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Photometric mapping of Asteroid (4) Vesta's southern hemisphere with Hubble Space Telescope

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We present the surface mapping of the southern hemisphere of Asteroid (4) Vesta obtained from Hubble Space Telescope (HST). From 105 images of Vesta through four filters in the wavelengths best to characterize the 1-µm pyroxene band, we constructed albedo and color-ratio maps of Vesta. These new maps cover latitudes -50° to $+20^{\circ}$. The southern hemisphere of Vesta displays more diverse albedo and color features than the northern hemisphere, with about 15 new albedo and color features identified. The overall longitudinal albedo and color variations in the southern hemisphere are comparable with that of the northern hemisphere, with a range of about $\pm 20\%$ and $\pm 10\%$, respectively. The eastern hemisphere is brighter and displays more diogenitic minerals than the western hemisphere. Correlations between 1µm band depth and band width, as well as between 1-µm band depth and albedo, are present on a global scale, attributed to pyroxene composition variations. The lack of correlations between albedo and the spectral slope indicates the absence of globalized space weathering. The lack of a global correlation between 1-µm band depth and topography suggests that the surface composition of Vesta is not completely controlled by a single impact. The distribution of compositional variation on Vesta suggests a possible large impact basin. Evidence of space weathering is found in regions, including the bright rim of the south-pole crater where the steepest gravitational slope on Vesta is, and a dark area near a gravitationally flat area. We propose to divide the surface of Vesta into six geological units different from the background according to their 1-µm absorption features and spectral slopes, including two eucrite-rich units, a low-Ca eucrite unit, a diogenite-rich unit, a space weathered unit, and a freshly exposed unit. No evidence of olivine-rich area is present in these data.

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1. Introduction

Vesta is the only known large asteroid to possess a basaltic surface, as first discovered using visible ground-based spectroscopy by McCord et al. (1970) and then confirmed by later observations (Larson and Fink, 1975; McFadden et al., 1977; Gaffey, 1997; Vernazza et al., 2005). Early rotationally resolved disk-integrated polarimetric (Degewij et al., 1979) and spectroscopic (Gaffey, 1983, 1997) measurements show a unique, compositionally diverse surface. It has long been considered the source of howardite–eucrite– diogenite (HEDs) meteorites (McCord et al., 1970) and small members of Vesta's dynamical family (the so-called vestoids) (Binzel and Xu, 1993). The discovery of a huge impact crater with a diameter of ~460 km, or $0.85 \times$ the diameter of Vesta, near its south pole (Thomas et al., 1997a) from Hubble Space Telescope (HST) observations with Wide Field Planetary Camera 2 (WFPC2) in 1994 and 1996 (Zellner et al., 1997) suggests that an impact with a ~35 km asteroid may have ejected the vestoids and HEDs (Thomas et al., 1997b; Asphaug, 1997). The internal structure of Vesta could still be intact, consisting of a metal core, an ultramafic mantle, and a basaltic crust (Keil, 2002). Therefore, the impact that excavated the huge crater provides an opportunity to look inside the body at its composition.

The disk-resolved images obtained from HST WFPC2 in 1994 were used to construct surface albedo maps of Vesta through four filters centered at 439 nm, 673 nm, 953 nm, and 1042 nm, from which the spatial variations in the characteristic 1- μ m band of basaltic minerals were studied, and a geological map was constructed (Binzel et al., 1997). Vesta's surface, within the coverage



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of those maps from -15° to $+50^{\circ}$, was found to be dichotomous at a hemispherical scale (Binzel et al., 1997). The eastern hemisphere was interpreted to be dominated by plutonic material possibly excavated by impacts, and the western hemisphere dominated by single component pyroxene. Many surface albedo and color markings were identified and interpreted as mineralogical features with various compositions (Binzel et al., 1997). Similar HST observations in 1996 suggested that the composition on the surface of Vesta is correlated with topographic height, related to excavation processes during the formation of the south-pole crater from impact (Thomas et al., 1997a). Disk-resolved images of Vesta in the near-infrared (NIR) wavelengths were obtained from ground-based adaptive optics (AO) at K'-band and L'-band (Zellner et al., 2005). They interpreted dark albedo features, which are at the same location as the dark albedo features in visible wavelengths (Binzel et al., 1997), as impact craters filled by basaltic lavas. Carry et al. (2010) studied disk-resolved spectral cubes obtained at I-, H-, and K-bands with AO, and concluded that the composition of the area they observed (220-330° longitude) is most compatible with howardite meteorites, with small diogenite-rich areas suggested. Carry et al. (2010) also compared the spectral slope and visible albedo and found no obvious correlation to support space weathering on Vesta (Marchi et al., 2005; Vernazza et al., 2006) in the area they observed.

In May 2007, Vesta approached the Earth much more closely (1.18 AU) than when the 1994 HST observations were made (1.68 AU). This is comparable to the distance of the 1996 observations (1.17 AU). More importantly, the sub-Earth latitude of Vesta during its 2007 opposition was about -19° , compared to $+26^{\circ}$ and about -9° for the previous HST observations in 1994 and 1996, respectively. We therefore obtained disk-resolved images of Vesta using the same instrument and the same filters used in both previous HST observations. In this paper we report results of photometric analysis and photometric and geological mapping. We will focus the analysis on characterizing the surface mineralogy of Vesta. This work will support NASA's Dawn mission, which will arrive at Vesta in 2011 to study the composition and internal structure of this asteroid in detail to understand the accretion processes and early evolution of terrestrial planets (Russell et al., 2007).

2. Observations and data reduction

The observing sequence was carefully designed to provide almost uniform coverage in a full rotation of Vesta (Fig. 1). Table 1 summarizes the images we obtained and used in this research. In addition to the four imaging filters, we also obtained several long exposures using wideband filter, F702W, to saturate Vesta for satellite search (Bastien et al., 2008). Related results will be reported elsewhere (McFadden et al., in preparation).

All images were reduced and calibrated following the same procedure as in Li et al. (2006). Deconvolution methods were applied to all images to help increase the spatial resolution and contrast of the final maps. We used the Maximum Entropy Method (MEM) for deconvolution, as implemented in the IRAF/STSDAS restore package at STScI (Wu, 1995). The TinyTIM package (Krist and Hook, 2004) was used to make point-spread-function (PSF) for each filter. All PSFs were subsampled by a factor of four. The WFPC2 camera produces a slight geometric distortion, which was not removed from the images. But the effect is trivial for our work since Vesta is always placed near the Planetary Camera (PC) chip center and subtends only about 20 pixels, rendering relative errors over that small distance extremely small. The deconvolution is very sensitive to any CCD defects (e.g., hot pixels) or unrejected cosmic rays, and this may be responsible for some artifacts seen in the output images. However, these small-scale artifacts are filtered out when



Fig. 1. The sub-Earth longitudes of all 105 Vesta images obtained in the seven HST orbits of this program (HST GO-10799). Five filters were used. Each number shows the sub-Earth longitude and the filter of the corresponding image. The number represents the HST orbit in which that image was obtained. Images from F702W filter were used for satellite search, reported elsewhere (McFadden et al., in preparation). Images from the other four filters were used to construct albedo, color, and geological maps reported in this paper.

combining images at various rotational phases to produce the final maps. As will be shown in Section 4.3, we produced maps from both original images and deconvolved images, and from the latter, better maps were generated with almost no noticeable artifacts.

3. Albedo mapping

3.1. Shape model

The shape model and pole orientation of Vesta from previous HST data (Thomas et al., 1997a,b) was compared to these new observations. A control point solution for the spin vector gave results indistinguishable from the previous values, and no difference in the dimensions of shape model was found to be significant (Fig. 2). Therefore, there is no need to update the current shape model of Vesta and its pole orientation from Thomas et al. (1997b).

3.2. Hapke's and Minnaert's modeling

In order to perform photometric mapping, the limb-darkening in each image needs to be removed. Both Hapke's model (Hapke, 1993, 2002) and Minnaert's model (Minnaert, 1941) were used to carry out photometric modeling in a disk-resolved sense.

The five-parameter version of Hapke's model was adopted, as used in previous work (e.g., Li et al., 2006). Due to the very limited coverage in phase angle (8.4–9.6°), we had to assume the parameters for opposition effect, $B_0 = 1.03$ and h = 0.04, and the phase function parameter, g = -0.3 (Helfenstein and Veverka, 1989). The shape model of Vesta was used to calculate the scattering

Table 1					
Summary	of images	obtained	for	this	analysis

Number of images	F439W	F673N	F953N	F1042M
	20	26	25	25
Date Heliocentric distance Earth range Phase angle Pixel scale Sub-Earth latitude Sub-solar latitude	May 14–16, 20 2.154 AU 1.18–1.17 AU 9.6–8.4° 39 km –18.9° to –18 –11.1° to –11	007 8.6° .5°		



Fig. 2. The shape of Vesta as measured from our images, compared with the shape model measured from previous HST images obtained in 1996 (Thomas et al., 1997b). The equatorial (solid symbols) and polar (open symbols) radii measured from our images are plotted with respect to (west) longitude, compared with the measurements from 1996 data plotted as crosses. The agreement is good, and therefore it is not necessary to update the shape model or pole orientation parameters.

geometry for each pixel, and then the *I*/*F* data were extracted from images for disk-resolved modeling.

We applied Hapke's model to both original images and deconvolved images. The modeled parameters are listed in Table 2. The single-scattering albedos (SSAs) from deconvolved images are systematically higher than those from original images, and the roughness parameters lower. The difference should be due to the effect of deconvolution, which concentrates the signal into smaller area to increase the contrast and increase the brightness of pixels right inside the edge of disk. Limb-darkening in deconvolved images is expected to be less than that in the original images, and the total flux within the boundary of the disk will be higher, resulting in higher modeled albedo.

In order to confirm above explanation, we performed several tests. First, we checked the total flux of Vesta in both original images and deconvolved images to make sure deconvolution preserves photometry. Second, given the full-width-at-half-maximum (FWHM) of the PSF of WFPC2 about 2–3 pixels wide compared to the size of Vesta ~13 pixels in diameter, even though we discarded all *I*/*F* data with incidence and emission angles higher than 50°, the data used for modeling are still substantially affected by the PSF. Since PSF enhances limb-darkening, the roughness parameter, of which higher values indicate stronger limb-darkening, was modeled to be much higher from original images than from decon-

Table 2

Modeled photometric parameters for Vesta's surface. Note that the models from predeconvolved images are not correct because the PSF may have altered the limbdarkening profile of the disk of Vesta significantly.

	Hapke's	Hapke's model			Minnaert model			
	w	Theta_bar	RMS%	k	Α	RMS%		
From pre-deconvolved images								
F439W	0.393	47.3	3.3	0.659	0.19	3.2		
F673N	0.437	49.3	3.4	0.680	0.21	3.2		
F953N	0.312	52.8	3.5	0.746	0.14	3.0		
F1042M	0.430	54.0	3.9	0.750	0.20	3.4		
From deconvolved images								
F439W	0.425	30.1	1.8	0.557	0.21	1.8		
F673N	0.477	31.5	2.4	0.551	0.23	2.3		
F953N	0.352	29.3	2.6	0.542	0.17	2.7		
F1042M	0.520	28.0	3.1	0.535	0.26	3.1		

volved images. Experiments using only the data with incidence and emission angle lower than 40° and 30° returned the modeled roughness parameter $\sim 45^{\circ}$ and 40° , respectively, consistent with above explanation. Therefore, the resultant roughness parameter of 50° from the pre-deconvolved images should not be interpreted as physically meaningful. Instead, it should only be used to characterize and remove the apparent limb-darkening in mapping process. On the other hand, the roughness parameter of $\sim 30^{\circ}$ as modeled from deconvolved images should more likely be real. Similarly, the modeled SSAs from deconvolved images are less affected by PSF and has higher values than those from pre-deconvolved images, and should more likely be real. The difference between the modeled SSAs from original images and from deconvolved images increases with wavelength, consistent with the fact that the PSF at longer wavelength is larger and has stronger effects. Finally, as a consistency check, we compared the disk-integrated phase function with the modeled Hapke's parameters from deconvolved images with ground-based photometric data from the Asteroid Photometric Catalogue data (Lagerkvist et al., 1995) within phase angles up to $\sim 25^{\circ}$, and found a good agreement.

In addition to Hapke's model, we also applied Minnaert model to both original images and deconvolved images. The modeled Minnaert parameters are listed in Table 2, too. Again, both the Minnaert k parameter and the Minnaert albedo, A, are affected by deconvolution. The Minnaert k parameter, of which higher values indicate stronger limb-darkening, has increasing values with wavelength as modeled from the original images, indicating stronger effect of PSF at longer wavelength. After deconvolution, the modeled Minnaert k has a value of ~0.55, which is independent of wavelength, suggesting that the effect of PSF has been almost completely removed. The modeled Minnaert k is also consistent with the modeled Hapke's parameters (McEwen, 1991). Similar to the SSA, the modeled Minnaert albedos have higher values from deconvolved images, and are more likely to be real.

3.3. Albedo mapping

After removing limb-darkening profiles with the above models, the images of Vesta were projected to a simple cylindrical longitude-latitude coordinate system, and combined to construct the surface reflectance maps. For an object with an SSA of about 0.48 at 673 mm as modeled for Vesta, multiple scattering contributes about 10% of total scattering assuming isotropic multiple scattering (Hapke, 1993). Therefore, the surface reflectance is not exactly proportional to the SSA, and, strictly speaking, the maps we constructed are not SSA maps. However, they are still good proxies to the variations of SSA, and therefore justifiably used to study the albedo features as well as the compositional and mineralogical variations on the surface of Vesta.

We tested both Hapke model parameters and Minnaert model parameters derived earlier for both original images and deconvolved images. In combining the partial maps projected from individual images, we also tested different methods including simple average, weighted average, median, and resistant mean. All maps produced were similar, suggesting that the final maps do not depend on the mapping algorithm, and therefore should be robust without significant artifacts. The maps from deconvolved images show better contrast and more details in features than those from original images. We decided to base our analysis on the maps constructed from deconvolved images with median combination. The maps were smoothed by a Gaussian core with an 8.5° FWHM in both longitude and latitude to reflect the pixel scale of WFPC2 images at the center of Vesta's imaged disk. The maps are shown in Fig. 3.

One important goal of this observation is to provide with Dawn project the best knowledge about the surface composition and mineralogy of Vesta for its planning and operation. Dawn will undoubtedly refine all the surface features significantly. Jointly with Dawn science team, we adopted the tiling scheme used by Roatsch et al. (2009) in our mapping and analysis when refer to albedo, color, and geological units on the surface of Vesta. This will provide a continuous reference system that will facilitate future comparisons of our maps with the progressively improved resolution obtained by Dawn, and help the interpretation of Dawn data.

This tiling scheme divides the surface of a nearly spherical body into five latitudinal zones, i.e., the north and south polar zones for latitudes higher than 66° , the north and south sub-polar zones for latitudes between 22° and 66° , and equatorial zone for latitudes between $\pm 22^{\circ}$. The sub-polar zones are further divided into four tiles of equal size, each covering 90° in longitude, and the equatorial zone is divided into five tiles of equal size, each covering 72° in longitude. Starting from the north polar tile and prime meridian, the 15 tiles are named as NP (north pole), NE (north east), NFE (north far-east), NFW (north far-west), NW (north west), EE (equatorial east), EFE (equatorial far-east), EDL (equatorial dateline), EFW (equatorial far-west), EW (equatorial west), SE (south east), SFE (south far-east), SFW (south far-west), SW (south west), and SP (south pole). Our maps cover 9 out of the 15 tiles, as marked in Figs. 3 and 4.

In addition to the tiling, we identified a number of surface areas with distinctive albedo and color properties (discussed in later sections) from their surrounding areas. The areas marked with letters are those identified by Binzel et al. (1997) in the equatorial regions, and clearly show in our new maps. Those features identified by Binzel et al. (1997) that do not clearly show in our new maps in the equatorial region are not marked in the maps. We designated the areas that we identified, either not covered by, or not clearly shown in, Binzel et al.'s (1997) maps, with numbers from #1 to #15.



Fig. 3. Surface albedo maps of Vesta. The scale bar marks the relative variation from the corresponding global average in each wavelength. We partitioned the surface of Vesta according to the tiling scheme adopted by Roatsch et al. (2009). The tiles covered by our maps are EE, EFE, EDL, EFW, EW, SE, SFE, SFW, and SW as marked in upper left of every panel. Letters and numbers in the top panel mark the albedo and color features we identified. Overall the albedo variation is ±20% peak-to-peak, with the largest variations in the shortest wavelength. The albedo features are consistent with those in the previous maps of the northern hemisphere (Binzel et al., 1997) in the overlapped equatorial region. Small-scale albedo features can also be correlated to small-scale variations in the lightcurves.



Fig. 4. Color ratio maps of Vesta constructed from the albedo maps shown in Fig. 3. Any albedo features related to topographical features should be effectively removed by taking the color ratios. The color bar marks the relative color variations from each corresponding global average. Same as in Fig. 3, the tiling scheme is adopted from Roatsch et al. (2009). The letters and numbers mark the albedo and color features we identified. The color variations over Vesta are mostly within ±10% for the strongest contrast.

Compared with previous maps in Binzel et al. (1997) over the overlapped region (-15° to $+20^{\circ}$ latitude), our maps are consistent in all wavelengths except for some small-size albedo features. Overall the eastern hemisphere is brighter than the western hemisphere. The darkest region is from 230° to 310° longitude, covering the borders of tiles EW and EFW. The dark area Olbers, through which the prime meridian was defined (Thomas et al., 1997b), shows in both our maps and the previous maps with the same size. Dark area #15, at about 100° longitude and on the border of tiles EFE and SFE, shows at the edge of Binzel et al.'s maps, and is fully covered by our new maps that extend to about -50° latitude. Some features in Binzel et al.'s maps, such as S, M, T, U, and R, were not identified and marked in our maps. But some of them may actually correspond to the features identified in our maps, but in slightly different positions due to different data processing, map generation processes, and brightness stretches. S could be #12; T could be part of #1; U could be part of #2 or #4. M and R are close to the edge of our map, and do not completely show up in our maps.

Further, our HST images have a pixel scale of \sim 38 km, compared to \sim 54 km in the previous observation. The longitudinal resolution of our observation is higher than that of the previous observation as well. Therefore the new maps shown in Fig. 3 appear smoother than the previous ones. A mapping process with all available previous HST/WFPC2 data combined will be extremely valuable in the future.

The surface of Vesta is variegated. The most obvious feature near the equator is the large dark region from 230° to 310° longitude, which has a nearly circular shape. Slightly brighter areas (#8 and #9) centered at about (270° and 345° , respectively) are inside the large dark region near the edge of tile EFW. The western hemisphere dark region appears to be connected to Olbers, which is at about (0° , + 10°). The eastern hemisphere has slightly milder contrast. A relatively dark area, #15, is located at (100° , -20°) near the border of tiles EFE and SFE. Near the rim of the south-pole crater, area #13 located at (20° , -40°) in tile SE appears to be the brightest area in all albedo maps, and form the center of an arc-like bright feature that starts just east of #10, and pass south of #15, through #14 with some hint of continuation to #5. Although both area #13 and the arc-like feature including area #15 are near the rim of the crater, we are confident that the brightness of these areas reflects the real reflectance of the surface, and is not likely to be associated with uncorrected effects due to surface morphology. This is because we used the shape model of Vesta that includes all the topographic features of the south-pole crater and its rim to correct for topography in our photometric modeling. Also those areas are less than 30° away from disk center in many images we used to construct the maps. As will be shown in the next section, there are many interesting color variations in this region near the rim of the crater. Color ratios should be able to completely remove morphological features. We will discuss the reflectance and color variations, in conjunction with the surface topography of Vesta to interpret the composition and mineralogy, in the following sections.

4. Geological mapping

4.1. Color-ratio maps

Starting from the albedo maps shown in Fig. 3, we can construct various color-ratio maps, and study their implications on the composition and mineralogy of the surface of Vesta. Any reflectance variations caused by small-scale topographical features that are not included in the shape model and/or not completely removed through the mapping process can be removed by taking the ratio of albedo maps. They therefore affect color maps much less than albedo maps. Four color-ratio maps are shown in Fig. 4. According to these maps (Figs. 3 and 4), we identified areas with albedo and color that are different from the surrounding areas, as marked in Figs. 3, 4, 8 and 10 by numbers and letters.

It has to be cautioned that all of our analysis and mineralogical interpretation of the albedo maps of Vesta are based on the four visible colors. Without any spatial information about the $2-\mu m$ pyroxene band of Vesta, our ability to study the surface composition is limited. Nevertheless, with the help from ground-based NIR observations (Gaffey, 1997) and laboratory work (e.g., Gaffey, 1976), we were able to derive the spatial distribution of compositional units on Vesta from these maps as one possible interpretation of our observations.

4.1.1. 673 nm/439 nm

The 673 nm and 439 nm maps are both outside of the 1-µm absorption band controlled by iron in mafic silicates, so the ratio of 673/439 nm albedos measures the red slope of the spectrum of Vesta. The higher the ratio is, the redder the slope is. Overall, the 673 nm/439 nm color ratio map (Fig. 4a) has small variations. In only a few areas the red slope deviates from average by more than 5%. The reddest areas on Vesta form a ring-like region, centered at about $(140^\circ, -20^\circ)$ and with a radius 20–30°, and is composed of areas #2, #1, N, #15, #3, and #4 (at \sim 185° longitude). It is interesting to notice that this area with very red slope includes both dark and bright albedo areas (Fig. 3). Therefore, different processes, such as composition, particle size, space weathering, must contribute to the redness of different areas. We will investigate this later after additional color ratios are considered and combined with the information from albedo variations and topography. Other small isolated areas that are redder than average include B, the area adjacent to C, as well as Q and Z.

The bluest area in the map is #13, centered at about $(20^\circ, -40^\circ)$ in tile SE, with a red slope bluer than the global average by ~5%. Interestingly, this area coincides with the brightest albedo (Fig. 3), which is on the topographic slope of the highest peak at

 $(20^\circ, -30^\circ)$ on the rim of the south-pole crater (Fig. 2 in Thomas et al. (1997a)). This area has the steepest topographic slope on Vesta. The color, albedo, and topography relationships of this area are similar to what was observed on Asteroid (433) Eros, where clear evidence of space weathering was identified on crater Psyche. The wall of crater Psyche has bright patterns, and the weathered dark materials concentrate near the flat bottom of the crater (Veverka et al., 2000; Clark et al., 2001; Murchie et al., 2002). It was suggested that seismic shaking induced by collisions may cause down-slope movement of the space weathered regolith on the top layer that is relatively darker and redder toward the bottom of crater, exposing an underlying layer of fresh, relatively bright, unweathered materials on the crater wall. The color and brightness of area #13 is thus the first hint of space weathering on Vesta. The discussion will continue in later sections.

In addition to area #13, there is some evidence that the area just north of Olbers, not fully covered by our maps, is slightly bluer than average. Also, area #12, possibly connected to area #13, is blue. Another slightly blue area is #14 in tile SFE.

4.1.2. 673 nm/953 nm

The 1- μ m band centers of HED meteorites are between 0.92 μ m and 0.95 μ m (Gaffey, 1976). The 1- μ m band center of Vesta's hemispherically averaged spectra at all sub-Earth longitudes are within that range (Gaffey, 1997). The wavelength center of F953N narrow band filter (954.5 nm) is very close to the 1- μ m band center of Vesta's spectrum, just slightly towards the long-wavelength side. Given the small range of shifts of the 1- μ m band centers in the spectra of the compositional units of Vesta, the 673 nm/953 nm color ratio is a good proxy of band depth, almost independent of any other band parameters such as band width and band area. Higher values of this ratio indicate stronger 1- μ m band center towards longer wavelength, and the above interpretation will not necessarily be correct. We will discuss the case with olivine later.

The most obvious feature in the 673 nm/953 nm color ratio map (Fig. 4b) is the large complex blue region from 240° to 310° in longitude and from -30° to $+20^{\circ}$ in latitude around the border of tiles EW and EFW, indicating a weak 1-µm absorption. The areas designated A and B by Binzel et al. (1997) are at the core of this region. Its shallower 1-µm band indicates either less Fe²⁺ in pyroxene or less abundant of high-Ca pyroxene in those region (Gaffey, 1997). The other region with a relatively weak 1-µm band is Olbers, which appears to be connected to areas A and B. Both areas are relatively dark in albedo at 439 nm and 673 nm (Fig. 3). Overall, these areas are not correlated with any topographic features.

On the other hand, in the eastern hemisphere, the regions with relatively red spectral slopes except for area #15 are dominated by a relatively deep 1- μ m band. Similar areas are #5 and #6, near (200°, -40°) and (210°, -20°) in tile SFW, and they seem to be connected to #1 and #2. Some small isolated areas such as areas N, Z, and #11, across tiles EFE and EE, also have relatively deep 1- μ m band. It is noticed that those areas (#1, #2, #4, #6, #5, and #3), together with the chain of spots extending from area #1 toward southwest (areas N, Z, and #11), almost form a circle on the globe of Vesta (Fig. 5a). The circle might pass through the south pole and the center of the south-pole crater. Also it is worth noting that the center of the circle of strong 1- μ m absorption feature is almost at the antipode of the complex dark region including areas A and B of the globe of Vesta (Fig. 5b). No correlations were found between these color features and topographical features (Fig. 5c and d).

4.1.3. 673 nm/1042 nm

Binzel et al. (1997) interpreted this color as the width of the 1- μ m band. However, although 673 nm filter samples the brightness outside of the 1- μ m absorption, 1042 nm is on the red side of the



Fig. 5. Panels a and b are the color ratio map 673 nm/953 nm wrapped onto the 3-D shape model of Vesta. Panels c and d show the topographic map of Vesta wrapped onto the shape model (Thomas et al., 1997b). The left panels have the same viewing geometry that points to the opposite side of Vesta from that of the right panels. The center of the ring-like region (red) with strong 1-µm absorption feature is almost antipodal to the region where minerals with weak 1-µm absorption are concentrated (top panels). No specific topographic features are found to associate with either mineralogical region (bottom panels). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

band. Therefore, the 673 nm/1042 nm color ratio is not only affected by the band width, but also affected by band depth. For example, a broader band and a deeper band will both increase the 673 nm/1042 nm ratio, so they cannot be distinguished from each other just from this color ratio. For this reason, we decided to use an alternative color ratio, i.e., the 953 nm/1042 nm, as an indicator for the band width, as discussed in the next section. In Fig. 4c, we show this color ratio for the purpose of comparing with the previous color-ratio maps reported by Binzel et al. (1997).

4.1.4. 953 nm/1042 nm

The center of F1042M filter (1022 nm, FWHM 276 nm) is inside the 1-µm mafic band of pyroxene and on the long-wavelength side of the band center. Both the depth and the width of the band affect the reflectance in this wavelength. If one assumes that F953N filter samples right at the center of the 1- μ m band, then because both reflectance values at 953 nm and 1042 nm are proportional to band strength, the color ratio 953 nm/1042 nm removes the effect of band depth, and thereby acts as a good proxy to the width of the band. The higher the color ratio is, the wider the band is, and vice versa. Because eucrites in general have broader 1-µm absorption than diogenite (Gaffey, 1976), the 953 nm/1042 nm color ratio serves as a good indicator of the amount of eucrite and diogenite for the areas without olivine, with higher values associated with more eucrite materials. The presence of olivine will significantly broaden the 1-µm band and cause the center of the band to shift toward longer wavelength in 1.05-1.10 µm range, both increase the 953 nm/1042 nm color ratio. On the other hand, olivine is redder than pyroxenes, causing high values in its 673 nm/439 nm color ratio. Therefore, high 953 nm/1042 nm ratio accompanied with high 673 nm/439 nm ratio indicates high olivine component.

Overall the 953 nm/1042 nm color map (Fig. 3d) has much smaller variations over the mapped area than 673 nm/439 nm and 673 nm/953 nm color maps. The most obvious features are

areas A, B, and Olbers, where the 953 nm/1042 nm ratio is the largest, suggesting either the most eucrite component in their pyroxene composition or the presence of olivine. Some small areas including #12, #8, and a small area to the east of C and partially inside our map also have high 953 nm/1042 nm color ratio. The opposite case occurs in part of the areas where the deepest 1-µm band is seen, including areas #1 in EFE, #2 and #4 in tile EDL, #5, #6, and #7 in tile SFW, and #3 in SFE. The relatively low color ratios of 953 nm/1042 nm reflectance of these areas suggest more diogenitic material.

Ground-based rotationally resolved spectra by Gaffey (1997) suggested that eucritic minerals dominate the western hemisphere of Vesta, and only a small area at about 130° longitude possibly contains concentrated olivine. In terms of spectral colors (Fig. 3a), only area B has slightly red 673 nm/439 nm color, consistent with possible olivine. Areas A and Olbers do not have any red color than background, seemingly more consistent with eucrites. Therefore, we consider that the high 953 nm/1042 nm color ratio in A, B, and Olbers is related to eucrite but not olivine. This is also consistent with the shallow 1-µm absorption and low albedo observed in these areas. On the other hand, in the longitude range $130^{\circ} \pm 20^{\circ}$ where Gaffey (1997) suggested the existence of olivine, there is no area showing particularly high 953 nm/1042 nm color ratio. Therefore the maps do not support the existence of olivine in this region, and are most consistent with the absence of olivine on the whole surface of Vesta.

4.2. Correlations between albedos, colors, and topographical height

4.2.1. Band strength vs. band width

Fig. 6 shows the correlation between 673 nm/953 nm color and 953 nm/1042 nm color for the observed area on Vesta. A strong correlation between the band depth and band width is evident for the whole mapped surface of Vesta. If, as discussed in



Fig. 6. The 673 nm/953 nm color ratio vs. the 953 nm/1042 nm color ratio for the whole surface of Vesta, as well as for the identified albedo or color features. Both color ratios are plotted relative to their corresponding global averages. The color of points represents their longitudes as indicated by the color bar. From the top left to bottom right, the plot shows the 1- μ m absorption band change from relatively shallow and broad to deep and narrow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Section 4.1.4, there is no olivine component on the mapped surface of Vesta, then the correlation of the 673 nm/953 nm and 953 nm/ 1042 nm color ratios (Fig. 6) shows the trend line of pyroxene compositions in HEDs. The compositions of minerals near the upper left corner are more eucritic; those near the lower right corner more diogenitic. From the color of points that represent longitude in Fig. 6, it appears that there is an obvious trend of compositional transition from the western to the eastern hemisphere, where more and more diogenitic minerals appear.

4.2.2. Spectral slope vs. albedo

No correlation between the spectral slope and albedo is seen. The non-correlation of spectral slope and albedo suggests that multiple factors affecting albedo and color are at play on Vesta. These could be space weathering, particle size, composition, or any combination of them. Since space weathering tends to both reduce the brightness and increase the spectral slope at the same time, the lack of correlation between albedo and spectral slope on Vesta does not support the existence of global space weathering processes on Vesta. This is consistent with the absence of spectral differences between HED meteorite spectra and Vesta's that are associated with space weathering.

4.2.3. Band strength vs. albedo

Unlike the spectral slope, the 1-µm band strength is strongly correlated with albedo (Fig. 7), where a stronger absorption band appears in the brighter area on a global scale. If, as indicated by the 673 nm/953 nm and 953 nm/1042 nm color-ratio maps (Fig. 4), band strength is associated with compositional variation, then the hemispheric albedo variation seems to be dominated by mineralogical variations. Other factors, including particle size (Hiroi et al., 1994) and space weathering (e.g., Clark et al., 2002) may also contribute to the correlation between albedo and 1-µm band. If space weathering does not dominate the global albedo distribution on Vesta as concluded in the previous section, then other than



Fig. 7. Similar to Fig. 6, showing the color ratio 673 nm/953 nm, which represents the strength of 1-µm absorption, vs. the albedo at 673 nm. Strong trend of the strength of 1-µm absorption with albedo is present. This suggests that the albedo variation is probably dominated by mineralogical variations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

mineralogical compositions, the albedo of Vesta will also be affected by particle size and roughness that are controlled by gardening processes from impacts after its last large scale resurfacing. The diogenite-like minerals on the eastern hemisphere of Vesta that formed in deep layers of the crust and were likely excavated by impact could be more fine-grained due to impact processing than those on the western hemisphere, which presumably has not experienced such violent impacts. This is consistent with the relatively higher albedo on the eastern hemisphere.

4.2.4. Band strength vs. topography

Using the topographical map reported by Thomas et al. (1997a) (Figs. 5c and d and 8c), we considered a possible correlation between topographical height and composition on a global scale. No correlation is evident between the 1- μ m band strength (673 nm/953 nm color) and topographic height on a global scale. It does not appear that the impact that generated the south-pole crater controlled the composition of the whole surface of Vesta, although the size of the south-pole crater is comparable with the radius of Vesta itself.

At smaller scales, some areas with particular albedo and/or color properties are correlated with some topographic features. Fig. 8 shows the contour of topographic height overlaid with two colorratio maps (panels a and b), as well as the geological areas marked in the topographic height map (panel c). Of immediate interest are those areas surrounding the south-pole crater (south of latitude -40°), and near the highest peak on the rim as well (#11). Areas #4, #5, and #6 are interpreted as diogenite-rich, and are all located on topographically high rims of the crater. They could well be related to the overturned materials excavated during the formation of the crater. Interestingly, the relatively low areas between areas #4, #5, and #6 have only slightly weaker yet still strong 1-µm bands (Fig. 8a and b), consistent with less accumulation of the overturned, diogenite-rich minerals. Similarly, area #11, which is the highest region on Vesta, only has a slightly stronger 1-µm band than the surrounding region. Area #10 is on the edge of the deepest



Fig. 8. Panels a and b show contour of topographic height overlaid with two color-ratio maps, which represent spectral color and strength of $1-\mu m$ absorption band, respectively. The contour lines are color-coded, where dark color represents topographic low and bright color topographic high. Panel c is the map of topographic height, reproduced from Fig. 2 in Thomas et al. (1997a), with the albedo and color features identified and discussed in the text marked. The range of topographic height is from -14 km to +14 km. The two horizontal lines mark the latitudinal area that is covered by our maps. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

area on Vesta, and has relatively shallow 1-µm band, presumably associated with more eucritic minerals. However, area #3 is topographically similar to area #10, but compositionally different. Moving around the highest peak on Vesta, areas #12 and #13 are both blue in their spectral colors, appear to be connected, and both are on topographical slopes (steepest slope on Vesta for #13). A more topographically interesting area is near #15, which is a saddle with its north and south sides lower and its east and west sides higher. Color-wise, this area is very red in spectral slope, with its north and south sides (towards areas N, Y, and #3) as red, and its east and west sides (towards areas #13 and #14) blue.

4.3. Geological mapping

Gaffey (1997) suggested that relatively dark howardites and polymict eucrite (pyroxene-plagioclase) assemblages dominate the background materials on the surface of Vesta. Recent near-IR observations confirmed this result (Vernazza et al., 2005). According to Gaffey's interpretation, low albedo eucrite assemblages dominate on the dark western hemisphere, producing the lightcurve minimum. Many distinct bright geological units are clustered on the eastern hemisphere. Around longitude 180°, there are some bright, low-calcium eucrite regions, at least one of which is located near the south pole. An olivine-bearing unit is located around 130° longitude (Leslie Formation as the suggested name by Gaffey). The howardite/polymict eucrite units were suggested to be the regolith-gardened original surface of Vesta, and have undergone some darkening processes (space weathering) to various extents. The geological maps proposed by Gaffey show some distinct mineralogical units (Fig. 13 in Gaffey (1997); reproduced in Fig. 9).

To better combine the albedo and color information from different maps, we constructed two different color composite maps, as shown in Fig. 10. Panel a is a mineralogical color composite, with 673 nm/953 nm color (1-μm band depth) in red, 953 nm/ 1042 nm (band width) in green, and 439 nm/673 nm (inversed spectral slope) in blue. The global average values of all three color-ratios combined would be gray. As such, the red color in color composite map means strong 1-µm absorption, the green color, broad absorption, and the blue color, the blue spectral slope. Note that the color map used in blue channel has 439 nm/673 nm rather than 673 nm/439 nm as shown in Fig. 4a, in order to emphasize the areas with blue spectral color. The different colors in this composite map represent difference in the spectral features. Panel b in Fig. 10 is a pseudo-color composite, with the albedos at 953 nm, 673 nm, and 439 nm represented by red, green, and blue colors, respectively. The mid tone gray color corresponds to the global average values of albedos at all three wavelengths. This color



Fig. 9. Gaffey's mineralogical maps. Panels a and b are the two geological maps proposed by Gaffey (1997), reproduced here with the longitude and latitude corrected to the current coordinate system defined by Thomas et al. (1997b) and used in this paper.

composite map emphasizes the overall albedo variations across the surface, as well as the difference in albedo variations in three wavelengths. Starting from the Gaffey (1997) conclusions, we will combine the information extracted from all albedo maps, color maps, and the color composite maps to discuss their mineralogical implications, identify or reject the mineralogical units proposed by Gaffey, and propose a mineralogical map from our observations.

First, in the western hemisphere, the dark region containing areas A, B, and Olbers have the shallowest 1-µm absorption band (Fig. 4b), slightly red spectral color (Fig. 4a), and broader band (more eucrite) (Fig. 4d). They appear to be bright green in the mineralogical color composite (Fig. 10a). All of these spectral features are consistent with eucrite assemblages that have a relatively high plagioclase component or multiple pyroxene components. Moving toward the eastern hemisphere, the dominant mineralogical unit is the red and orange circular region (Fig. 10a, including areas #1, #2, #4, #5, #6, #3, #11, Z, and N). The relatively deep $1-\mu m$ absorption of this region (Fig. 4b) is consistent with relatively high diogenite component with respect to the background. However, part of this region, such as areas #1, #2, #3, N, and Z (orange region in Fig. 10a), has a different spectral slope (Fig. 4a). Also the band width of areas #2, #3, N, and Z are almost indistinguishable from background, arguing that eucritic material could also dominate over diogenitic. Note that the location of this ring-like region (100-180°) is close to the longitude where low-calcium eucrite was proposed by Gaffey (1997). If this is the case for areas #2, #3, N, and Z, then the higher iron composition in low-calcium eucrite relative to typical eucrites could be a plausible explanation for producing the red slope, as well as the 1-µm absorption as deep as areas #4, #5, and #6, which have a less red spectral slope and relatively narrow absorption band, presumably diogenite-rich.

An interesting area is #15. It has the reddest spectral color over the mapped surface of Vesta (Fig. 4a). Its 1- μ m band strength is just slightly shallower than the background minerals, neither as deep as the surrounding regions that are interpreted either as low-calcium eucrite or as diogenite, nor as shallow as the eucrite-rich area in the western hemisphere (Fig. 4b). Its band width is not much different from the surrounding background area (Fig. 4d). In other words, the absorption feature of this area is indistinguishable from the background minerals, but its spectral slope is much redder, making it grayish red in mineralogical color composite map (Fig. 10a) and dark gray in pseudo-color map (Fig. 10b). It is a geologically different region from all other areas.

Another region that is different from all others is area #13, and probably #12 as well, where its 1- μ m band characteristics are similar to background, but its spectral slope is significantly bluer, appearing light blue in the mineralogical color composite map (Fig. 10a), but bright in the pseudo-color map (Fig. 10b). This region, and probably area #15 as well, are possibly related to space weathering of background materials. These will be discussed later.

Putting together the mineralogical units identified above, we generated a mineralogical map of Vesta (Fig. 11) for the area covered by our observations. Six geological units are identified, numbered from (I) to (VI), as shown in the mineralogical color composite with different colors (Fig. 10). The eucrite-rich area is divided into two units (I and II) in order to show the broad range of compositional variations in this region. Region (III) with red spectral slope and deep and broad 1-µm absorption are distinguished from region (IV) with neutral spectral slope and deep and narrow 1-µm absorption. Two units with similar 1-µm absorption features but different colors are marked as (V) and (VI) for their extremely blue and extremely red spectral colors, respectively. The four-point spectra of these six units are plotted in Fig. 12, where they are all normalized to the reflectance at 673 nm and shifted with respect to each other for clarity. The spectral and color features for the six geological units can be clearly distinguished from their 4-point spectra.

One mineralogical unit of particular interest is the olivine-rich area proposed by Gaffey (1997), located between 90° and 150° in longitudes. With much wider 1-µm absorption band centered at longer wavelength as well as a redder color than pyroxenes (Gaffey, 1976; Cloutis et al., 1986), olivine concentration is expected to show relatively high values of both 953 nm/1042 nm and 673 nm/439 nm color ratios. However, in our color-ratio maps. there is no particular geological unit in the corresponding longitudinal region showing such properties. Therefore, no direct evidence in this region is found to support the existence of an olivine-rich region. Given the sub-observer latitude of our observations -19° and that of Gaffey's (1997) +20° to +22°, it is possible that such an olivine concentrated area as reported by Gaffey (1997), if it exists, is probably in the northern hemisphere that is not covered by our maps. Rivkin et al. (2006) reported a north-south difference in the 2.95 μ m/2.20 μ m hemispheric integrated color ratios. If as confirmed by their observations there is no 3-µm absorption on Vesta, then this variation can be interpreted as caused by the variation of the 2-µm absorption band associated with olivine. The relatively small value of 2.95 μ m/2.20 μ m, which is out of the range of HED meteorites, in the northern hemisphere is consistent with more olivine that does not have a 2-µm band.

5. Discussion

5.1. Evolutionary history of the surface of Vesta

It is generally considered that the impact that generated the giant crater near the south pole controls the surface composition of Vesta, at least in the southern hemisphere (Thomas et al., 1997a). The eucritic minerals represent the original surface of Vesta that formed on the surface layers of the crust. The diogenitic minerals formed in deep layers of the crust and were exposed to the surface by impacts. Howardites are mixtures of eucrites and



Fig. 10. Panel a is the mineralogical color composite maps constructed from three color-ratio maps with the albedo and color features discussed in the text marked. Panel b is pseudo-color composite constructed from three albedo maps. The colorful surface of Vesta is an extremely geologically diverse world, awaiting exploration by the Dawn spacecraft. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



Fig. 11. Mineralogical map proposed from our albedo and color maps. Six different geological units are identified and each labeled and interpreted for their possible composition. The four-point spectra of these geological units, compared with the background minerals, are plotted in Fig. 12. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

diogenites. Due to the violent impact history of the surface of Vesta, it is mostly composed of brecciate howardites and polymict eucrites, while the diogenite-rich areas represent relatively new surface that has been exposed. Thomas et al. (1997a) reported correlations between compositional variations and topographic height near the rim of the south-pole crater supporting the dominance of



Fig. 12. Four-point spectra of the six geological units proposed in Fig. 11. They are all normalized to 673 nm and vertically offset for clarity. The dotted lines overplotted with every spectrum are the measurements of background minerals for comparisons. The six geological units can be clearly distinguished. Compared to background minerals, the red slope of units I, II, and IV are similar to background, units III and VI are much redder, and unit V is much bluer. The 1-µm absorption of units I and II are shallower and wider than background, that of III and IV are deeper, and that of V and VI are similar to background.

the impact over the mineral composition near the south pole. We looked for similar correlations using their topographic map and our new color-ratio maps (Fig. 8) as discussed in Section 4.2. In the eastern hemisphere where the rim of the crater is covered by our maps, the distribution of mineralogical components appears to follow the crater rim. This may be associated with the excavation and overturning of material forming the crater, which presumably was caused by a giant impact (Thomas et al., 1997a; Asphaug, 1997). However, it is hard to clearly see from the maps that mineralogical distributions are correlated with topographic height.

The regions near area #11, where the highest peak on Vesta is located, and the area surrounding the saddle topography near area #15 are probably the place where clear correlations between topography and compositions are apparent. Located in the highest area on the rim of the south-pole crater and also the highest point on Vesta, area #11 is compositionally distinctive from its surrounding areas, similar to geological unit IV, which we interpreted as diogenite-rich. If the minerals in this area are the overturned materials excavated by the giant impact, then its relatively weak spectral features, small size, and isolated mineralogical composition from the surrounding area do not seem entirely consistent with the impact scenario. Areas #4, #5, and #6 have slightly high topographic height on the crater rim, and have compositions that are consistent with diogenitic minerals. They therefore better represent the overturned materials. If the single impact dominates the composition around the crater, then the mineralogical composition should be distributed along the contour lines of topographic height. The non-uniform distribution of the excavated minerals is probably related to the possible obliquity (non-zero impact parameter) of the impact, or more than one large impact at different sites, or some other processes that have changed the mineralogical composition surrounding the crater.

5.2. Another giant impact?

Fig. 5a and b shows that the center of the ring-like region where the 1-µm absorption is relatively strong is almost at the antipode of the region where that absorption is relatively weak. Yet there are no topographic features appearing to be associated with the ring-like feature (Fig. 5c and d). Following the reasoning that cratering processes controlled the mineralogical compositions around a crater, if the strong absorption is interpreted as associated with plutonic minerals that formed in deep layers in the crust, whereas weak absorption indicates minerals that formed in shallow layers on the surface, then the distribution of these two different mineral compositions on almost exactly opposite sides of Vesta may not be pure coincidence. The data are most consistent with another giant impact, which is similar to the one that created the south-pole crater, creating these compositional features. From the size of the ring-like region of strong 1-µm absorption, this hypothetical impact should be as energetic as the one that created the south-pole crater.

Multiple lines of evidence support the hypothesis that there are more than one giant impact happened on Vesta. Bogard and Garrison (2003) concluded that several large impact heating events have occurred on Vesta between 4.1 and 3.4 Gy ago from ³⁹Ar-⁴⁰Ar age-dating of eucrites, particularly concentrated on 4.48 ± 0.02 Gy and 3.4–3.7 Gy. Simulations of the dynamical evolution of impact ejecta from Vesta, presumably the source of many Vtype asteroids, identified a low orbital inclination group of V-type asteroids that could be liberated from Vesta's surface before or during the Late Heavy Bombardment (LHB) epoch ~3.8 Gy ago (Nesvorny et al., 2008). This possible impact time scale is much earlier than the formation of the south-pole crater (Asphaug, 1997). Most recently, Moskovitz et al. (2010) reported that the group of V-type asteroids with low orbital inclinations has their band centers shifted towards longer wavelengths, possibly implying an older population of collisional fragments from Vesta than the main population of vestoids. The evidence shown in our maps is therefore consistent with the possible giant impact proposed by various researches above.

The almost systematic distribution of the minerals with strong 1- μ m absorption, however, does not correlate with any topographical features that could be the rim of the crater. If that impact happened during or before the LHB, or it is strong enough to cause substantial melting around the impact site, then it is not hard to imagine scenarios that erased the topography of the crater that formed from this impact. The erosion over a long time due to impacts, micrometeorite bombardment, or seismic shaking could be possible. The melting caused by the impact could ease the topography. Or if that impact occurred when Vesta is still geologically active, then lava flows can also fill the impact basin. But the more important question is the different outcome mineralogical distributions from two seemingly similar impacts, one observed and one proposed here.

Of course, the spectral features in the ring-like region are not completely uniform, possibly composed of different minerals, and therefore not formed simultaneously or from the same origin. The areas with strong 1-µm absorption may just form the ring-like region coincidently. Nevertheless, the lack of large scale correlations between the topographical features associated with the south-pole crater and compositional distribution that is consistent with an impact might suggest that the composition on Vesta may not be entirely controlled by the single impact and cratering processes of the south-pole crater. This puzzle, as well as the interesting distribution of compositional features on the opposite sides of Vesta, will be the prime candidates for study when Dawn arrives. We should look for large eroded crater on Vesta, and confirm compositional variations suggested by these four color maps.

5.3. Space weathering

Space weathering generally decreases albedo, reddens spectral slope, and dilutes spectral absorption features. The lack of space weathering induced spectral mismatches between HED meteorites, which are considered ejected from Vesta, and Vesta itself suggested that the surface of Vesta is relatively less weathered compared to the surfaces of the Moon and other S-type asteroidal parent bodies (Clark et al. (2002) and references therein). While laboratory experiments showed that the compositional minerals on the surface of Vesta become weathered after exposure to solar wind particles within a time scale of 10^4 – 10^6 years (Vernazza et al., 2006; Brunetto et al., 2006), the apparent lack of weathering on Vesta implies that the surface of Vesta is either relatively young due to a recent global resurfacing event or protected from space weathering. Vernazza et al. (2006) proposed that Vesta might possess a weak magnetic field that prevents solar wind particles from reaching the surface. Any weathering may only occur in the areas where the magnetic field lines reach the surface. Carry et al. (2010) looked for correlations between albedo and color in the near-IR wavelengths within the relatively small area on Vesta they observed and did not find any.

As mentioned earlier, area #13 is extremely blue, very bright, and located on the steepest slope on Vesta, yet its 1-µm absorption features are indistinguishable from the background materials. Exactly the same correlation, except for the much smaller color variation, was observed on the wall of crater Psyche on Eros, and was interpreted as direct evidence of space weathering (e.g., Clark et al., 2001; Murchie et al., 2002). However, our map does not have coverage on the immediate topographical low next to this area to confirm whether there is corresponding deposition of weathered materials transported from the slope.

On the other hand, another special area, #15, which does not show any spectral difference in the 1-µm band region from background materials, is extremely red compared to everywhere else on Vesta covered by our maps (Figs. 4 and 12). It also has low albedo in all visible wavelengths compared to the whole eastern hemisphere (Figs. 3, 4 and 10). Topographically, it is near a saddle point (Fig. 8c). The topographically lower north side (area Y) and south side (area #3) are red and dark, but the higher east side (area #14) and west side (areas #13) are blue and bright (Fig. 8a). Although the composition of the red and dark areas is probably different from that of the background materials for their either stronger (#3) or slightly weaker (Y) 1-µm absorption, they should be different from the composition of geological unit (IV), which is more likely diogenite-rich. Since the compositions of the blue and bright areas (#13, #14) are similar to the background materials, it is plausible that area #15 represents weathered surface that is either old and weathered in place or transported from the topographic high areas to the east and west. The weathered materials in area #15 could also be transported toward topographic low areas in the north and south. Both blue areas #13 and #14 are on the side of the ridge of the crater rim along the line of area #11 towards the north of areas #15 and #14. consistent with the down-slope movement of weathered materials and exposure of underlying fresh materials.

If space weathering is indeed acting on Vesta, then the low albedo of the western hemisphere (geological units I and II) could also be affected in part by space weathering. It is generally considered that this region has a relatively older surface than the eastern hemisphere, which may have been largely resurfaced by impact and be fresher. However, overall the color of western hemisphere is not as red as area #15. Thus it is not obvious that we should attribute the darkening on the western hemisphere to space weathering. After all there is no correlation between brightness and color found on a global scale. Therefore, it is not likely that there exists any multi-pole magnetic field proposed by Vernazza et al. (2006) as one possible form of magnetic field on Vesta. Further, the existence of space weathering rules out the existence of a global magnetic field, unless the regions (geological units V and VI) where evidence of space weathering was seen are close to a magnetic pole.

6. Conclusions

To summarize, we used the disk-resolved images of Vesta at a sub-Earth latitude of -19° obtained with HST WFPC2 through four filters centered at 439 nm, 673 nm, 953 nm, and 1042 nm to construct surface albedo and color maps covering -50° to $+20^{\circ}$ latitudes, and interpreted them with respect to the geological composition of the surface of Vesta. These maps have more coverage of the southern hemisphere close to the giant crater near the south pole than previous maps (Binzel et al., 1997), and are consistent in the regions of overlap.

The surface of Vesta has about $\pm 20\%$ peak-to-peak albedo variations. The contrast is relatively small near the 1-µm center and high outside the band, especially in 439 nm. The color-ratio maps show about $\pm 10\%$ peak-to-peak color contrast. The albedo and color variegations suggest a geologically diverse surface of Vesta. We recognized about 10 features in the equatorial region that have been identified by Binzel et al. (1997) from their maps, and identified another 15 albedo and color features in the southern hemisphere outside of the coverage of the previous maps, numbered from #1 to #15.

In order to clearly refer to the albedo and color features on Vesta and prepare a continuous reference frame for the analyses of progressively higher-resolution maps that will be obtained by Dawn upon its arrival to Vesta, we followed the partitioning scheme used by Roatsch et al. (2009) and divide the surface of Vesta into 15 tiles, with 9 (partially) covered by our maps.

Overall the western hemisphere of Vesta is darker than the eastern hemisphere, consistent with its single-peak rotational lightcurve. The color-ratio maps suggest that minerals with relatively shallow 1-µm absorption band dominate the dark western hemisphere, and those with relatively deep 1-µm absorption band dominate the bright eastern hemisphere. If deep 1-µm band is interpreted as associated with diogenite-rich minerals, then the bright, red eastern hemisphere, especially the region near the 180° longitude, is dominated by relatively young materials, possibly excavated from subsurface by impacts. The areas with deep 1µm band form a circle centered at the antipode of the dark region, which is interpreted as composed of relatively old, eucrite-rich minerals, in the western hemisphere. The areas with deep 1-µm band appear to contain two different geologic units that have different band widths and spectral slopes. We interpreted the areas that have similar 953/1042 nm color ratio with background materials but redder color as a low-Ca eucrite composition. The areas where the 953/1042 nm ratio is significantly lower than background (suggesting narrow 1-µm band) and 673 nm/439 nm color is similar to that of the background are interpreted as diogeniterich.

We identified three areas on Vesta showing clear evidence of space weathering. Area #15 on the boundary of plates EFE and SFE is relatively dark, and is one of the reddest areas on Vesta. Area #12 in plate SE and area #13 on the boundary of SW, SE, EW, and EE are relatively bright, and much bluer than background. On the other hand, all three areas have 1-µm absorption characteristics that are similar to those of the background, suggesting similar mineralogical compositions. The topographic map (Thomas et al., 1997a) shows that area #13 is at the steepest slope on Vesta, and areas #15 and #12 are on gravitationally flat areas. All of these are consistent with the scenario of space weathered materials being transported down-slope to gravitationally flat areas and exposing the underlying fresh materials. This is essentially the same scenario proposed to explain similar observations on Eros from NEAR data (e.g., Clark et al., 2001; Murchie et al., 2002).

We propose to divide the surface of Vesta into six geological units distinctive from the background, and refer to them as I–VI. Areas A and B represent eucrite-rich area (I); the areas surrounding it also have enriched eucritic material and is the transitional area to background (II); the area with deep but narrow 1- μ m band and red spectral slope is possibly low-Ca eucrite (III); the area with deep and wide 1- μ m band and neutral red slope is possibly diogenite-rich (IV); the freshly exposed, unweathered minerals (V); and weathered minerals (VI). Those six geological units and the background minerals are visually identified from various color composite maps and easily distinguished from their different spectra. We did not find evidence to support the olivine-rich areas proposed by Gaffey (1997) to explain the ground-based spectra, but this could be due to different latitudes of observations.

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