 1996], and only those spectra that did not show an erroneous inflection at 950 nm are listed. We show the 750/950 values rather than the 750/900 ratio because this is the more standard ratio used by the lunar science community, and we want to compare our values to those taken by others. In addition to the domes and cones studied in this paper, we also show the spectral ratios of the Taurus Littrow and Aristarchus Plateau dark mantle deposits (DMDs). The Taurus Littrow DMD refers to the regional deposit located at the southeastern edge of Marc Serenitatis. Samples returned from the Apollo 17 site, located at the eastern edge of the Taurus Littrow DMD, indicate that the deposit contains submillimeter crystalline black beads mixed with lesser amounts of orange glasses [Heiken et al., 1974; Pieters et al., 1974]. The black beads are compositionally equivalent to the orange glasses and were produced from the same eruption, but the presence of olivine and ilmenite crystals reflects slower cooling rates [Arnold and von Engelhardt, 1987]. Whereas the Taurus Littrow DMD is spectrally dominated by crystallized beads [Pieters et al., 1973; Adams et al., 1974; Gaddis et al., 1985; Hawke et al., 1990], Aristarchus Plateau is dominated by volcanic glasses [Zisk et al., 1977; Lucey et al., 1986; McEwen et al., 1994; Weitz et al., 1998].

On the basis of the spectral properties listed in Table 1, the domes of the Rumker Hills have the lowest 415/750 ratio and therefore are the reddest feature studied in this paper, even redder than the Mairan and Gruthuisen highland domes. The Aristarchus Plateau DMD is also very red and has a 750/950 value similar to the Rumker Hills. However, the red color of the Aristarchus Plateau may be due to the high Ti content of the volcanic glasses [Bell et al., 1976], while the red color of the Rumker domes indicates a very low Ti content in the mare [Pieters, 1978]. Additionally, the 750/905 nm value for the Rumker Hills reflects the strength of the high-Ca pyroxene absorption in the mare, while the ratio indicates the presence of a glass band absorption in the Aristarchus Plateau DMD.

In terms of reflectance, the Rumker Hills have the highest values compared to all the other mafic features studied. The dome Grace in northern Tranquillitatis has a similar color and reflectance to the low-Ti domes in Marius Hills, as well as a mafic signature characteristic of mare soils. A low-Ti dome of Marius Hills has a 415/750 value similar to the high-Ti mare of Serenitatis (22°N, 29°E), illustrating that the lowest titanium mare units at Marius Hills are actually relatively high in titanium compared to other lunar mare. An intermediate color dome at Marius Hills has a slightly stronger mafic band than both the low- and high-Ti domes. Except for the low-Ti dome, the domes at Marius Hills have lower reflectances than other lunar domes and both Mare Serenitatis mare units.

The Rima Parry V cones are spectrally identical to their surrounding dark mantle deposits. Telescopic near-infrared reflectance spectra of 25 localized dark mantle deposits taken by Howke et al. [1989] indicate three compositional groups, depending upon their 1.0 μm absorption. Clementine UVVIS spectra confirm the three compositional groups [Gaddis et al., 1997]. After applying an offset for comparison to Clementine spectra obtained by Gaddis et al. [1999], we find that the Rima Parry spectra fall between groups 1 and 2, with the 950/750 value matching that of group 2 (fragmented basaltic material) and the 415/750 ratio similar to that of group 1 (mixture of highland and glassy juvenile material with smaller amounts of basalt material). The Rima Parry cones and dark mantle have a 715/950 value similar to the Aristarchus Plateau DMD but slightly bluer in color. One possibility is that the cones and dark mantle are composed of glassy material, with the

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<th>Table 1. Representative Spectral Ratios and Reflectance</th>
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<td>Marius Hills black cones</td>
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<td>Mons Esam</td>
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<td>Marius Hills high-Ti dome</td>
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<td>Marius Hills intermediate dome</td>
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<td>Taurus Littrow DMD</td>
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<td>Marc Serenitatis high-Ti</td>
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<td>Diana</td>
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<td>Grace</td>
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<td>Marius Hills red cones</td>
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<td>Marc Serenitatis low-Ti</td>
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<td>Rima Parry</td>
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<td>Aristarchus Plateau DMD</td>
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DMD, dark mantle deposit.
* Ratios have been normalized to 30° phase angle.
difference in color between the glasses at Aristarchus Plateau and those at Rima Pardy resulting from distinct titanium contents [Bell et al., 1976]. However, this hypothesis cannot be determined with certainty because the spectra represent mature surfaces, whereas the studies by Bell et al. [1976] were for pure, fresh volcanic glasses. If the Rima Pardy glasses were partially crystallized, they would plot closer to the Taurus Littrow 750/950 value. Since they do not, we believe they have a higher proportion of glasses. The cones themselves are likely to be composed of glassy spatter to develop the constructs. A further examination of how they formed is discussed in section 5. Rima Pardy cones have the highest reflectances of all the cones, although they are lower than the Rumker Hills domes. The cone Osisr has spectral ratios consistent with mare soils.

To account for the spectra of the dark spots in Marius Hills that correspond to cones (Table 1, Marius Hills black cones) requires a material that will darken the soil and remove any mafic signature, similar to the effect that agglutinates produce in lunar soils. On Earth, the flanks of basaltic volcanic cones are composed of scoria, including spatter and cinder, and we assume that the lunar cones are formed of similar scoria in order to build up a cone. Basaltic spatter sometimes has a microcrystalline structure (microlites) because of a cooling rate that allowed nucleation of crystals but inhibited their growth [Cas and Wright, 1988]. Glasses are also unstable over time and can devitrify to form microlites, a common process in obsidians on Earth [Lofgren, 1971] and thought to have occurred in the Apollo 17 orange glasses [Weitz et al., 1996]. Assuming that lunar spatter has similar microlites, they would have been crushed to fine-grained sizes during regolith formation and could act as a darkening agent to explain the spectra for the dark spots. The cones of Mons Fiam in northern Tranquillitatis basin are similar to the cones of Marius Hills, and their spectral signatures indicate that they too may have microlites to decrease the reflectance and mafic absorption, as well as produce a bluer color. Because the Marius Hills and Mons Fiam cones have stronger mafic absorptions than the Taurus Littrow DMD, we suggest that they developed fewer ilmenite crystals to allow a stronger mafic signature to be identified.

The annular red spots (Table 1, Marius Hills red cones) that correspond to the cone flanks and surround some of the dark spots have a very strong mafic absorption and similar 415/730 nm ratios to the other mare units. They do not have spectral ratios that match any of the three groups of localized dark mantle deposits [Gaddis et al., 1999]. Strombolian and Hawaiian eruptions produce some fine ash and acheneliths (small glassy fragments, such as Pele tears) that are glass-rich and can be carried farther away from the vents than the larger spatter. If submillimeter glass beads were produced during cone formation, then we should be able to identify these glasses by looking for a glass absorption similar to that seen in dark mantle deposits composed of volcanic glass beads, such as the Aristarchus Plateau. The Marius Hills red spots are bluer and have a much stronger glass band absorption than the Aristarchus Plateau volcanic glasses. Bell et al. [1976] determined that the color of volcanic glasses is a function of their Ti and Fe contents. Therefore, assuming similar Fe contents, the redder color of Aristarchus Plateau volcanic glasses may reflect a higher Ti content compared to the glasses on the cone flanks. The stronger mafic band in the red spots is difficult to explain but may result from a combination of the mafic and glass absorptions around 1000 nm, assuming that the cone flanks are a mixture of lava and glass-rich spatter.

5. Formation of Lunar Volcanic Features

In a manner similar to basaltic eruptions on Earth [Wilson and Head, 1981; Head and Wilson, 1989], a variety of volcanic features can form on the Moon, depending upon the accumulation rate and temperature of the clasts. The highest fluxes, accumulation rates, and clast temperatures will tend to form sinuous rilles. The high temperatures and turbulent nature of the flows cause thermal erosion of the underlying substrate to form the rilles and their source depressions [Carr, 1973; Hulme, 1973; Head and Wilson, 1980; Wilson and Head, 1980]. Clementine data show that the rilles expose fresh mare along their walls, consistent with layering visible in Apollo 15 photographs of Hadley rille [Howard et al., 1972]. As clast temperatures and accumulation rates decrease, lava ponds and lava flows will result. Actual preserved pyroclasts do not form until the clasts reach sufficiently low temperatures that they can cool rapidly.

Basaltic cones are common constructs on Earth. The cones form around a vent and result from Hawaiian or strombolian style eruptions that commonly produce associated lava flows [Wilson and Head, 1981; Head and Wilson, 1989]. Cinder cones often have slopes related to the angle of repose for cinder, and they have large craters relative to their basal width [Wood, 1979]. Basaltic spatter cones form above dikes where large clasts land hot but accumulate slowly so there is sufficient time to cool before the next clast lands.

On the Moon, lunar domes are thought to form from relatively low eruption rates and low gas contents, both of which would tend to cause build up of lava around a vent. Lower lava temperatures leading to increased viscosity may also favor dome formation, rather than extensive mare flows. Domes can form from strombolian or Hawaiian eruptions when hot magma clasts are not accumulating rapidly and there is adequate time for the clasts to cool and increase their viscosity before the next one is deposited. On Earth, low effusion rates formed the low shield Mauna Ulu in Hawaii [Swanson et al., 1979], and lunar domes, like those of Rumker Hills and Northern Tranquillitatis, may have also resulted from low effusion rates, particularly in the terminal phases of eruptions that emplaced the mare.

The Marius Hills represent a distinct type of domes owing to their somewhat steeper slopes and rougher surfaces. If mare lavas erupted over jagged highlands, then the rough topography associated with the Marius Hills domes could be explained by thin mare overlaying a rougher substrate. However, no underlying highlands are visible or exposed by impact craters, implying that the dome morphology is a result of the magmas that compose them. Their morphology must therefore result from higher-viscosity magmas, shorter flows, or lower effusion rates. There are several processes that can increase magma viscosity, including an increase in silica content, lower magma temperatures, and higher crystal contents [Head et al., 1978]. It is unlikely that lunar magmas were able to differentiate to produce more evolved compositions [Rutherford et al., 1974]. Lower eruption temperatures and higher crystal contents are expected in magmas erupted in the terminal stage of an eruption when the mass flux has decreased. Therefore we interpret the Marius Hills domes to represent the result of cooler, more viscous
magnas erupted during the later phases of eruptions; these domes subsequently became embayed by younger, more fluid
magne lavas.

Volcanic cones on Earth can be produced by Hawaiian,
strombolian, and Vulcanian style eruptions. Formation of
volcanic cones on the Moon requires high cooling rates that
allow clasts to land cool enough to form spatter and cinder
rather than lava. Cones must be composed of clasts that are
larger than submillimeter; otherwise, the clasts will be widely
dispersed to form dark mantle deposits [Wilson and Head,
1981]. Completely and partially welded spatter will produce
volcanic cones, as will cinders. For terrestrial cones, spatter
and cinder are both produced from the same fragmentation
process at the vent, but the larger size of spatter allows it to
cool more slowly and form irregular shapes, while cinder is
smaller scoria that is deposited as a solid. Lunar volcanic
cones most likely formed either at the end of eruptions when
eruption rates were lower or by degassing of near-surface dikes
[Head and Wilson, 1993]. Many lunar cones, like those in
Marius Hills and Isis, have associated small lava flows,
indicating that some clasts landed hot and could coalesce to
form flows.

Wood [1979] found that average terrestrial cinder cones
were produced from magma chambers at depths of ~3 km,
whereas larger cones could have source depths at the base of
the crust (~40 km). He suggested that the smaller volume for
lunar cones implies either lower effusion rates from shallower
magma chambers or higher eruption rates from brief eruptions
[Wood, 1979]. In terms of volume, Osiris is 0.13 km^3, the
larger cones in Marius Hills are 0.5-0.8 km^3, and cinder cones
in Arizona are 0.2-0.4 km^3 [Head and Wilson, 1979]. On
the basis of morphometric relations, Wood [1979] proposed that
Isis and Osiris represented cinder cones, while three cones in
the Marius Hills region were equivalent to terrestrial shield
volcanoes. However, Head and Wilson [1991] outlines evidence
that shallow magma reservoirs should be very rare on
the Moon because of the density trap at the base of the
anorthositic crust. This density trap prevented abundant dikes
from stalling in one location in the shallow crust, which is
required to form shield volcanoes on Earth. The smaller size of
lunar volcanoes implies that there were fewer eruptions or one
long eruption that could build up a small shield. Lower
effusion rates would have prevented lavas from traveling far
from the vent, which would favor dome formation.

In the case of Isis, Osiris, Mons Esam, and Rima Parry V,
the cones most likely formed along a rift by degassing of a
near-surface dike [Head and Wilson, 1996]. At a certain depth
below the surface, the dike will cause enough extension to
produce a graben. If the dike is shallow enough, then
degassing of the dike can occur and pyroclastic cones will be
produced. Head and Wilson [1993] have calculated that the
dike at Rima Parry V had a width of ~150 m and was located at
depth of ~650 m. Rima Parry V has an associated dark mantle
deposit that is spatially similar to DMDs composed of
volcanic glasses. Therefore, at Rima Parry, the erupted
submillimeter clasts formed a thin blanket of debris, which
became the DMD, while the larger clasts resulted in spatter that
built up the cones. Isis and Osiris may not have similar dark
mantle deposits because (1) they have been embayed by
younger mare that would have covered them up or (2) little or
no fine-grained clasts were produced in the eruptions. Isis is
breached to the north indicating that it produced an associated
lava flow where clasts were hot enough after landing to
coalesce and form lava, while at Osiris, all clasts landed cold
enough to form only spatter. The morphological differences
between Isis and Osiris may reflect the location along the dike
where they formed, with Isis forming at one end where clasts
stayed hotter in an optically dense plume compared to a lower
optical density plume at Osiris. The differences in plume
optical density could be from either a lower gas content or a
higher volume flux at Isis.

Mons Esam also has no visible dark mantle deposit and
more closely matches the spectral characteristics of the Marius
Hills volcanic cones, even though its morphology is similar to
the Rima Parry cones. The low reflectance and weak mafic
signature of the Mons Esam cones implies a similar cooling
history to the clasts that form the Marius Hills cones; namely,
clasts that formed spatter to develop a cone and some cooling
in the clasts to form microcrysts. The lack of associated dark
mantle deposits at both Mons Esam and Marius Hills cones
indicates that gas bubbles in the magma were sufficiently large
to form only larger clasts during fragmentation. The cones at
Rima Parry V, Isis, Osiris, and Mons Esam are aligned
linearly, but no alignment is recognizable for the cones in
Marius Hills. This observation suggests that the cones at
Marius Hills represent the terminal stages of earlier eruptions
due to decreasing mass fluxes. Near the end of these eruptions,
the magma rise speed may have decreased sufficiently to allow
gas bubbles to coalesce into larger bubbles, which would
subsequently burst at the surface to produce spatter or cinder.
This style of eruption is characteristic of strombolian activity
on Earth.

The Marius Hills complex illustrates the variety of volcanic
features that can form on the Moon. The high concentration of
sinuous rilles, domes, and cones suggests something unusual
about this region compared to the rest of the Moon [Whitford-
Stark and Head, 1977]. Crustal thickness calculated by Zuber
et al. [1994] showed no unusually thin crust here that would
favor eruptions at this location compared to elsewhere on the
Moon. One possibility to account for the presence of these
volcanic features is an anomalous crust, and perhaps mantle,
beneath the region. Recently, Lunar Prospector has measured
high concentrations of Th in Oceanus Procellarum and Mare
Imbrium [Lawrence et al., 1999]. This region, termed the
Lunar Hot Spot, is believed to have formed before the Imbrium
impact [Korotov, 1999]. Marius Hills is located toward the
center of the Procellarum basin, and its centralized location
may have resulted in the unusual volcanism seen here. There
are several different compositions for the mare units in the
complex, indicating that several magma sources are required,
each with a different Ti content. In summary, we propose that
the Marius Hills Complex formed by numerous dikes
propagating to the surface and erupting lavas that produced
extensive mare units at high mass effusion rates. At the
terminal stages of these eruptions, the mass flux decreased,
resulting in the formation of the domes by increased
crystallization in the magmas and decreasing temperatures,
and the cones by explosive activity from higher volatile
contents in the latter stages of the eruptions.

6. Conclusions

The spectral properties of the lunar domes and cones can be
summarized as follows:
1. There are several mare units in the Marius Hills complex
and the wide range of titanium contents in these units argues
for multiple eruptions from several distinct source regions at
depth. The domes at Marius Hills are spectrally identical to the
adjacent mare and occur in both the high- and low-Ti mare units. The cones are spectrally distinct from the mare and domes with lower reflectances, weaker mafic absorptions, and bluer colors. The spectral properties of the cones are consistent with spatter that has some fine-grained crystallization.

2. The cones Isis and Osiris are spectrally similar to the adjacent mare units.

3. The Rima Parry V cones may represent glassy spatter whose associated dark mantle deposit may be composed of volcanic glasses similar to those found at the Aristarchus Plateau, but with higher titanium contents.

4. The Mons Eamus cones of northern Mare Tranquillitatis were erupted concurrently with the high-Ti mare at this location and are spectrally similar to those at Marius Hills. The domes of northern Mare Tranquillitatis, including Gracce and an unnamed dome, are spectrally similar to the low-Ti mare in the region. The dome Diana has an intermediate color between the high- and low-Ti mare units.

5. The domes of Rumker Hills are spectrally identical to the very low-Ti mare that is also on the Rumker Hills.

6. The Maar of Gruntiuse cones are spectrally similar to the adjacent highland soils except that they are redder and have higher reflectances. They are not mare domes but instead have a highland-like signature.

The formation of the volcanic constructs studied in this paper is interpreted as follows:

Domes: The flatter (<3°) dome domes formed at low effusion rates that would allow a small shield to develop. The steep-sided domes at Marius Hills suggest very low mass fluxes at cooler temperatures and with high crystallization contents, perhaps at the terminal stages of the eruptions that emplaced the earlier mare and flatter domes.

Cone: The Rima Parry cones are aligned linearly, parallel to an adjacent graben, and are interpreted to have formed by degassing of a near-surface dike producing both spatter and volcanic glasses but no associated lava flows. Other cones, such as Isis, Osiris, and Mons Eamus, are aligned linearly, supporting eruptions from near-surface dikes that did not emplace dark mantle deposits. The Marius Hills cones show no similar alignment and are therefore considered to be from strinoblastal activity marking the transition from effusive eruptions that produced the mare and domes to more explosive cone-forming activity at the terminal stages of these eruptions.

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