Lunar regional dark mantle deposits: Geologic, multispectral, and modeling studies

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Abstract. Clementine five-channel UV-visible (UVVIS) data have been used to study seven regional dark mantle deposits (DMDs) on the Moon. The DMDs were mapped in distribution to determine their extent and stratigraphic relationship to other geologic units. Based upon the spectral properties for each DMD, the crystallization of the beads in each deposit was inferred and used to estimate cooling rates in the volcanic plumes that emplaced the deposits. Deposits with a high concentration of glasses reflect volcanic plumes that had low optical densities and high cooling rates, whereas deposits dominated by crystallized beads indicate plumes with slower cooling rates due to higher optical densities. Spectral data from each of the regional DMDs show that their glass:crystallized bead ratio can be estimated based upon their 415/750 and 750/950 nm values and comparison to laboratory spectra for the beads. Patches of young dark mantle in the Sinus Aestuum DMD represent one extreme with the bluest color (highest 415/750) and weakest glass band absorption (lowest 750/950) of all the DMDs. At the other extreme is the Aristarchus Plateau DMD with the reddest color and strongest glass band absorption. The other nearside DMDs, including Taurus-Littrow, Sulpicius Gallus, Rima Bode, and Mare Vaporum lie between these two extremes due to intermediate mixtures of the crystallized beads and glasses with other local soils. The Orientale Ring DMD on the western limb is dominated by volcanic glasses and is spectrally similar to the localized DMDs found in Alphonsus crater. We have identified a central vent for the Orientale Ring DMD and model the eruption as degassing of a near-surface dike to produce a 20-km-high umbrella-shaped plume with ejection velocities of 360 m/s and deposition of the glasses at an average radius of 80 km from the vent. Although we cannot identify the exact sources for the other regional DMDs (probably because they are buried beneath younger mare), the eruptions most likely resulted from dikes breaching the surface and producing a volcanic plume dominated by larger (greater than submillimeter) hot clasts that formed mare and sinuous rilles. The small percent of clasts that form the volcanic beads are carried by the expanding gas cloud to large distances, in some cases >100 km, to produce the observed continuous regional DMDs. The lack of basalt samples that can be petrologically related to the volcanic glasses may be a result of their spatial separation, with the basalts flowing into the basins while the beads are deposited both into the basins and on the adjacent highlands.

1. Introduction

Dark mantle deposits (DMDs) refer to diffuse deposits with very low albedos that mantle mare and highland regions. After the Apollo 17 mission to the Taurus-Littrow DMD, it was realized that the DMDs were composed of high-Ti submillimeter volcanic beads produced by explosive volcanic eruptions [Heiken et al., 1974; Pieters et al., 1974]. There were six regional DMDs (Figure 1) identified on the Moon before the Clementine mission with areas >4000 km² [Head, 1974; Gaddis et al., 1985]: (1) Taurus-Littrow in southeastern Mare Serenitatis, (2) Sulpicius Gallus in southwestern Mare Serenitatis, (3) Mare Vaporum in the southeast of the Vaporum basin, (4) Rima Bode in eastern Sinus Aestuum, (5) Sinus Aestuum scattered about the southern edge of the Aestuum basin, and (6) the Aristarchus Plateau. The Clementine data of the farside of the Moon have shown at least one more regional DMD, the Orientale Ring in the southern portion of the Orientale basin [Head et al., 1997; J. W. Head et al., The dark ring in southwestern lunar Orientale basin: Origin as a single pyroclastic eruption, submitted to Journal of Geophysical Research, 1998, hereinafter referred to as Head et al., submitted manuscript, 1998]. It has been recently proposed that there may be additional regional DMDs located on the farside [Craddock et al., 1997; Hawke et al., 1997], but these deposits are only recognizable in spectral data and appear to be relatively thin and well-mixed with other local soils, making it difficult to determine with certainty that the deposits contain volcanic beads. Four smaller regional DMDs also exist on the nearside (Montes Harbinger, Palus Putredinis, Mare Humorum, and Mount Carpatus), but they were not part of this study. All of the regional DMDs are visible because the volcanic beads have high Fe and Ti contents which cause the low reflectances. However, there may be DMDs composed of low-Ti glasses, like the green glasses collected at Apollo 15, but because these deposits do not have low reflectances in the visible wavelengths [Bell et al., 1976], it is impossible to identify them without additional spectral coverage at 0.6 mm and into the near-infrared (NIR) where they have strong diagnostic features or using radar data [Zisk et al., 1974; Gaddis et al.,...
Figure 1. Locations of the seven regional dark mantle deposits studied in this paper.
Therefore this study emphasizes regional DMDs composed of beads with relatively high Fe and Ti contents. Regional DMDs are quite extensive with areas at least \( >2500 \text{ km}^2 \) and up to \( 37000 \text{ km}^2 \) for the Aristarchus Plateau [Gaddis et al., 1985]. In contrast, localized DMDs are smaller in extent and are more widely distributed across the lunar surface [Coombs et al., 1988; Hawke et al., 1989]. The localized DMDs tend to concentrate on crater floors in association with small pit craters aligned on linear rilles, while the regional DMDs are located adjacent to the major basins and are superimposed on the older mare and highlands [Head, 1974]. All the regional deposits on the lunar nearside have been emplaced by younger mare, making it difficult to determine the original extent of the DMDs. While there are perhaps a hundred localized DMDs, only 11 regional DMDs have been identified on the Moon. The paucity of regional DMDs may be a result of their burial by younger mare since they tend to occur at the edges of the large impact basins. Furthermore, regional DMDs may require eruption conditions that are infrequent on the Moon, such as high mass effusion rates and volatile contents [Wilson and Head, 1981].

Although the Moon is deficient in volatiles and completely lacks \( \text{H}_2\text{O}, \text{CO} \)-rich gas produced by graphite oxidation is considered the most likely volatile driving the explosive eruptions that emplaced the DMDs [Sato, 1979; Wilson and Head, 1981; Fogel and Rutherford, 1995; Weitz et al., 1997a]. The low gravity and lack of an atmosphere on the Moon caused gas bubbles in the magma to burst at the surface [Wilson and Head, 1981], resulting in the submillimeter volcanic glasses identified in all the Apollo soils [Delano, 1986]. In contrast, the higher atmospheric pressure on the Earth prevents these volatiles from completely degassing, and the bubbles remain trapped as vesicles in the magma. Just as there are several styles of explosive volcanic eruptions on the Earth associated with basaltic magmas, the two types of lunar DMDs are thought to reflect different eruption styles. The regional

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**Plate 1.** Color ratio images for the regional dark mantle deposits. The images were made by placing the 415/750 nm ratio in the red channel, the 750/950 nm ratio in the green channel, and the 750 nm in the blue channel. The mosaics are not geometrically projected, and each has a slightly different color stretch applied to it. (a) Taurus-Littrow Valley; (b) Taurus-Littrow DMD; (c) Sulpicius Gallus DMD; (d) Mare Vaporum DMD; (E) Rima Bode DMD; (f) Orientale Ring DMD. See text for a description of each image. (g) Sinus Aestuum DMD. Alternate orbits only show the 750-nm frames due to very low phase angles which made the ratio images of poor quality. (h) Aristarchus Plateau DMD. See text for a description of each image.
Plate 1 (continued).
DMDs probably result from larger, Hawaiian-style fire fountain eruptions, while the localized deposits are thought to have been emplaced by gas-rich vulcanian eruptions [Head and Wilson, 1979; Wilson and Head, 1981; Hawke et al., 1989; Weitz and Head, 1995].

On the basis of studies of the lunar samples [Heiken et al., 1974], the glasses tend to be smaller in size and probably experienced a shorter time suspended in an optically thin fire fountain. In contrast, the crystallized beads reflect slower cooling times either because of their larger sizes or because they erupted inside an optically dense portion of the fire fountain where cooling was slower [Head and Wilson, 1989; Weitz et al., 1996]. Experiments by Arndt and von Engelhardt [1987] suggest that the crystallized black beads from the Apollo 17 landing site cooled at rates of 100°C/s, which is much slower than blackbody cooling expected in a vacuum, indicating that the main factor controlling the cooling rate of the beads is the cooling of the volcanic gas cloud. Therefore the crystallized beads must have been erupted as part of a volcanic gas cloud that inhibited cooling and allowed crystallization of minerals, while the glass beads either cooled rapidly because of their smaller sizes or they were ejected into the outer fringes of the cloud where cooling rates were higher. Because the crystallized beads require a hot gas cloud to inhibit cooling, it is unlikely that any significant crystallization occurred after deposition on the surface. The difference between night and day temperatures will also not be strong enough to affect the cooling rates, assuming free flight rates calculated using the Stefan-Boltzmann equation [Arndt et al., 1984].

Telescopic spectral data of the regional DMDs [Pieters et al., 1973; Adams et al., 1974; Zisk et al., 1977; Gaddis et al., 1985; Hawke et al., 1991a] indicate that the Taurus-Littrow, Rima Bode, Sinus Aestuum, and Mare Vaporum DMDs are dominated by crystallized black beads, the Sulphius Gallus DMD may represent an equal mixture of glasses and black beads, while the Aristarchus Plateau DMD is dominated by glasses. More recent Galileo data of the Orientale Ring deposit [Pieters et al., 1993] on the western limb suggested that it is composed of crystallized beads. In this paper, we have used the Clementine UV-visible (UVVIS) data to model the crystallinity of the beads in each deposit in order to provide insight into the size and shape of the volcanic plume that emplaced the beads. The distribution of the beads within each deposit has been mapped to indicate potential source vents and their locations. Finally, the geology of the surrounding terrain has been mapped and characterized using the Clementine data in order to understand the stratigraphic relationships between the DMDs and the other geologic units.

2. Clementine UVVIS Data

2.1. Calibration and Procedures

The Clementine UVVIS data consist of five spectral channels centered at 415, 750, 900, 950, and 1000 nm. The data were calibrated (C. M. Pieters et al., Clementine UVVIS data, calibration and processing, 1997, available at http://www.planetary.brown.edu/clementine/calibration.html) by applying four steps: (1) Remove electronic offset and correct for an added signal that accumulates after exposure as the frame is being transferred to the buffer. No correction for scattered light has been attempted at this time, however. (2) The nonuniformity of sensitivity across the detector must be corrected pixel by pixel by using flat fields derived for each channel from in-flight data. (3) A photometric correction to account for differences in viewing geometry from scene to scene adjusts the measured signal, acquired at one geometry, to the equivalent signal at the standard geometry (i = 30°; e = 0°; a = 30°). 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. (4) Spectral calibration to transform the calibrated DN into bidirectional reflectance uses Apollo 16 soil as ground truth. Even after applying these corrections, some calibration errors still exist at the level of about 1%, particularly from scattered light.

For our spectral analyses, we have only used images taken at 15-50° phase angle because at the higher and lower angles, the spectral calibrations are less accurate. Spectra were extracted using either 4x4 or 2x2 pixel boxes depending upon the size of the feature being analyzed. For each DMD, we have only obtained spectra taken at similar phase angles, allowing spectra within each scene to be compared. However, these spectra cannot be compared between the different DMDs because they have not been corrected for the wavelength dependency at different phase angles. Specifically, in this analysis, the same photometric correction applied to the 750-nm channel was used for all wavelengths, yet there is a wavelength dependence to this correction. This wavelength dependent correction principally affects the continuum slope, causing lunar spectral properties at higher phase angles to appear redder than those acquired at lower angles [McEwen, 1996; C. M. Pieters et al., data 1997, available at http://www.planetary.brown.edu/clementine/calibration.html]. Since the wavelength dependent photometric corrections continue to be refined and because spectra taken from individual scenes were at similar phase angles, we did not apply the wavelength dependent photometric corrections to the individual scenes. Instead, only when we compare quantitative spectral ratio values for each DMD do we apply this wavelength correction.

Color ratio images were produced for each DMD and used to assist in mapping the various geologic units. Plate 1 shows the color ratio image for the seven regional DMDs studied in this paper. Each color ratio consists of (1) 750/415 nm ratio in the red channel; (2) 750/950 nm in the green channel; and (3) 750-nm in the blue channel. Features that have a high 750/415 ratio are bright red in color and typically indicate mature highland soils or glasses (impact or volcanic). A high 750/950 nm value produces a green color and implies the presence of Fe-bearing material, which is referred to here as a mafic signature. The DMDs are low in albedo and therefore have very little signal in the 750-nm wavelength region which is represented by the blue channel. In contrast, the bright, fresh highlands have a high albedo and show up as dark blue in the color ratio images. It should be noted that each color ratio image has a different stretch applied to it to bring out contrasts that vary between the images, and therefore the same type of geologic unit may have a slightly different color in each image. Because the DMDs cover large areas, several individual Clementine image cubes were mosaicked together both along and across orbits. These mosaics were produced manually by merging features from adjacent frames rather than by using latitude and longitude reference grids. Hence these images may have small errors in the precise location of features if compared to a reference map because they have not been geometrically corrected.
Because we are studying low-reflectance features, we used only the longer exposure frames to obtain the best data quality of the DMDs. This caused some saturation in the brightest features, and in the case of the western two frames that cover the crater Aristarchus (Plate 1h) we used the shorter exposure frames to avoid intense saturation of the crater in the color ratio image. In addition to the Clementine color ratios images, we have also used Lunar Orbiter and Apollo photographs to assist in the production of the geologic maps for each DMD. Therefore geologic boundaries shown in the geologic maps may not always correspond exactly to albedo or color boundaries seen in the Clementine images. Finally, for the Taurus-Littrow, Sulpicius Gallus, and Aristarchus Plateau DMDs, topography data derived from Apollo 15 stereo images have been combined with the Clementine data to assist in our interpretation of the geology of these regions.

2.2. Spectral Properties of the DMDs

Lunar volcanic glasses (i.e., quenched glass without crystals) can be identified in spectra by an absorption at 1.0 and 1.8 \( \mu m \) due to electronic transitions of Fe\(^{2+} \) in glass. The amount of Ti in the glasses is reflected in an absorption in the visible wavelengths due to Fe-Ti charge transfer. The higher the Ti content in the glasses, the stronger the absorption edge in the visible region [Bell et al., 1976]. On the other hand, a lower Ti content in mature mare basalts which contain complex amorphous weathering products (agglutinatic glass) corresponds to a lower UVVIS value, while higher ratios indicate higher Ti contents [Pieters, 1978; Pieters et al., 1993]. In contrast to mature mare soils, lunar volcanic glasses show the opposite correlation between color and Ti content, with high-Ti glasses appear red or orange and low-Ti glasses appearing green or clear [Bell et al., 1976]. Figure 2 illustrates the effect of Ti content and crystallinity in the lunar glasses. The Apollo 15 green glasses (15401) have <0.5 wt \% TiO\(_2\) [Delano, 1986], and this results in a strong reflection peak at 0.6 \( \mu m \). In contrast, the Apollo 17 orange glasses (74220) have 9 wt \% TiO\(_2\) and a stronger absorption in the visible region. Black beads that represent the partially crystallized equivalents of the orange glasses (74001) have a strong, broad absorption in the visible centered about 0.6 \( \mu m \) due to ilmenite. The crystallized low-Ti beads will still have a relatively high reflectance because they only crystallize olivine but not ilmenite, and we would not be able to easily detect these deposits of crystallized low-Ti beads in the Clementine data due to their high albedos.

In this paper, we have used the five spectral channels in the Clementine UVVIS data to distinguish between the glasses and crystallized beads with high-Ti and -Fe contents based upon their UVVIS slope between 415 and 750 nm and the approximate strength of the glass band absorption at 1000 nm. Using the laboratory spectra for the beads as a reference and our understanding of maturity (see discussion in sections 3 and 4), we expect that the glasses should have a low UVVIS value and a glass absorption around 1000 nm in the Clementine UVVIS data. In contrast, the crystallized beads should have a lower reflectance and relatively featureless spectra along the continuum slope. Although the Ti contents probably vary for each deposit, we cannot determine the exact composition of the beads and, consequently, assume that they have similar Ti contents. In reality, the varying Ti contents will affect the UVVIS slope and may influence the amount of ilmenite crystals in the beads, which in turn will affect the strength of the glass band absorption.

The thickness of the DMD and the material that the DMD is mixed with will both influence the spectral results. Typical lunar rock types that may be mixed with the DMD include anorthosite, norite, anorthositic norite, impact melt breccia, gabbro, and mare basalt. Anorthosite is dominated by plagioclase, which has a high reflectance and no absorption from 400 to 1000 nm [Pieters, 1986; Hawke et al., 1991b; Tomp...
kinds, 1997]. Norite is a mixture of low-Ca pyroxene and plagioclase. In the Clementine data, norite has a lower reflectance than anorthosite and an absorption centered about 900-950 nm [Tomkins, 1997]. In actuality, there is a continuum between the different highland rocks that can be identified in the Clementine data based upon mixtures of anorthosites, norites, gabbros, and troctolites [Tomkins, 1997]. Mafic basalt is dominated by high-Ca pyroxene, and its absorption is shifted to slightly higher wavelengths (950-1000 nm) than norite.

It is well-known that the maturity of lunar soils due to space weathering causes the overall reflectance and mafic absorption strength to decrease as well as to produce a red continuum slope [Pieters, 1978]. Unfortunately, it is not possible to use the five channels from Clementine to estimate this continuum and remove it from the spectra [Fi scher and Pieters, 1994]. In our analysis, we attempt to distinguish between young immature soils and more mature soils in order to estimate the effect of the continuum on the spectra for the different rock types. In the case of mature soils, we assume that they have reached a steady state in which they have a similar abundance of agglutinates [Fischer and Pieters, 1994]. On the basis of our understanding of the spectral properties for the different lunar soils, we have attempted to estimate the effect of mixing the volcanic beads with these soils. When the DMD is mixed with the highland soils, the UVVIS slope (750/415 nm) should increase, and any glass band absorption should weaken, although the exact effect depends upon the maturity of the soil, the amount of glass in the DMD, and the Ti content of the glass. If the DMD is dominated by glasses and has a high 750/415 slope, then mixing in mature highland soil would not strongly effect the slope, whereas a DMD dominated by crystallized beads would show an increase in the UVVIS slope due to mixing with highland soils. The mafic absorption from mafic soils should enhance any glass band in a DMD dominated by crystallized beads but have little influence on a DMD composed of glasses. The effect mafic soils have on the UVVIS slope depends upon the Ti content of the mafic basalt, with low-Ti basalts having a steeper UVVIS slope and redder color than high-Ti basalts [Pieters, 1978].

Unless indicated otherwise, the DMD spectra shown in this paper were taken where the DMD had the lowest albedo, and therefore, were considered to be the least mixed with soils composed of other rock types. However, it is likely that even where the DMD is darkest, there may have been some mixing with materials during regolith development. Additionally, the darkest area may represent a region containing shadows, and the low reflectance may simply reflect a shaded portion of the DMD, although this will not affect the spectral shape of the selected feature. Because all the DMDs were imaged at relatively low phase angles (<40°), it is unlikely that significant shadows exist, even in the rugged highlands. The thickness of the dark mantle also varies throughout the deposit and is generally thickest on the flatter terrain and thinnest on the steeper slopes, particularly those of the highlands [Gaddis et al., 1985; Hawke et al., 1991a]. In this paper, we have tried to recognize how the DMDs may be mixing with the other geologic units so that inferences can be made concerning the crystallallinity of the beads in each deposit. As will be discussed in section 4, the crystallallinity of the beads is a useful parameter for providing insight into the size and shape of the volcanic plume that emplaced the beads.

3. Spectral Results

3.1. Taurus-Littrow Deposit

The Taurus-Littrow deposit is the only regional DMD where samples were collected (a clod of green glass was sampled at the Apollo 15 site, but it is unknown where the associated DMD is located [Hawke et al., 1979]). The Apollo 17 mission retrieved several soil samples containing the dark mantle material from the Taurus-Littrow Valley. In general, the Apollo 17 soils contain a mixture of volcanic beads, impact glasses, agglutinates, highland lithic fragments, and basalt fragments [Heiken and McKay, 1974]. The volcanic beads in the soils are predominantly high-Ti orange glasses and their partially crystallized equivalents (black beads) [Heiken et al., 1974]. The crystallized beads are more abundant, although there is significant variation in the ratio of orange:black beads depending upon the soil sample [Heiken and McKay, 1974]. Other volcanic glasses have been identified in the Apollo 17 soils, but they constitute only a minor portion of the pyroclastic debris collected at the site [Delano and Lindsey, 1983; Weitz et al., 1997c]. A drill core taken on the rim of the 110-m-diameter impact crater Shorty showed that the orange glasses erupted earlier and then progressively changed to an eruption producing mostly the black beads [Heiken and McKay, 1977; Bogard and Hirsch, 1978]. The black beads have a range of proportions of olivine and ilmenite crystals, but in general, the ilmenite coats olivine and produces the black color of the beads. Ages for the orange glasses range from 3.48 to 3.66 [Tera and Wasserburg, 1976; Alexander et al., 1980], whereas the high-Ti basalts have older ages [Huneke et al., 1973].

3.1.1. Taurus-Littrow Valley. A Clementine 750-nm image taken at 106 m/pixel resolution of the Taurus-Littrow Valley, including the Apollo 17 site, is shown in Figure 3. We have used this image to correlate the Clementine data to ground truth samples and high-resolution Apollo photographs and topography. A simplified geologic sketch map of the region (Figure 3) illustrates the distribution of the DMD and its relationship to other major geologic units in the image. In general, our interpretations using the Clementine data agree well with the geologic map by Wolfe et al. [1981] produced using Apollo photographs. The geologic history of the area [Wolfe et al., 1981] includes (1) massif formation by ejecta from the southern Serenitatis basin in the pre-Imbrian; (2) flooding of the valley by basalt during the Imbrian; (3) deposition of the dark mantle in the valley during the Imbrian; and (4) crater secondaries from Tycho, several of which produced the light mantle deposit. The low exposure age of the volcanic beads in the Apollo 74001/2 core [Bogard and Hirsch, 1978] argues for a rapid burial of the DMD by either younger basalt flows or by ejecta from a neighboring crater [Heiken et al., 1974; Wolfe et al., 1981]. Because no younger basalt samples have been identified in the sample collection, burial by crater ejecta is the preferred process. In our geologic map, we do not distinguish between the massifs and older highlands identified by Wolfe et al., although in the color ratio image (Plate 1a), the massifs tend to be dark blue in color compared to the redder color of the older highlands (i.e., Sculptured Hills). The color ratio image shows the DMD as a brown to light green color on the valley floor. The DMD is darkest just north of the light mantle deposit and in the southeast of the valley away from the crater clusters.
Figure 3. Clementine 750-nm reflectance image of the Taurus-Littrow Valley and geologic map of the Taurus-Littrow Valley after Wolfe et al. [1981].
Spectral reflectance values for different geologic units are illustrated in Figure 4. The spectrum for the DMD is relatively featureless from 415 to 1000 nm, indicating the presence of partially crystallized beads in a mature mare soil. The central portion of the valley floor is dominated by the crater clusters and their ejecta [Lucchitta, 1977], which appears as a green color in the color ratio image and has a strong mafic absorption. Adjacent to the highlands (South and North Massifs), the valley floor spectra are dominated by mature highland soils that have mass-wasted downslope and mixed with the mare soils.

Ejecta from the 110-m-diameter Shorty Crater is visible in the Clementine data because of its low albedo due to the dark mantle and mare basalt it exposed as they were excavated from underneath the light mantle deposit. The spectrum for Shorty Crater ejecta is featureless and similar in shape to the DMD spectra (Figure 4); however, it is slightly higher in reflectance due to mixing with the bright landslide material that the crater penetrated into. Photographs taken by the astronauts indicate that the ejecta also contains basalt fragments from the underlying mare, and this suggests that the dark mantle in the valley is 10 m thick [Heiken and McKay, 1974; Wolfe et al., 1981]. The Clementine data show a mafic signature in the walls of the craters Camelot, Sherlock, Steno-Apollo, Powell, Faust, and Emory. These craters, all of which are between 0.5 and 1 km in diameter and most of which are considered to be secondaries from Tycho [Lucchitta, 1977; Wolfe et al., 1981], have exposed the underlying high-Ti basalts in the valley. The crater Steno-Apollo, which is 450 m in diameter and has the greenest color (highest 750/950 nm) of all the crater clusters in the valley, suggests that it is the youngest. Camelot, which is 650 m in diameter and about 80 m deep, has a much weaker mafic signature than the surrounding smaller craters, supporting an older age [Wolfe et al., 1981]. The largest crater on the valley floor is located in the southeast. It is 1.15 km in diameter and has a strong high-Ca pyroxene absorption around its wall, but its floor has the same spectral properties as the adjacent valley soils, indicating that material has mass-wasted down the walls and onto the crater's floor.

A 0.1-km-diameter crater and its smaller neighbor in the southern edge of the Sculptured Hills were mapped as being among the youngest craters in the valley [Wolfe et al., 1981]. In the Clementine data, the two craters appear as one larger feature with a very strong noritic signature (Figure 4, crater C1) and a light blue color in the ratio image due to its high albedo and mafic absorption. The northeastern edge of Bear Mountain also has a noritic signature, but it is light green in color because it has a lower albedo and hence a smaller contribution in the blue channel compared to the crater C1. The Bear Mountain feature appears to be associated with a young crater, whereas the rest of the Mountain is composed of material with an anorthositic composition and appears dark blue in Plate 1a. Several other patches of norite are visible in the massifs, indicating that either Mg-rich plutons or noritic LKFM have been mixed with the anorthositic highlands during the massif formation from the Serenitatis basin impactor [Wolfe et al., 1981]. While the steep slopes on the North and South Massifs have fresh anorthositic spectra and appear dark blue in the color ratio image, the Sculptured Hills show more heterogeneity with mixtures of fresh and mature highlands soils as well as several patches of fresh norite. Even though the valleys in the highlands are lower in albedo, suggesting the presence of dark mantle, the color ratio image shows that the valleys are filled with mature highland soil. We have classified the highlands here as unmantled because no DMD can be identified in the Clementine data. However, there could still be small amounts of DMD mixed with the soils but either because it is too thin or it has been mixed with the highland soils, any DMD signature
has been obscured. Heiken and McKay [1974] and Korotev and Kremser [1992] have determined that the percentage of volcanic beads in highland soil samples from Apollo 17 is less than 5%, with one sample perhaps having up to 12%, supporting that the highlands have been contaminated by the pyroclastic material but only to a minor extent. On the basis of these results from the Taurus-Littrow Valley, it appears possible to reliably use the Clementine UVVIS data to infer whether the pyroclastic component of a DMD is dominated by crystallized or glassy beads and to determine the composition of the geologic units in the surrounding region.

3.1.2. Taurus-Littrow Dark Mantle Deposit. Clementine UVVIS spectra are shown in Figure 5 for the Taurus-Littrow DMD, located adjacent to the Taurus-Littrow valley. The mosaic covering the DMD was taken at 170 m/pixel resolution and is shown in Figure 6 and Plate 1b. The DMD spectra have a low reflectance, a high UVVIS ratio, and a relatively featureless spectrum from 415 to 1000 nm, which is characteristic of the black beads. The DMD can be seen as the unit in the center of Plate 1b with a green color and as the mantled mare unit in the geologic map shown in Figure 6. The younger low-Ti mare basalt unit, which is approximately the same unit as the MS-2 standard located in the southern part of Mare Serenitatis, is visible in the northwestern part of Plate 1b and appears as an orange color. The unmantled high-Ti mare is only visible in the upper and lower right of Plate 1b (green color), although it also underlies the DMD at the center of the figure. Where the high-Ti mare appears to be mantled, it has a lower albedo and weaker 1000-nm mafic absorption compared to the unmantled high-Ti mare visible in the northeastern and southern parts of Figure 6. As shown in Figure 5, both unmantled mare units have characteristic mare soil spectra [Pieters, 1978] and high 750/950 nm values (0.936), but they differ in the slope between the 415- and 750-nm channels, reflecting different Ti contents [Charette et al., 1974]. The high-Ti mare has a 415/750 ratio of 0.628, while the low-Ti mare has a value of 0.600.

A fresh crater in the surrounding low-Ti basalts of Mare Serenitatis has a characteristic strong high-Ca pyroxene absorption spectrum expected for fresh basalt (Figure 5). The majority of fresh craters in the DMD, however, do not show a high-Ca pyroxene absorption from the underlying mare; instead, they have high albedos and spectra corresponding to noritic or anorthositic soils (Figure 5, crater CI) and appear blue in the color ratio image. The surrounding highlands have spectra corresponding to anorthositic to noritic soils. Therefore it appears that most of the craters in the DMD are penetrating through the DMD and mare basalt layers to expose the underlying nonmare materials. In contrast, the higher-resolution images from the Taurus-Littrow valley to the east revealed a mafic (basaltic) signature in the smaller craters there. Given that the thickness of the pyroclastic deposit in the valley to the east is 10 m and it is only a minor component of the surface regolith, it is likely that the DMD in the west is greater than 10 m in thickness and has a larger component of the volcanic beads due to its much lower albedo.

Young small craters in the highlands and DMD have exposed fresher dark mantle beneath the regolith. Additionally, small craters in the north have penetrated through the bright ejecta blanket from the 7.2-km-diameter crater Clerke, exposing the underlying DMD. These black spots in the color ratio image (Plate 1b) have the same spectral shape as the DMD but average about 2% higher in reflectance (Figure 5) because they have mixed with brighter soils, similar to the effect occurring at Shorty Crater. Similar black spots were previously identified in the highlands using Apollo 15 photographs, but they were interpreted as possible cinder cones [McGetchin and Head, 1973]. Instead, we believe that the black spots indicate that dark mantle was deposited in the highlands, but later mixing with the bright highland soils
obscured and buried most of the dark mantle in the higher elevations. Therefore the original extent of the DMD may have been over much of the highlands, but it has unfortunately been obscured by later regolith development and mass wasting. The thickness of the DMD on the valley floor is thought to be about 10 m [Heiken and McKay, 1974; Wolfe et al., 1981], and this probably represents a maximum for the original thickness of the DMD on the highlands as well.

Although we do not distinguish between the two highland units mapped by Wolfe and Scott [1981], the massifs are easily recognizable by their bluer color in Plate 1b. The sinuous rille, Rima Carmen, is partially visible in Figure 6 where it cuts through the mare and has a higher albedo. At this location, it is about 1 km wide and 180 m deep. However, where the rille traverses through the highlands to the northwest, it becomes narrower and shallower and is no longer visible in the both the color ratio and 750-nm images. Rima Carmen is located too far south in the DMD to be the sole vent responsible for the eruption and emplacement of the DMD, although it may have contributed some volcanic beads to the area [Weitz et al., 1997b]. The most plausible location of the source vent that emplaced the 74001/2-type beads, which dominate the DMD, is to the northwest buried beneath the younger low-Ti mare of Serenitatis [Weitz et al., 1996]. At this location, the vent would have emplaced the DMD predominantly in the basin, although some would also have been deposited on the
highlands and high-Ti mare in the Taurus-Littrow valley where it would have been preserved from burial by the younger low-Ti mare.

### 3.2. Sulpicius Gallus Deposit

The Sulpicius Gallus DMD is located partially on the mare and highlands in southwestern Serenitatis basin, on the opposite side of the basin as the Taurus-Littrow DMD (Figures 1 and 7). The color ratio image (Plate 1c) produced from three Clementine orbits (33, 34, and 165) shows the DMD as an orange color, while the adjacent highlands appear more pinkish. Initial mapping of the area by Carr [1966] from telescopic data suggested an Imbrian to Eratosthenian age for the deposit due to its superposition on the older dark mare visible at the basin edge but its burial by the intermediate age mare unit of Serenitatis [Boyce et al., 1974]. Our geologic sketch map shown in Figure 7 was produced using the Clementine data and Apollo 15 stereo images. The geologic sequence for the region based upon our mapping agrees with earlier interpretations [Carr, 1966; Lucchitta and Schmitt, 1974]: an older mare unit covering some of the highlands, followed by dark mantle deposition on top of the older mare unit and adjacent highlands, concluding with the emplacement of the younger mare unit in Serenitatis. Photographs of the deposit taken during the Apollo 17 mission showed layers of orange and red glasses along with black beads exposed in several crater walls [Lucchitta and Schmitt, 1974]. Unfortunately, we are unable to distinguish between these layers in the DMD at this low spatial (116-162 m/pixel) and spectral resolution.

Two spectra from the Clementine UVVIS data (Figure 8) taken from orbits 33 and 165 show that the dark mantle varies in the strength of the glass band and the UVVIS ratio across the deposit. A DMD spectrum taken on the edge of the mantled highlands (DMD1) has a relatively low 415/750 nm ratio (0.585) and a moderate 750/950 nm glass band absorption of 0.936, while another spectrum from higher up in the mantled highlands (DMD2) has a similar 415/750 nm ratio (0.584) but a weaker glass band of 0.894. The weaker glass band and higher reflectance for DMD2 can either be explained by increased mixing with the underlying highlands or by a higher percentage of the crystallized beads [Hawke et al., 1991a].
Figure 8. Spectra of geologic units in the Sulpicius Gallus DMD area. All spectra were taken at 30° phase angle except DMD2 which was acquired at 20°. DMD1 shows a moderate glass band absorption and steeper UVVIS slope compared to Taurus-Littrow DMD. Orange spots in the highlands have a steep slope between 415 and 750 nm and a strong glass band absorption, both indicating fresher exposures of glasses. The crater Sulpicius Gallus has a mixture of mare and highlands along its walls.

Clearly, the original thickness of the dark mantle, the amount of mixing with the surface soils, and the ratio of glass/crystallized beads all affect the spectra for the dark mantle at each location within the DMD. On the basis of the Clementine spectra and Apollo photographs of the area, we suggest that the DMD is dominated by the volcanic glasses with some crystallized beads mixed in as well, supporting previous interpretations by Gaddis et al. [1985] and Hawke et al. [1991a].

Lucchitta and Schmitt [1974] estimated that the DMD was 50 m thick based on crater excavation depths. Numerous small craters in the highlands, which appear as bright orange dots in the color ratio image (Plate 1c), have a higher reflectance, steeper UVVIS slope, and stronger glass band compared to the surrounding DMD. These craters probably excavated underlying layers of the volcanic beads beneath the regolith in a similar manner to the dark spots seen in the Taurus-Littrow DMD. Much of the ejecta from the crater Sulpicius Gallus (12 km diameter) has been emplaced by younger Mare Serenitatis basalts (Figure 7). The walls of the crater have spectra corresponding to anorthositic norite and basalt (Figure 8, Figure 8, Sulp Gallus 1 and 2). Lucchitta and Schmitt [1974] suggested that DMD was visible in the upper layer of the walls of Sulpicius Gallus. No DMD layer is visible in the Clementine data of the crater, and this may reflect either a resolution problem or there may not be any DMD at this location. Lucchitta and Schmitt also identified dark material on the inside of a 1.5-km-diameter fresh impact crater located in the mare just northwest of Sulpicius Gallus crater and suggested that a dark mantle layer occurred beneath the younger mare at the edge of the Serenitatis basin. The crater is light green in the color ratio image and the Clementine spectra (Figure 8, Crater on Mare) show a strong high-Ca pyroxene absorption, indicating that the dark interior is in fact young, fresh basalt. Given that the dark material originally thought to be DMD by Lucchitta and Schmitt [1974] has now been identified as fresh basalt, it is likely that the same dark material identified in Sulpicius Gallus crater is also a mare deposit rather than DMD.

Perched mare ponds in the highlands are visible to the south and west of the DMD as illustrated in Figure 7. Lacus Odii has a weaker 750/950 value compared to the unmantled mare unit of Serenitatis but a similar 415/750 nm ratio. Rimae Sulpicius Gallus are partially visible in the color ratio image as green lines crossing through the mantled mare unit (Plate 1c). The Apollo 15 photos show a 5.5-km-long kidney-shaped depression in the DMD with orange and red layers visible in its walls [Lucchitta and Schmitt, 1974]. The depression is visible in the color ratio image as a green oval surrounded by the orange color of the DMD. Clementine spectra for the depression show a low 415/750 and high 750/950 value around the walls, supporting a mafic composition in the walls, but no dark mantle could be resolved. Because of the unusual shape of this depression, it has been proposed as a possible source vent for the DMD [Lucchitta and Schmitt, 1974]. However, the depression is located toward the southern end of the DMD, requiring the eruption of the beads to have been asymmetric, with most of the beads ejected to the north. This seems highly implausible; it is more likely that the depression may have contributed only partially to the eruption and emplacement of the DMD. Alternatively, the depression may represent a graben, similar
3.3. Mare Vaporum Deposit

This dark mantle deposit is concentrated on the highlands at the southeastern end of the Vaporum basin (Figure 1) and it appears elongate in the NW-SE direction as seen in Figure 9.

in width but much shorter in length than other rilles in the area. A more likely source vent for the DMD would be located to the northeast, buried beneath the younger mare of Serenitatis. More discussion on the source vent for the Sulpicius Gallus DMD occurs in section 4.2.3.

Figure 9. Mosaic of 750-nm reflectance frames for the Mare Vaporum DMD. The DMD is superimposed on the highlands and is elongate in the NW-SE direction. The rille Hyginus (lower left) is unusual because it traverses through smooth plains and has numerous pit craters along its floor. Unit names in the geologic map refer to geologic units identified by Wilhelms [1968].
Three orbits provide coverage of the region (33, 34, and 188) with resolutions of 112-145 m. The phase angles for orbits 33 and 34 varied from 25° to 27°, while orbit 188 had low angles from 10° to 18° with calibration errors that prevented us from using spectra along this orbit. In the color ratio image (Plate 1d), the DMD appears red, while the surrounding unmantled highlands appear pink. Unfortunately, the mare units in the highlands are also red and low in reflectance, making it difficult to distinguish between the DMD and these mare units. However, Lunar Orbiter images show the boundary between the mare and highland, while young impact craters in the mare appear green in the color ratio image compared to the blue color of fresh highland craters. A detailed geologic map of the region was produced by Wilhelms [1968], and we used this map as a reference for identifying geologic units in the Clementine data.

Spectra for geologic units taken along orbits 33 and 34 are illustrated in Figure 10. A small, smooth unit in the west (Figure 9, Icah) has a bright red color and was mapped by Wilhelms [1968] as Cayley Formation that is more undulating than the smooth plains that dominate in the southern part of the image (Figure 9, Ica) and appear pink in Plate 1d. The unit Icah is about 4% lower in reflectance than Ica, and it has lower 415/750 and 750/950 values than Ica, suggesting that Icah has mixed with the adjacent unmantled mature highlands (Figure 10). In the Vaporum basin, Wilhelms identified two mare subunits; however, we only see one unit in the Clementine data and map the unit as Mare Vaporum (Figure 9). This unit is yellow in the color ratio image and has a 415/750 value of 0.616 and a 750/950 value of 0.937. There are also several mare ponds in the highlands that we have identified and mapped (Figure 9, Green Mare in Highlands) which were not mapped by Wilhelms [1968]. One of these green mare units in the highlands has a lower reflectance and higher 415/750 value (0.650) compared to the Mare Vaporum unit (0.616), indicating a higher Ti content. We have also identified the young mare unit that is located in the lower left of the image, just south of unit Icah. This mare unit (Figure 9, CEmI) appears green in the color ratio image and has a 750/950 ratio of 0.915, which is similar to the mare ponds in the highlands, but a 415/750 value of 0.609, which is redder than both the highland and Vaporum mare units. The redder color is most likely due to a lower Ti content in the mare, although it could also reflect mixing with the smooth plains at this location (Ica).

The spectrum for the DMD (Figure 10) shows a weak ferrous absorption and flat UVVIS slope. The 415/750 ratio is 0.627 and the 750/950 value is 0.896, indicating a redder color than the Taurus-Littrow DMD but bluer than the Sulpicius Gallus DMD. The strength of the glass band is comparable to that of the Taurus-Littrow DMD, implying a mixture of crystallized beads and glasses but domination by the crystallized beads. Additionally, the redder color compared to Taurus-Littrow may reflect mixing with the surrounding highlands, as was the case for the Sulpicius Gallus DMD. The unmantled highlands have a higher reflectance, a lower 415/750 value, and a higher 750/950 value compared to the DMD. Hence the redder color of the DMD compared to Taurus-Littrow could be due to mixing with highland soils, although this should have also increased the value of the 750/950 ratio. If the DMD is even more domi-

![Mare Vaporum DMD](image-url)

**Figure 10.** Spectra taken from the Mare Vaporum DMD region. The DMD spectra are low in reflectance and relatively featureless except for the continuum slope. The various mare units differ in the strength of their mafic absorption around 1000 nm and their UVVIS slope between 415 and 750 nm. Exposures along Mare Hyginus indicate fresh highland material while the surrounding smooth plains have a spectrum more characteristic of mature highland soils.
Figure 11. Mosaic and geologic map of the Rima Bode DMD. The DMD is located on the highlands and has been embayed by younger mare to the west. The boundary between the DMD and highlands is difficult to identify because of mixing between the two units. Unit names refer to geologic units identified by Wilhelms [1968].
nated by crystallized beads than at Taurus-Littrow, then mixing with mature highland soils would decrease its 415/750 and increase its 750/950 values, thus explaining its spectral properties.

The rille Rima Hyginus is unusual because it has numerous pit craters along its otherwise flat floor. The walls associated with these pit craters and with the rille itself have a strong 1000-nm absorption due to exposure of immature highland material, while the smoother rille floor is spectrally the same as the surrounding smooth, mature highland terrain. The lack of a mare signature along most of the rille suggests that it formed by collapse, supporting earlier interpretations that it formed by extension [Wilhelms, 1968]. The pit craters suggest intrusion at depth by magma [Head and Wilson, 1994], similar to the formation of pit craters in terrestrial volcanoes. Because the rille is outside of the DMD, it cannot be the source for the DMD. Another candidate source vent is an irregular crater located in the southeastern part of the DMD that actually appears to represent a coalescence of three impact craters (Figure 9, C1). The crater walls appear to be composed of unmantled highlands (Figure 10), while its floor matches that of the surrounding mantled highlands. Wilhelms [1968] interpreted the crater as an irregular ring of material formed by extruded basalt. Because the depression has an upraised rim crest, is not centrally located in the DMD, and has no associated volcanic features, we believe that it most likely represents an impact feature rather than a potential source for the DMD. Rather, the source (if centrally located in the DMD) should lie to the northwest buried beneath the Mare Vaporum unit.

3.4. Rima Bode Deposit

The Rima Bode DMD (Figure 1) was mapped by Gaddis et al. [1985] as two units: (1) a very dark unit on the highlands and mare basalt in the west and (2) a dark, thinner DMD unit on the highlands in the east. A more detailed geologic map of the region was produced by Wilhelms [1968] and has been used to assist in the interpretation of the Clementine data. Three Clementine orbits (37, 169, and 170) cover the Rima Bode DMD and have been used to produce the color (Plate 1e) and 750 nm reflectance (Figure 11) mosaics. The center strip is from orbit 37, which was taken at 25° to 26° phase angle and at 140-145 m/pixel resolution. Unfortunately, the eastern and western image strips (orbits 169 and 170) were acquired at 9° to 12° phase angle, which is too low to be adequately calibrated. Hence the individual frames along these mosaicked orbits are visible due to erroneous albedo variations. Consequently, spectra were only extracted from orbit 37 down the center of the image. We used the low phase angle orbits to assist in mapping the DMD and other geologic units, however.

The Rima Bode DMD spectrum, shown in Figure 12, is similar in shape to the Taurus-Littrow DMD but slightly lower in reflectance, suggesting that it is dominated by the crystallized black beads [Gaddis et al., 1985; Hawke et al., 1991a]. However, the 415/750 value is 0.600 and the 750/950 value is 0.906, which means that the DMD is slightly redder and has a stronger glass band absorption compared to the Taurus-Littrow DMD but is slightly bluer than the Sulpicius Gallus DMD. In the color ratio image (Plate 1e), the DMD appears dark red, while the surrounding unmantled highlands appear pink and bright red in color. The DMD has been partially covered by mare to the west and south, although small kapukas of the DMD are still visible in the southern lava pond.

Three elevated mare ponds are visible in the highlands and show no mantling by DMD (Figure 11). It should be noted that the small mare unit in the northeast of the image (Figure 11, CEm1) is not a mare pond in the highlands but rather is a young Copernican mare unit identified by Wilhelms [1968] in

![Rima Bode DMD](image)

Figure 12. Spectra taken from the center orbit (Rev 37) that covers Rima Bode DMD at a phase angles of 24°-27°. The DMD is low in reflectance and shows a small glass band absorption. Most of the craters, including those in the perched lava pond, have highlands spectra.
western mare Vaporum. Spectrally (Figure 12), the middle and southern ponds are very similar in reflectance and shape. The southern mare pond has a 2-km-diameter impact crater on it with a spectrum similar to the highlands (Figure 11, C1) and no visible mafic absorption. In contrast, the smaller craters on the pond show a strong mafic band. The northern pond is slightly lower in reflectance but has very similar 415/750 and 750/950 values to the middle and southern ponds, indicating that all three ponds have similar Ti contents. Although the Sinus Aestuum mare unit was not covered along orbit 37, we can compare its spectral character taken from orbit 170 (low phase angle) to that of the southern pond taken along the same orbit. These results show that the Sinus Aestuum mare is very similar in reflectance and shape to the southern pond which means that it also is compositionally similar to the three mare ponds in the highlands. Wilhelms [1968] mapped the three mare ponds and Sinus Aestuum mare as Imbrian in age, which supports our Clementine results of similar ages and compositions.

A 6.5-km impact crater (C3 on Figure 11) in the DMD has a spectrum consistent with highland rocks, as do the majority of craters in the DMD due to their penetration through the thin dark mantle to the underlying highlands. In the center of the image at the contact between the basalts of Sinus Aestuum and DMD, the eastern rim of a 12-km-diameter impact crater (C2 on Figure 11) is still partially visible in the mare and dark mantle can be seen on top of this rim (Figure 11). Originally, this crater was mapped by Wilhelms [1968] and Gaddis et al. [1985] as partially located on the highlands in the east, but the Clementine data reveal that the crater has been embayed by mare on all sides and the crater walls have a mafic signature. In fact, the Sinus Aestuum mare eastward of the crater appears lower in albedo than the mare to the west, suggesting that the regolith there is a mixture of the mare and the underlying DMD, as shown in the geologic map of Figure 11. Additionally, small dark spots on the mare indicate that craters penetrate through the mare to expose the underlying DMD. However, it should be noted that without calibrated spectral data, it is difficult to distinguish between the mare and highlands using only the Clementine reflectance images at this location.

In the center of the image, the dark mantle dominates the regolith because the mare has not embayed it, and the DMD is relatively thick enough to prevent obscuration by mixing with the underlying highlands. In the eastern half of Figure 11, the DMD is higher in albedo and more patchy, supporting that it is thinner and mixed with the surrounding highlands [Gaddis et al., 1985]. The spectra for the highland regions (Figure 12) indicate a mixture of anorthositic and noritic material, similar to the highlands found at Taurus-Littrow. At these low phase angles, it is difficult to identify rilles in the area. Nevertheless, it is possible to distinguish the linear rille Rima Bode II in the north as it cuts NW-SE through the DMD. The rille varies in color from bright green in the mare to the northwest and red to the northeast where it transects through the highlands. Rima Bode I is partially visible in the southern mare pond, and it is bright green in the color ratio image, indicating fresh mare is exposed along the rille walls. Both rilles were considered unlikely source vents for the DMD because they are located outside of the lowest albedo in the DMD [Gaddis et al., 1985]. Instead, Gaddis et al. [1985] suggested that the source vent was located to the west in Sinus Aestuum buried beneath the younger mare, an interpretation that we support based upon our geologic mapping.

3.5. Southern Sinus Aestuum Deposit

A Clementine mosaic covering the Sinus Aestuum DMD is illustrated in Figure 13 and consists of nine orbits. This deposit is actually several distinct DMDs, with two larger patches located to the east and west (Figure 1). The western patch (Sinus Aestuum I) is located 100 km southeast of the crater Copernicus while the larger eastern patch (Sinus Aestuum II) is located just southwest of the Rima Bode DMD. Smaller DMD patches located between the two larger DMDs but to the south are included as part of the regional DMD description. Because this DMD is located southwest of the Rima Bode DMD, the same second cycle orbits that have low phase angles for Rima Bode have even lower phase angles at these lower latitudes. These orbits include 171, 172, 173, and 174 with phase angles from 0 to 10°. In both the color ratio (Plate 1g) and 750-nm reflectance (Figure 13) mosaics, these orbits have visible frame boundaries because of the inability to calibrate the data properly. Four of the five orbits acquired at higher phase angles (Revolutions 39-42) suffered from low exposure times, even for the longer exposures of each exposure pair, causing strong compression artifacts and noisy data. Nevertheless, the phase angles were high enough (23°) to acquire spectral data and to produce valuable color ratio images. Spectra of various geologic units taken from these orbits with the higher phase angles are shown in Figure 14. Clementine data resolutions varied from 122 to 140 m/pixel. Apollo 12 panoramas at oblique angles were used to determine the topography of the region and, along with Lunar Orbiter IV images, to aid in mapping the DMD for those Clementine orbits acquired at low phase angles. A geologic map of the eastern DMD, including Sinus Aestuum II and a portion of the southern patches, was produced by Wilhelms [1968] and used to assist in our interpretation of the Clementine data.

The Sinus Aestuum I DMD is ~90 km across and is situated on small highland hills. Because it is located ~100 km southeast of the crater Copernicus, it has been heavily disrupted by ejecta and secondary impacts. Rather than a continuous deposit, the DMD appears very patchy in the Clementine data. The darkest patches of DMD appear to be associated with small secondary impact craters from Copernicus, indicating that pure dark mantle exists at depth. The DMD is superimposed on larger patches of highlands that have been embayed by the younger mare of Sinus Aestuum, which is the same mare unit seen at the Rima Bode DMD [Wilhelms, 1968]. The DMD has a relatively high 415/750 ratio (0.677) and a low 750/950 value (0.896). In comparison to the Taurus-Littrow DMD, it shows the same lack of a glass band but is slightly bluer in color. The numerous crater rays from Copernicus are blue in color (Plate 1g), suggesting that some of this blue material (probably highlands) may be mixed with the DMD, increasing its 415/750 value. In terms of crystallinity, the DMD must be spectrally dominated by the crystallized beads.

To the east of Sinus Aestuum I DMD are two patches of low albedo debris associated with impact craters (Figure 13, Dark Halo Craters). These dark halo craters have a stronger mafic band (Figure 14), indicating that the dark material is underlying mare rather than DMD. Still farther south (2°N, 350°E) and in between the Sinus Aestuum I and II DMDs are dark patches located on remnant highlands (Figure 13). These low albedo patches (Figure 14, Southern Dark Spot) have a 415/750 value of 0.710 and 750/950 value of 0.875. The DMD here has a weaker glass band absorption and a higher reflectance than the
Figure 13. Nine orbits were mosaicked together to produce this image of the Sinus Aestuum DMD. Four of these orbits were acquired at very low phase angles (<10°) which caused them to have visible frame boundaries because of the inability to calibrate the data properly. Crater ejecta and rays are visible across the image from the crater Copernicus located to the northwest of the image. The geologic sketch map of the DMD has been divided into several units, including larger units to the west (Sinus Aestuum I) and east (Sinus Aestuum II), and smaller patches in the south.
Figure 14. Spectra from the various DMD units of Southern Aestuum. A dark spot in the Sinus Aestuum II unit has a very low reflectance and a relatively flat slope between 415 and 750 nm. The dark spot represents a fresh exposure of crystallized beads excavated by a young impact crater. The other DMD units have steeper continuum slopes and higher reflectances because they represent more mature soils composed of crystallized beads.

The Sinus Aestuum II DMD, located 130 km to the east of the Sinus Aestuum I DMD, is also very patchy as seen in both the Apollo 12 panoramas and the Clementine data (Figure 13). Rather than one homogeneous albedo across most of the DMD, there are numerous low albedo spots of dark mantle that have been exposed by various size impact craters. This suggests that the DMD is quite thick since all the craters expose only fresher dark mantle rather than underlying highlands or mare. Only toward the edge of the DMD can craters be seen exposing highland and mare units in the walls while the ejecta is dominated by dark mantle. Clementine spectral data for one of these dark spots of DMD (Figure 14, Sinus Aestuum II DMD Dark Spot) show a very low albedo, a relatively flat spectrum between the 415 and 750 nm (415/750 value it 0.726), and no glass band absorption (750/950 is 0.834), consistent with the crystallized black beads. On the basis of the laboratory spectra for immature crystalized beads (Figure 2), the spectrum for the Sinus Aestuum II DMD Dark Spot appears to be the best spectrum for immature volcanic black beads obtained remotely.

The overall spectral character of the Sinus Aestuum II DMD (i.e., the more continuous deposit) has a 415/750 ratio of 0.663 and a 750/950 ratio of 0.880, indicating a weaker glass band than the Taurus-Littrow DMD and a slightly bluer color but not as blue as the Sinus Aestuum I DMD to the west. Therefore, while the overall Sinus Aestuum II DMD is spectrally similar to the Taurus-Littrow DMD, the small patches of dark mantle indicate a fresher soil exposed by young impact craters that is composed of pure crystallized beads with fewer agglutinates (lower UVVIS slope).

Apollo and Lunar Orbiter photos of the DMD here indicate that it is superimposed on the remnant highlands. Small patches of DMD on the outskirts of the main DMD unit appear to represent buried DMD that has been exposed by impact craters into the younger mare of Sinus Aestuum. Farther to the east of the main Sinus Aestuum II unit, the DMD becomes redder in color and higher in reflectance. Spectrally, the DMD in the east has a slightly lower 415/750 nm value (0.640) but the same 750/950 nm ratio (0.885) compared to the DMD located in the western portion of Sinus Aestuum II. The slightly redder color and higher albedo may be due to mixing with the highlands, as supported by the numerous blue craters that are visible in the DMD (Plate 1g). The red units directly to the south, although similar in color, are spectrally distinct as mature unmantled highland soils associated with an older impact crater rim (Schroteri) that has been embayed by younger mare (Figure 13).

In addition to the DMD, blue streaks are visible in the color ratio image and represent rays from Copernicus composed of highland material, consistent with telescopic near-IR observations [Pieters et al., 1985]. In several locations, fresh outcrops of highlands are visible, and they have an anorthositic signature in the spectra (Figure 14, Unmantled Highlands). Additionally, numerous mare units appear as various shades of green in Plate 1g. The mare units differ spectrally in the strength of the mafic absorption but have similar UVVIS slopes. In both the Clementine 750-nm reflectance image...
These deposits, therefore, probably represent only the outer different distances from the vent, with the glasses tending to have been two distinct eruptions for each DMD. We favor a separate eruption and source vent because the Rima Bode DMD is spatially separated from the Sinus Aestuum DMD by unmantled highlands, and these highlands should also be mantled if the vent were located to the southwest and emplaced both the Rima Bode and Sinus Aestuum DMDs. It should be noted that on Wilhelms' [1968] geologic map of the region, the DMD is mapped as a continuous unit between the Sinus Aestuum II and Rima Bode DMDs, suggesting that the deposits are related. If we accept that the two DMDs were produced from the same vent and assume a centered location for this vent based upon the location of the Rima Bode and Sinus Aestuum DMDs, then the vent should also have emplaced DMD on the northern highlands around the Aestuum basin, which is not the case. Only if the volcanic plume deposited dark mantle in an asymmetric nature could the deposit be concentrated in the south compared to the north; however, in the lunar environment, volcanic plumes should produce a symmetric deposit [Wilson and Head, 1981]. Therefore the Rima Bode and Sinus Aestuum DMDs require separate vents and eruptions.

Sinus Aestuum I and II DMDs appear to require different mixtures of glass:crystallized beads, with the Sinus Aestuum I DMD having a higher concentration of orange glasses compared to the Sinus Aestuum II DMD to account for the larger glass band absorption. The variations in glass:crystallized bead ratio may reflect a position in the deposit that represents a more glassy deposit compared to the Sinus Aestuum II and Sinus Aestuum DMDs. These deposits, therefore, probably represent only the outermost and highest standing deposits on remnant patches of highlands while the rest of the DMD located in the lowlands at the center of the basin became buried by the younger basalts of Sinus Aestuum. An approximate location for this central vent would be at 4°N, 348°E. At this location, volcanic beads would not be ejected far enough to be deposited on the northern highlands that correspond to the southern rim of Imbrium basin.

3.6. Aristarchus Plateau Deposit

The Aristarchus Plateau (Figure 15) is an elevated crustal block about 170×220 km that is surrounded by younger mare basalts [Head, 1974; Zisk et al., 1977; Pieters, 1978]. Telescopic observations showed that the plateau was covered by volcanic glasses [Zisk et al., 1977; Whifford-Stark and Head, 1977, 1980; Gaddis et al., 1985; Lucey et al., 1986] and radar data indicated that it has the lowest reflectivity for any large area on the Moon [Zisk et al., 1974; Thompson, 1974]. Preliminary Clementine observations of craters on the Plateau were used to estimate a thickness of 10–30 m for the DMD and 200–600 m for the underlying mare [McEwen et al., 1994]. The color ratio image (Plate 1h) shows the DMD as the dark red unit on the plateau to the west. Unfortunately, much of the surrounding mare is also red in color, making it difficult to distinguish between the mare and DMD without the aid of Lunar Orbiter images and Apollo 15 derived topography. Although there are several mare units visible in the color ratio image, we do not distinguish between them in our geologic map and instead refer to the geologic map by Zisk et al. [1977] for a description of these units.

The DMD is darkest to the northwest, most likely due to mixing and burial of the dark mantle to the southeast by ejecta from the 40 km diameter Aristarchus crater. One of the darkest patches of dark mantle occurs in association with Rima Aristarchus on a mare unit in the northern part of the Plateau. The DMD may be very dark there because it is mixing with a mare unit compared to brighter highlands elsewhere on the plateau. The second dark patch surrounds Herodotus χ, a 1-km-high bright hill in the northwest of the plateau. There is no associated mare basalt in this area, but the region is composed of rough highlands that may have protected the DMD from Aristarchus ejecta and younger mare by simple embayment, both of which have covered DMD in the southern half of the plateau (see discussion in section 4).

Spectra from various geologic units in the image are shown in Figure 16. Spectrally, the DMD has a low 415/750 value of 0.544 and a high 750/950 of 0.960 due to the strong glass band absorption. Numerous small bright hills interspersed throughout the DMD, as well as Herodotus χ and the Agriola Mountains, appear dark blue in the color ratio image. The Clementine data indicate the presence of anorthosite whereas telescopic near-infrared spectra suggest olivine in the hills [Hawke et al., 1995]. Presumably, most of these highlands represent uplifted blocks or ejecta from the formation of Imbrium basin, although some minor patches in the southeast could represent ejecta from Aristarchus crater [Zisk et al., 1977]. The highlands of Montes Harbinger are also visible to the northeast of the crater Prinz.

Topography shows that the highest point on the plateau is located 40 km north of Cobra Head in a green area in the color ratio image (Plate 1h). This area was originally mapped as mantled mare and highlands by Zisk et al. [1977], but the Clementine data show little if any DMD here. Instead, our results agree with those of McEwen et al. [1994] that indicate the green unit is unmantled lobes of ejecta from Aristarchus. The greener color may reflect highlands that are mixed with either a noritic or basaltic signature exposed by the Aristarchus and Aristarchus A craters. Although the edge of the plateau is easily visible in the west, the eastern boundary is not mappable on the color ratio image because the mare is a similar red color to the plateau. Therefore we have used the topography derived from Apollo 15 stereo and Lunar Orbiter (LO) IV images to map the plateau boundary in the east, in conjunction with previous geologic maps [Zisk et al., 1977; Whifford-Stark and Head, 1977].

Impact craters in the area are particularly useful for determining the stratigraphy at depth in this region. The ages of the craters vary from Imbrian (Prinz and Herodotus), late Imbrian (Krieger), and Copernican (Aristarchus) [Zisk et al., 1977]. Figure 17 shows spectra for several craters in the region. The floor of Aristarchus crater (~3 km deep) and its
Figure 15. Mosaic of the Aristarchus Plateau as seen in the 750-nm reflectance. The dark mantle is distributed over the plateau and the highlands to the east, but the darkest patches are visible in the northwest. The crater Aristarchus has disrupted much of the DMD on the plateau. Because this crater is so bright in reflectance, the two frames that cover the western half of the crater are from the shorter exposure times to prevent saturation of the crater. The rest of the crater and the remaining image were produced from the longer exposure time frames. In the geologic map, we do not distinguish between the numerous mare units in this region, which have been previously described by Zisk et al. [1977]. Many sinuous rilles that are visible in Apollo and Lunar Obitor (LO) photos are not identifiable in the Clementine data and have not been mapped here.
Figure 16. Spectra of DMD and mare units from the Aristarchus Plateau and surrounding terrain. The DMD on the plateau and on the highlands by the crater Prinz have steep UVVIS slopes and strong glass band absorptions, characteristic of the red glasses. The surrounding mare units vary in their UVVIS slopes and mafic absorptions depending upon their Ti contents and maturity.

Figure 17. Spectra of selected impact craters from the Aristarchus Plateau and surrounding terrains. A crater near Cobra Head has a very strong mafic absorption due to fresh exposure of underlying mare beneath ejecta from Aristarchus crater. The crater Toscanelli has a low-Ca pyroxene absorption, indicating that norite underlies the mare here. Small craters along the walls of Valles Schroteri and scattered throughout the plateau have a fresh highlands signature, as do portions of Aristarchus crater.
central peak both show an anorthositic signature by the lack of any ferrous absorption. Various spectral units can be identified along the walls of the crater, including anorthosite, norite, and basalt, consistent with telescopic near-IR spectra by Lucey et al. [1986]. Ejecta located to the southwest and a patch in the west have a strong anorthositic signature and are dark blue in color, while ejecta farther out is more purple, perhaps due to mixing with an underlying mare unit [McEwen et al., 1994]. In contrast, the ejecta in the north-northwest appears asymmetric in distribution and as various shades of green in the color ratio image. The higher concentration of ejecta farther north of Aristarchus is due to an asymmetry in the ejecta curtain that has been noted previously [Guest, 1973; McEwen et al., 1994]. Additionally, there may be contributions from the smaller crater Aristarchus A, which also appears to have excavated underlying highlands [Lucey et al., 1986]. The 35-km-diameter crater, Herodotus, has two distinct units on its floor: a red mare unit in the center, but slightly offset to the west, and an underlying older green mare unit, best seen in the northeast of the floor. Other craters interspersed out of the plateau are light blue in color and have a strong low-Ca pyroxene absorption. The crater Toscannelli and others located just east of the plateau also have a fresh noritic signature (Figure 17) showing that highlands underlie the thin red mare unit here. The crater Prinz in the east has been completely covered by younger mare to the southwest, but its northern rim is still visible and has a dark blue color, indicating that anorthositic highlands underlie the mare here as well.

The walls of Vallis Schroteri and a few of the smaller rilles have a mafic signature supporting the existence of basalt beneath some of the DMD [McEwen et al., 1994; Hawke et al., 1995]. However, the source of Vallis Schroteri (Cobra Head) and parts of the rille wall exposed by small impact craters have spectra indicating anorthosite, suggesting that the rille transsects both mare and highland material as it thermally eroded the underlying substrate. The small inner rille of Vallis Schroteri is best seen in the west, and it can be traced to the southwestern edge of the plateau where it disappears into the mare. The source head for Rima Prinz located on the mare to the east also has a mafic signature while the rille itself is indistinguishable from the surroundings. The strongest mafic signature of all the craters on the plateau is from a 1.4-km-diameter crater located just west of Cobra Head, indicating that mare underlies the Aristarchus ejecta and DMD at this location. In the albedo image (Figure 15), the crater is very dark while in the color ratio image it is bright green. The mare must thin to the southwest because larger craters begin to show noritic/anorthositic signatures, whereas only the smaller craters still show a mare component.

The mare unit of the Agricola Straits seen in the northwest is redder than the surrounding younger mare of Oceanus Procellarum. Spectra for this unit (Figure 16) show a similar UVVIS slope to the DMD but a stronger mafic absorption. On the basis of these results, we agree with earlier interpretations that some dark mantle may be deposited on the older mare unit here [Zisk et al., 1977; McEwen et al., 1994]. To the northeast, the color ratio image shows a bright red color associated with the highlands of the crater Prinz and Montes Harbinger. Spectra from this area show that it is similar to the DMD on the plateau, supporting that dark mantle has been deposited here as well [Zisk et al., 1977]. In contrast, the red mare to the north [Zisk et al., 1977; Pieters, 1978] can be distinguished from the DMD by a weaker 1000-nm absorption and higher 415/750 nm ratio, indicating no glass band is present and a slightly bluer color. Any of the numerous sinuous rilles in the northeast may have been a source for the DMD, or, alternatively, the DMD may have been erupted from the same source that deposited dark mantle on the plateau (i.e., Cobra Head). For example, the distance between Cobra Head and the DMD on the westernmost Agricola Straits is about 200 km; a similar distance to the northeast would include the DMD located around the crater Prinz.

3.7. Orientale Ring Deposit

The Orientale DMD ring is centered on the Montes Rook in southwestern Orientale (Figure 18) at 29°S and 263°E. Three low-resolution (180-195 m/pixel) and two high-resolution (111 m/pixel) orbits have been used to produce the mosaic of the DMD shown in Figure 19. Phase angles vary from 30° to 34° for the low-resolution orbits and 32° to 38° for the high. The DMD ring is not uniform in albedo nor shape: it is darkest and widest (47 km) to the north and narrowest and brightest in the west. The DMD ring has an orange color in Plate 1f, while the surrounding highland terrain appears pink. At the center of the DMD is an elongate depression 9.7 km wide by 20 km in length which we interpret as the vent source for the DMD. The depression, which appears light blue, is slightly narrower toward its center, and the lower half of it has been partially disrupted by a nearby crater and its ejecta. The closest distance of the DMD to the elongate vent is 49 km and the farthest is 108 km in the north. The average radius of the DMD from the center of the vent is about 80 km, which is shown in the geologic map of the area (Figure 19). In the west the deposit appears closer than this average radius, while in the east it appears slightly farther. These two locations correspond to places where the DMD is difficult to identify, and therefore the DMD may in fact fall closer to this radius than has been mapped. Even though darkest and widest to the north, an 8.3-km-diameter crater caused some mixing and brightening of the DMD here. In the south, a 9.7-km-diameter crater impacted into the middle of the DMD causing significant mixing with brighter material and burial of the DMD. In the west, the DMD is mixed with the bright highlands of Montes Rook, making it difficult to map out the distribution of dark mantle. To the east, bright highlands have caused an increase in the DMD albedo; however, the increase is not as large as in the west.

Previous observations of the Orientale Ring deposit by the Galileo spacecraft showed that it was composed of a mixture of pyroclastics and highland materials [Pieters et al., 1993; Greeley et al., 1993] and the beads were thought to be crystallized [Belton et al., 1992]. However, the Clementine UVVIS spectra for the DMD shown in Figure 20 has a glass band absorption (750/920 value of 0.937) and a steep slope in the UVVIS with a 415/750 value of 0.584, indicating that the DMD is dominated by volcanic glasses. Spectral results also indicate that the vent has a noritic signature similar to that found in the local crater walls (C2 in Figures 19 and 20), supporting that it is a collapse feature exposing underlying noritic highlands (Head et al., submitted manuscript, 1998). The highlands, which are part of Montes Rook, have a high albedo and appear dark blue in the color ratio image except where the steep slopes show dark material shedding off them. Spectra for the highlands indicate outcrops of anorthosite [Bussey and Spudis, 1997]. The dominant geology of the area is composed of hilly terrain (Figure 19), which is a mixture of small, bright hills interspersed throughout smooth, darker terrain. The spectra for the hilly terrain indicate a mixture of
highlands and possibly impact melt produced during the formation of the Orientale basin [Head et al., 1993; Bussey and Spudis, 1997]. A few large patches of darker, smoother material are visible in the hilly terrain and are considered to be pools of impact melt due to their morphology and similar spectral shape to the hilly terrain.

A small unusually dark streak has been mapped in the eastern highlands, just outside the DMD (Figures 19). The streak is composed of a 1-km-long dark spot on the highlands and a tail of debris shedding downslope to the west. The spectra for the streak show a strong mafic absorption and the streak appears light green in the color ratio image, indicating that it is not composed of volcanic glasses. Instead, the streak may represent a mafic unit underlying the highlands that has been exposed by a small impact crater at this location. A very small impact crater on the hilly terrain a few kilometers to the south and the large 21.5-km crater at the bottom of Figure 19 also show strong mafic signatures, suggesting localized mafic material exists at depth in some locations as plutons, dikes, or cryptomare. Other dark streaks along the slopes of the highlands, such as those visible in the northwest, do not show this mafic signature; instead, they represent mature highland soil that is mass wasting down.

4. Discussion

4.1. Comparison of the Five Regional DMDs Spectra

Selected dark mantle spectra from all five regional DMDs are shown in Figure 21 to demonstrate their relative reflectances. The spectra from two localized DMDs located on the
Figure 19. The Orientale Ring DMD as seen in this 750-nm reflectance mosaic. A 20-km-long depression that represents the central vent is located at an average radius of 80 km from the DMD ring. The DMD is widest and thickest to the north where it lies on a smoother impact melt unit, whereas on the adjacent highlands, the DMD is less visible. The mafic debris unit is low in albedo but can be distinguished from the DMD by its mafic signature in the spectra (see Figure 20). The circle shown in the geologic map indicates a radius of 80 km from the vent, showing that most of the DMD falls close to this average radius.
Figure 20. Spectra from the Orientale Ring DMD and surrounding terrain. The DMD has a relatively high reflectance compared to the other DMDs and a strong glass band absorption. The hilly terrain has an anorthositic signature, while the vent wall and several impact craters have a noritic signature. The dark streak can be distinguished from the DMD by a mafic absorption.

Figure 21. Spectra for all the regional DMDs in this study. The spectra are only shown for the mature soils to avoid variations caused by maturity differences. The spectra from Alphonsus DMD1 and DMD2 represent localized DMDs located on the floor of the crater Alphonsus that most likely formed by vulcanian eruptions. Aristarchus Plateau, both Alphonsus DMDs, and the Orientale Ring DMD have the highest reflectances and strongest glass band absorptions compared to the other regional DMDs.
Figure 22. Plot of 415/750 versus 750/950 values for the regional DMDs. The 415/750 value reflects the color and maturity of the deposit, while the 750/950 value is a function of the glass band absorption. A wavelength dependent photometric correction [McEwen, 1996] has been applied to all the spectral ratios. The dashed line has been drawn between the two extreme end-member DMDs: Sinus Aestuum II dark spot as the bluest and most crystallized deposit and the Aristarchus Plateau DMD as the reddest deposit dominated by volcanic glasses. All the other DMDs represent mixtures of these two extremes as well as other local soils. See text for a complete description of each DMD unit.
rocks in the soils. We can, however, identify other soil types that may have been mixed with the DMDs based upon where the DMD falls relative to the line between the two extreme DMDs.

Sinus Aestuum I DMD is bluer than Taurus-Littrow DMD, but this may be due to lateral mixing with fresh highlands ejecta or vertical mixing with underlying highlands. In terms of crystallinity, spectra of this deposit suggest that it is similar to that at Taurus-Littrow DMD. The Orientale Ring DMD is spectrally similar to the Aristarchus Plateau DMD, supporting that it represents a glass-rich deposit. The deposit also has similar ratios to the two Alphonsus localized DMDs. Recent Clementine results for the Alphonsus DMDs [Gaddis et al., 1997] confirm earlier telescopic results that the volcanic glasses have mixed with wall rock during the volcanic eruption [Head and Wilson, 1979; Hawke et al., 1989; Coombs et al., 1990]. In the case of the Orientale DMD, it is unlikely that any wall rock was deposited as part of the annular DMD. Instead, the DMD has mixed with the surrounding highlands and impact melt units by post-impact gardening. Two Sulpicius Gallus DMDs are shown to illustrate the variability in the deposit. In fact, both spectra are intermediate in color and have a relatively strong glass band absorption. The major difference between the two spectra is in the strength of the glass band. Because the highland soils near the Sulpicius Gallus DMD have spectral ratios that plot very close to the Sulpicius Gallus DMD 1 point, the difference between the two DMD points can best be explained by more mixing of the surrounding highland soils with the Sulpicius Gallus DMD 1. As discussed, this deposit probably represents a mixture of glasses, crystallized beads, and highlands soils. Finally, both the Rima Bode and Vaporum DMDs have relatively red colors and intermediate glass band absorptions, suggesting that the DMDs may represent mixing of the crystallized beads with the surrounding highland soils or, in the case of Rima Bode, the mare soils.

Table 1 summarizes the spectral results for each regional DMD. The volumes listed in Table 1 for each DMD have been estimated assuming a constant thickness of 10 m. At the Taurus-Littrow DMD, a 10-m-thick deposit was calculated based upon the diameter of Shorty crater which excavated a 70-cm-thick deposit of volcanic beads. Crater excavation depths from the Aristarchus Plateau DMD [McEwen et al., 1994] indicate a thickness of 10-30 m, so our volume estimate for this DMD represents a minimum. It is clear from our results that mixing between the various bead types and compositions as well as with other lunar soils have all affected the spectral properties for each DMD. The five spectral channels of Clementine UVVIS data have provided some insight into the crystallinity of the beads within each deposit, but there are still many unknowns that must be determined before these results can be measured quantitatively. Future laboratory reflectance studies, using mixtures of mare basalts, highlands soils, and volcanic beads that vary in both Ti content and crystallinity, could provide valuable insight into our results from the Clementine data. For now, our spectral results are only qualitative and await further high spectral resolution data to perform a more quantitative analysis.

4.2. Implications for Eruption Conditions

4.2.1. Umbrella-shaped volcanic plumes. The Orientale DMD is the only regional deposit that can be used to model the eruption of volcanic beads because it has not been destroyed by younger features, and we can identify its full extent and source vent [Head et al., 1997]. Consequently, it provides the best insight into the size and shape of volcanic plumes that emplaced the regional DMDs. In contrast to the interpretation by Schultz and Spudis [1978] that the DMD ring represents several localized DMDs produced from a remnant system of vents aligned along an older basin, we interpret the DMD as a deposit resulting from one eruption from the central elongate vent. The Orientale DMD is an annular deposit, which means that the ejecta was concentrated at the maximum distance from the elongate vent. Wilson and Head [1981] have theoretically shown that eruptions from a fissure source will concentrate the ejecta in the outer part of the deposit, while eruptions from a circular vent concentrate clasts near the vent and at the maximum range.

We hypothesize that the eruption began when a dike became emplaced near the surface, stabilized, and eventually degassed to form an upper foam layer (Figure 23a). When the foam reservoir became overpressurized, a crack propagated to the surface, and evacuation of the foam layer caused the subsequent eruption (Figure 23b). The geometry of the vent can be used to

<table>
<thead>
<tr>
<th>Name</th>
<th>415/750 nm at 30° Phase</th>
<th>750/950 nm at 30° Phase</th>
<th>% Reflectance at 750 nm</th>
<th>Area, km²</th>
<th>Volume, km³</th>
<th>Character of Beads in DMD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taurus Littrow</td>
<td>0.646</td>
<td>0.894</td>
<td>7.9</td>
<td>4,000</td>
<td>40</td>
<td>dominated by black beads, some orange glasses and mixing with mare soils</td>
</tr>
<tr>
<td>Sulpicius Gallus</td>
<td>0.571</td>
<td>0.917</td>
<td>7.3</td>
<td>6,000</td>
<td>60</td>
<td>dominated by orange/red glasses, some crystallized beads and highland soils</td>
</tr>
<tr>
<td>Mare Vaporum</td>
<td>0.627</td>
<td>0.896</td>
<td>7.0</td>
<td>10,000</td>
<td>100</td>
<td>dominated by black beads, some glasses and mixing with highland soils</td>
</tr>
<tr>
<td>Rima Bode</td>
<td>0.600</td>
<td>0.906</td>
<td>7.5</td>
<td>10,000</td>
<td>100</td>
<td>mixture of glasses and crystallized beads with additional highland soils</td>
</tr>
<tr>
<td>Sinus Aestuum</td>
<td>0.663</td>
<td>0.880</td>
<td>8.1</td>
<td>30,000</td>
<td>300</td>
<td>fresh patches dominated by crystallized beads; mature DMD mixture of crystallized beads and highland soils</td>
</tr>
<tr>
<td>Aristarchus Plateau</td>
<td>0.544</td>
<td>0.960</td>
<td>10.5</td>
<td>37,400</td>
<td>374</td>
<td>dominated by glasses, some mixing with highland and mare soils</td>
</tr>
<tr>
<td>Orientale Ring</td>
<td>0.584</td>
<td>0.937</td>
<td>13.9</td>
<td>15,080</td>
<td>151</td>
<td>dominated by glasses, mixing with highland soils</td>
</tr>
</tbody>
</table>

*Assuming a thickness of 10 m.
†From Gaddis et al. [1985].
A. Orientale DMD Pre-eruption

B. Orientale Plume During Eruption

Figure 23. Illustration of the preeruption and eruption phases that produced the Orientale Ring DMD (adapted from Head et al., submitted manuscript, 1998). (a) Before the eruption, a dike stalled several kilometers beneath the surface and slowly built up a foam layer of gas bubbles at the top of the dike. Once the foam layer reached sufficient overpressurization, a crack propagated to the surface and degassing produced an explosive eruption (B). The volcanic plume resembled an umbrella with an average radius of 80 km and a height of 20 km.

We have modeled the eruption that produced the Orientale DMD using simple ballistic trajectories from a central vent, similar to models developed for eruptions on Io [Strom and Schneider, 1982]. This is because the plumes are pressure-balanced jets and the gas and particles coupled to the gas follow simple ballistic trajectories in the vacuum environment [Kieffer, 1984]. Using an average radius of 80 km and assuming an ejection angle of 45° to simplify the calculations, we calculate an eruption velocity of 360 m/s and a flight time of 5 minutes. It should be noted that ejection angles probably varied from 0° (vertical) to perhaps 55°, like those suggested for umbrella plumes on Io [Strom and Schneider, 1982]; however, the majority of clasts will still be deposited at the maximum range to form the observed annular deposit. The greatest height above the surface for particles on this 45° trajectory is 20 km. The farthest deposit located at 108 km radius yields an ejection velocity of 420 m/s and a flight time of 6 minutes. For comparison, the annular deposit Prometheus on Io is 330 km in diameter and had a plume height of 77 km. Ejection velocities from Prometheus are thought to be between 450 and 650 m/s [Strom and Schneider, 1982]. Arndt et al. [1984] calculated that the Apollo 15 green glasses must have been suspended in a gas for about 10 minutes to produce the cooling rates required to form the mineral textures in the crystallized beads, which is considerably longer than the times calculated from ballistic transport. Hence our calculated flight times suggest that the beads should be dominated by glasses rather than crystallized beads and the Clementine data support this conclusion.

4.2.2. Fire fountain volcanic plumes. The other seven regional DMDs appear to represent another style of eruption more analogous to the fire fountain eruptions seen in Hawaii. However, because we do not see the full extent of these DMDs, it is possible that some of them (Taurus-Littrow, Sulpicius Gallus, Sinus Aestuum, and Rima Bode) may have formed by umbrella-shaped plumes, and only a portion of the ring is now visible. Nevertheless, on the basis of their size and extent, it is more likely that these DMDs formed by fire-fountain-style eruptions. Shearer and Papike [1993] suggest three models for the formation of the volcanic glasses based upon their petrological character: (1) the glasses experienced limited fractional crystallization compared to the mare basalts and originated from similar depths (>300 km); (2) the glasses originated from volatile-rich sources at depths >400 km while the mare were produced from shallower depths in volatile-poor sources; and (3) the glasses are from sources located at depths >1000 km that experienced polybaric melting during ascent,
while the mare are from volatile-poor sources at <400 km depth. In all cases, they suggest that the mare and volcanic glasses have distinct sources based upon their petrology. We argue in this paper that the regional volcanic glasses may have produced associated mare basalts, but the basalts flowed into the adjacent basins while the beads were ejected over great distances. Therefore the petrological differences between the mare and glasses simply reflect a sample problem, namely, that the mare basalts produced from the same eruptions that emplaced the beads were not sampled during the Apollo missions. Support for this assumption includes work by Longhi [1987] showing that liquid lines of descent calculated for low-pressure equilibrium and fractional crystallization of the Apollo picritic glass samples can produce both glasses and mare from the same eruptions. In addition, the eruptions could have initially been explosive, producing both beads and basalts, but then changed to predominantly effusive eruptions, producing only basalts. Finally, we favor concurrent eruption of beads and mare because gas-rich eruptions that produced only beads would emplace the beads in an annular deposit similar to the Orientale Ring DMD, and at least for the Aristarchus Plateau, this could not have happened. We suggest that the glasses studied by Shearer and Papike [1993] may have been produced from more localized gas-rich eruptions which are more common on the lunar surface compared to the regional DMDs [Coombs et al., 1988]. Therefore we now model the eruptions of the nearside regional DMDs assuming that both mare and glasses were emplaced simultaneously.

The Aristarchus Plateau is the best candidate to model as a fire fountain eruption because it is dominated by sinuous rilles, volcanic glasses, and mare. In this eruption, we hypothesize that the source head of the sinuous rille represents the vent source, although for the other DMDs, the source vent may not necessarily be associated with a sinuous rille. As illustrated in Figure 24, large clasts erupted will land near the vent and are still hot enough to coalesce and form lava. If the lava flows in a turbulent fashion, then thermal erosion of the underlying substrate will occur and a sinuous rille will form [Hulme, 1982; Wilson and Head, 1980; Head and Wilson, 1980; Wilson and Head, 1981]. The basalts will flow to low-lying areas, which for the DMD eruptions will be the adjacent local and broad lows; hence most of the basalts erupted in association with the DMDs will eventually form mare that fills in these basins. The volcanic beads make up only a minor volume of the erupted clasts [Wilson and Head, 1981], and they remain suspended in the expanding gas cloud. As the larger clasts decouple from this gas cloud and get deposited near the vent, the submillimeter beads still locked to the gas cloud gain added momentum and can be carried several tens of kilometers from the vent [Housley, 1978; Wilson and Head, 1981]. This may explain why there seem to be no basalt samples that can be petrologically related to the volcanic glasses [Longhi, 1987; Delano, 1986]; the glasses are expelled great distances onto the adjacent highlands, while the basalts fill in the adjacent basins and are subsequently buried by younger mare.

In the case of Aristarchus Plateau, the DMD is dominated by glasses rather than crystalized beads, indicating that the beads cooled rapidly (Figure 24a). It is possible that there were several eruptions from the numerous source heads in the region which allowed the glasses to be continuously deposited over such a large area. The lack of any crystallized bead signature in the Clementine data, even near the sinuous rille source heads and in crater ejecta of various sizes, suggests that the optical density of these plumes remained low throughout their eruptions and did not fluctuate in style over time. Alternatively, crystallized beads may have been erupted, but they would have landed closer to the vent and would thus be more likely to be covered by mare produced during the same eruption. Assuming

Figure 24. The majority of regional DMDs erupted in volcanic plumes that resembled Hawaiian fire fountains. (a) In low optical density plumes, most of the clasts are widely distributed and cool rapidly to produce the glasses. Smaller clasts near the vent cool slow enough to produce crystallized beads while larger clasts land hot and coalesce to form lava flows. (b) In high optical density plumes, the majority of submillimeter clasts form crystallized beads due to the slow cooling rates.
that Cobra Head is the only source vent for the DMD, we can model the eruption by varying certain eruption parameters, such as mass eruption rate, released CO content, and weight percent of submillimeter droplets. The maximum range of the dark mantle from Cobra Head is about 200 km to the Agricola Straits. Wilson and Head [1981] have shown that in order for submillimeter volcanic beads to be ejected to 50 km range, they must comprise 0.1 wt % of the total mass fraction erupted assuming a mass eruption rate and released CO content of $10^6$ kg/s and 750 ppm, respectively. If the mass flux is increased to $10^7$ kg/s, then the range would only increase to about 100 km. There are three options that can be proposed to account for the large ejection ranges at the Aristarchus Plateau DMD: 

1. The weight percent of submillimeter beads was much less than 0.1%; 
2. The CO content was much higher (>750 ppm); 
3. Cobra Head cannot be the source for the more distant volcanic beads. Given the large volume of the Aristarchus Plateau DMD (>370 km$^3$), if the beads made up less than 0.1 wt % of the ejected clasts, then huge volumes of larger clasts producing mare are required. The geology of the plateau shows some mare in the south but not enough to account for the volume of DMD, unless mare produced from the eruption flowed off the plateau and became buried by the younger Oceanus Procellarum lavas. The CO contents of lunar magmas are not well constrained, so it is possible that they may have been higher than 750 ppm and would be able to eject beads to greater ranges. The final possibility, that Cobra Head is not the only source for the DMD, is also feasible given the numerous other rilles in the region. However, Valles Schrotteri is significantly larger than any of the other rilles, supporting an eruption with a high mass flux resulting in the formation of large volumes of both volcanic beads and mare. In summary, although Cobra Head may be the only source for the DMD on the Aristarchus Plateau, we cannot rule out the possibility that other rilles in the area may have also contributed glasses to the deposit.

Taurus-Littrow and Sinus Aestuum DMDs are dominated by the crystallized beads and therefore reflect slower cooling rates in an optically dense plume which allowed olivine and ilmenite crystals to form (Figure 24b). The Rima Bode and Mare Vaporum DMDs have redder colors which may indicate slightly higher concentrations of orange glasses and therefore slightly lower optical density plumes than at Taurus-Littrow and Sinus Aestuum. The location of all the deposits partially on the highlands and mare at the edges of the basins suggests that the source vents were located farther inside the basins and later buried by younger mare. On the basis of the composition of the volcanic beads sampled at the Apollo 17 landing site [Delano and Lindley, 1987; Weitz et al., 1996], the Taurus-Littrow DMD must have been emplaced by one major eruption, although the plume fluctuated in its optical density since the orange glasses dominated the initial part of the eruption, while the black beads dominated later. Sulpicius Gallus may represent several eruptions: one producing the red glasses, another producing the orange glasses, and a third that erupted the crystallized beads. Alternatively, the optically density of the volcanic plume may have fluctuated with time, causing a change from glasses to crystallized beads, as suggested for the Taurus-Littrow deposit [Weitz et al., 1996]. However, the red and orange glasses must represent two separate eruptions varying in the amount of TiO$_2$ in the magma. The crystallized beads may have been erupted with either the orange or red glasses, or even with both.

Optical density differences in the plumes could result from variations in gas content and volume flux, as occurs in terrestrial fire fountains [Head and Wilson, 1989]. A low optical density plume would have a thinner gas cloud and wider separation between beads, which in turn would cause higher cooling rates and lead to the formation of glasses. Only when the volcanic plume was optically dense enough to cause the cooling rates to fall below 100°C/s could the crystalized beads form [Arndt and von Engelhardt, 1987]. Hawaiian fire fountains begin as eruptions at several vents aligned along a fissure before becoming concentrated into one vent. The change from eruptions along a fissure to one eruption at a central vent will cause an increase in the optical density of the plume with time as more material is concentrated into a smaller area. This increase in optical density will cause the beads to cool at slower rates, and therefore we expect to see a change from volcanic glasses to crystallized beads with time. Small changes in gas content may also occur during the eruption, and this will also affect the optical density of the plume. Assuming a constant volume flux, an increase in gas content will cause the optical density to decrease as the clasts become more widely dispersed [Head and Wilson, 1989], and this will favor formation of volcanic glasses over crystalized beads. At the Taurus-Littrow DMD, where the beads changed from glassy to crystallized with time, a decrease in gas content may have occurred during the eruption which would lead to a progressive increase in the plume optical density over time [Head and Wilson, 1977; Weitz et al., 1997a]. The Aristarchus Plateau DMD is dominated by glasses with no crystalized beads indicated by the Clementine data. The plume must have maintained a low optical density throughout the eruption to emplace a large volume of glasses over 200 km in distance, although concurrent eruption of larger clasts would cause the submillimeter beads to be more widely dispersed in the plume and lead to higher cooling rates.

### 4.2.3. Source vents for the DMDs

For each of the seven DMDs studied in this paper, we have tried to identify the most likely source vent or location for this vent. The only DMD where we have confidently identified the source vent is for the Orientale Ring. The vent is an elongate 9x20 km depression that is centrally located at an average radius of 80 km from the annular DMD. In the case of the Aristarchus Plateau DMD, Cobra Head is a likely source vent for some, if not all, of the DMD in the region. The vent and its associated rille, Vallis Schrotteri, are the largest on the Moon and imply very high mass fluxes. If any volatiles were exsolved in the magma as it approached the surface, then under the lunar environment, large quantities of volcanic submillimeter beads would be produced and expelled to great ranges [Wilson and Head, 1981]. There are over a dozen other sinuous rilles on and around the plateau that may have also contributed to volcanic beads to the DMD, but the vast size of Cobra Head and Vallis Schrotteri suggest that this vent contributed the highest volume of beads to the DMD.

At the Taurus-Littrow DMD, we suggest that the vent is located to the northwest of the DMD. At this location, volcanic beads would be deposited on the remnant highland of Serenitatis basin, but the DMD located elsewhere was later buried by the younger low-Ti basalts that fill in most of the basin. The Apollo 17 core 74001/2 indicates that at least 70 cm of the deposit is compositionally homogeneous and was therefore produced from one eruption [Blanchard and Budahn, 1978; Weitz, 1998]. Other volcanic beads identified in Apollo 17
soils were produced from separate eruptions, but these beads were much smaller in volume compared to those from the 74001/2 core. Therefore we propose that a vent existed in the northwest and that this vent erupted a mixture of mare and volcanic beads with the same composition of the 74001/2 beads.

Sulpicius Gallus DMD has an unusual 5.5-km-long kidney-shaped depression that Lucchitta and Schmitt (1974) suggested as a possible source vent for the DMD. Although much smaller in size than the elongate vent at the Orientale Ring DMD, the depression is similar in shape. There are two difficulties with this kidney-shaped depression being the source vent for the Sulpicius Gallus DMD: (1) The depression is not centrally located in the DMD, and under lunar conditions, we expect the volcanic beads to be expelled equally in all directions; and (2) the DMD is not an annular ring around the depression, like at Orientale, but is a continuous deposit. Because of these two problems, we do not favor this depression as the vent but rather suggest that the source vent is located to the northeast buried beneath the younger mare in Serenitatis. Therefore, while the depression in Sulpicius Gallus DMD may have contributed some DMD to the deposit, most of the DMD must have been from another vent that we suggest is buried to the northeast. In fact, the depression may simply be tectonic in origin rather than volcanic and would have no role in the deposition of the DMD.

For the other DMDs, including Mare Vaporum, Rima Bode, and Sinus Aestuum, we also propose that the vents are buried beneath younger mare. At first, this may seem very unusual that in the majority of the regional DMDs, the source vent is buried beneath younger mare. However, based upon our stratigraphy of the DMDs, it is clear that the deposits occurred concurrently with the emplacement of mare. Because the DMDs are all located on the edges of the major basins, it is not unreasonable to expect that much of these deposits have been buried beneath younger mare and only portions of the DMD are still visible on elevated highlands around these basins. Just as older mare in the basins have been buried by younger mare, so too have the DMDs. The vents for the DMDs could have been at the edges of these basins and would be more likely to be buried by younger mare, while the volcanic beads produced from the eruptions would be expelled for great distances to be deposited on highlands around the basins and thereby safe from later burial. In summary, it is not surprising that most of the source vents for the DMDs are buried by younger mare.

5. Conclusions

The Clementine UVVIS data with five-channel spectral resolution and relatively high spatial resolution have enabled us to provide new information about regional DMDs and their surrounding geology.

1. The volcanic beads in each DMD vary in the inferred degree of crystallinity, with dark patches in Sinus Aestuum DMD having the highest concentration of crystallized beads and the Aristarchus Plateau DMD dominated by glasses. All other DMDs fall between these two extremes because they represent more intermediate mixtures between the glasses and crystallized beads. Additionally, determination of the ratio of glass to crystallized beads is complicated by mixing with the surrounding soils and possible differences in Ti contents between the beads. The Taurus-Littrow DMD appears to be a mixture of the crystallized beads and glasses, which is confirmed based upon lunar samples from the Apollo 17 mission [Heiken et al., 1974]. Mare Vaporum DMD is spectrally similar to Taurus-Littrow, whereas Rima Bode and Sulpicius Gallus DMDs are interpreted to have a higher percentage of the glasses and to have been more affected by mixing with highland soils. The Orientale Ring DMD is dominated by glasses and is spectrally similar to the Alphonsus localized DMDs.

2. The Orientale Ring deposit on the lunar farside, which is the only annular regional DMD identified on the Moon, has provided insight into another style of lunar pyroclastic eruption. The volcanic plume associated with this DMD may have resembled the umbrella-shaped plumes seen on Io that also produce an annular deposit around a central vent. The plume resulted from a near-surface dike that degassed with time until overpressurization allowed an eruption to the surface resulting in a 20-km-high plume with average ejection velocities of 360 m/s and ranges of 80 km from the vent.

3. The other six regional DMDs are more continuous in their distribution, making it more difficult to determine the location of the vents and model the eruptions. Most likely, these DMDs were produced from plumes similar to Hawaiian fire fountain eruptions but due to the lower gravity and lack of an atmosphere on the Moon, the plumes were broader and higher. Larger clasts quickly decoupled from the expanding gas cloud and landed near the vent where they coalesced to form lava flows that subsequently flowed into the lunar basins. The submillimeter beads remained locked to the gas cloud and were expelled tens of kilometers, eventually to be deposited on top of highlands where they were protected from subsequent burial by younger mare.

4. The variation in bead crystallinity for each deposit can best be explained by optical density in the volcanic plume, with a higher bead crystallinity reflecting slower cooling rates in an optically dense plume. The domination of glasses in the Aristarchus Plateau DMD compared to the other regional DMDs (excluding the Orientale Ring) suggests very low optical densities and a broad plume shape to inhibit crystallization from occurring in the beads, even those that landed near the vent(s).

At Sinus Aestuum, the beads are predominantly crystallized and indicate high optical densities that enabled the beads to cool slowly in the plume and crystallize ilmenite and olivine. The differences in plume optical density between the DMDs may reflect variations in volume flux and gas contents.

5. Although the source vents for the eruptions appear to be buried by younger mare, it is likely that they may have been erupted in association with volcanic activity that also produced sinuous rilles due to the high mass fluxes required by these eruptions [Wilson and Head, 1981]. We identified some unusual depressions inside a few of the DMDs, but their small sizes and noncentral locations within the DMDs argued against them being the sole source vents, except for the Orientale Ring DMD. Instead, we favor that each DMD was emplaced by only one or two large eruptions rather than many small eruptions from multiple vents producing localized deposits that overlapped spatially.

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