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Eucritic crust remnants and the effect of in-falling hydrous carbonaceous chondrites characterizing the composition of Vesta's Marcia region

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ABSTRACT

The equatorial Marcia quadrangle region is characterized by the large, relatively young impact craters Marcia and Calpurnia and their surrounding dark ejecta field, a hill with a dark-rayed crater named Aricia Tholus, and an unusual diffuse material surrounding the impact crater Octavia. The spectral analysis indicates that while this region is relatively uniform in the pyroxene band centers, it instead shows large differences in pyroxene band depths and reflectance. A large variation of reflectance is seen in the quadrangle: bright and dark materials are present as diffuse material, and as concentrated spots and outcrops. Moreover, OH signature is pervasive in the quadrangle, with a few exceptions. The region, especially the Marcia ejecta field, is characterized by spectra showing the 2 μm band shifted at long wavelengths. This is commonly associated with eucritic material, believed to have crystallized as lava on Vesta's surface or within relatively shallow-level dikes and plutons, thus suggesting that this region is a remnant of the old Vestan basaltic crust. However, other characteristics of the spectra do not fully fit the eucritic composition, indicating an alternative explanation for the band center distribution, including the presence of carbonaceous chondritic material mixed with the native Vestan pyroxene.

The detailed mineralogical analysis of the Marcia quadrangle indicates that this quadrangle is the result of the mixture of the Vestan "endogenic" minerals with the "exogenic" carbonaceous chondrites. The stratigraphic units around Marcia clearly show the bright, uncontaminated material interlaced and mixed with the dark material that contains a strong OH signature. Only few small areas can be considered as representative of the old Vestan original material.

1. Introduction: Vesta mineralogical background

Visible and near-IR spectroscopy from Earth-based telescopes and Hubble data show that the surface of Vesta exhibits absorption features indicative of basaltic minerals, similar in composition to the howardite–eucrite–diogenite (HED) family of basaltic achondrite meteorites (McCord et al., 1970; and many subsequent articles, Gaffey, 1997; Binzel et al., 1997; Vernazza et al., 2005; Reddy et al., 2010). Basaltic eucrites are basalts; cumulate eucrites are gabbros; and diogenites are orthopyroxenites, harzburgites, or dunites (cumulates of orthopyroxene and/or olivine). The first link between Vesta and HEDs is reported in McCord et al. (1970) and Consolmagno and Drake (1977).

This link was strongly reinforced by the discovery of a number of small asteroids with spectra similar to Vesta and to the HED meteorites (Binzel and Xu, 1993; Duffard et al., 2004; De Sanctis et al., 2011a,b; Burbine et al., 2001; Moskovitz et al., 2010; Mayne et al., 2011; Hiroi et al., 1995; Reddy et al., 2011). Most of them can be directly linked to Vesta, forming its dynamical family (Milani et al., 2014), and the discovery of a huge impact basin (Thomas et al., 1997) on Vesta's south pole strengthened the genetic relationship between Vesta, Vesta family asteroids, and HED meteorites. Vesta's giant impact basin Rheasilvia (Schenk et al., 2012) was discovered by the Hubble Space Telescope and was suggested as the source for the Vesta family asteroids (Thomas et al., 1997), fragments of which probably were injected into nearby resonances to become the HED meteorites. Most HEDs were probably excavated from the terrain where the Rheasilvia basin is identified. Thus, eucrites, diogenites, and

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howardites comprise parts of the surface of Vesta, and images and spectral maps of Rheasilvia and of the rest of Vesta reveal their geologic settings and provide insight into their formation (McSween et al., 2013). The detailed characteristics of HEDs and their genetic link to Vesta are described in McSween et al. (2013).

The color and spectral data revealed that the surface is not uniform, but instead exhibits regional color and albedo variations of 10–20% (e.g., Gaffey, 1997; Binzel et al., 1997; Thomas et al., 1997; Li et al., 2010). These remote observations were interpreted in different ways in terms of the types and distributions of the different minerals.

NASA's Dawn spacecraft observed Vesta from orbit for slightly more than a year (Russell, 2013) with a suite of three instruments: a visible and infrared spectrometer – VIR (De Sanctis et al., 2011c), two redundant Framing Cameras – FC (Sierks et al., 2011), and a gamma ray and neutron detector – GRaND (Prettyman et al., 2012). The pyroxene mineral mapping from Dawn's orbit (De Sanctis et al., 2012a) finally yielded the distribution of the mineralogical species, identifying the diogenite-rich and eucrite-rich regions, and providing regional and local geologic context for Vesta's HED lithologies.

VIR spectra of Vesta's surface show ubiquitous absorption bands centered at approximately 0.9 and 1.9 μm, confirming the widespread occurrence of iron-bearing, low-calcium pyroxenes (De Sanctis et al., 2012a). Vesta spectra, on average, resemble those of howardites (breccia of eucrites and diogenites) in terms of the overall shape as well as band center positions, indicating a surface highly reworked and well mixed (De Sanctis et al., 2013).

HED meteorites were apparently formed under reducing and volatile-poor conditions and suggest that Vesta has an anhydrous surface. However, ground-based observations reported different results on the presence of a 2.8-μm band on Vesta. Hasegawa et al. (2003) reported hydrated and/or hydroxylated minerals on the surface of part of the high albedo hemisphere of Vesta, whereas Rivkin et al. (2006) reported a small variation in the 2.95/2.20-μm band ratio, but found no conclusive evidence for the presence of hydrated materials on Vesta. VIR observed a feature at 2.8-μm in some areas on Vesta (De Sanctis et al., 2012b). The 2.8-μm OH absorption band is unevenly distributed across Vesta's surface, indicating areas both rich and poor in hydrated materials. The hydration signature is primarily associated with dark material on Vesta, and the origin of most of the OH is likely related to contamination of Vestan primordial material due to OH-bearing, low-velocity impactors (McCord et al., 2012; De Sanctis et al., 2012b; Reddy et al., 2012). Further evidence of volatiles on Vesta is provided by the measurement of H in unidentified molecular form (Prettyman et al., 2012) and the existence of pitted terrains, interpreted as areas where volatiles were lost (Denevi et al., 2012).

2. Data

The data used in this paper have been obtained by the two imaging systems on board Dawn: FC and VIR (De Sanctis et al., 2011a,b,c; Sierks et al., 2011). VIR is derived from VIRTIS-M aboard Rosetta and Venus Express (Coradini et al., 1998; Ammannito et al., 2006). VIR has two spectral channels: the VIS channel, between 0.25 and 1.05 μm, and the IR, between 1.0 and 5.1 μm. The high spatial (IFOV = 250 μrad/pixel, FOV = 64 × 64 mrad) and spectral ($\Delta\lambda$VIS = 1.8 nm/band; $\Delta\lambda$IR = 9.8 nm/band) performances allow for the identification and mapping of the mineralogical units across the surface. Using a scanning mirror, the scene is scanned one line at a time through the slit of the spectrometer. Each line is made up of 256 pixels, each having a spectrum in the 0.25-μm to 5.1-μm range. VIR's imaging capability combined with an extensive spectral range provides the geological context for mineralogical investigations: spectra and derived spectral parameters can be mapped on the surface of Vesta with a resolution never achieved before.

Dawn was planned as a mapping mission (Polanskey et al., 2011; Russell, 2013) and the mapping program was devised to take advantage of the progressively increasing spatial resolution provided by Dawn's three orbital phases: a Survey orbit at ~2700 km altitude (FC resolution of 260 m/pixel, VIR nominal resolution of 700 m/pixel), High Altitude Mapping Orbit (HAMO) at 685 km altitude (FC resolution of 70 m/pixel, VIR nominal resolution of 200 m/pixel), and a Low Altitude Mapping Orbit (LAMO) at 200 km altitude (FC resolution of 20–25 m/pixel, VIR nominal resolution of 70 m/pixel). The spectral data, obtained during LAMO, were not used for the mapping purpose, due to the strong limitation in coverage (only a few percent of the total surface).

All the coordinates are given in the Dawn team's preferred coordinate system, known as "Claudia" (Russell et al., 2012; Roatsch et al., 2013).

3. Tools and technique: band parameters, colors, etc. and their meaning

The near-infrared reflectance spectra of minerals contain absorption features that are diagnostic of mineralogy, grain size, and crystal structure. Band analysis methods are useful for characterizing spectral data and can be used as a starting point for deriving mineralogical information (Gaffey et al., 2002; Adams, 1974; Gaffey, 1997; Beck et al., 2011; Burns, 1993; Klima et al., 2007, 2011). VIR spectra of Vesta's surface are dominated by absorption bands centered at approximately 0.9-μm and 1.9-μm (hereafter called BI and BII, respectively) confirming the widespread occurrence of iron-bearing, low-calcium pyroxenes seen by ground- and space-based observations (McCord et al., 1970; Gaffey, 1997; Binzel et al., 1997; Li et al., 2010). To analyze a large dataset like the one considered in this work, we have developed the VIR Mineralogy Tool (VMT), an automatic data processor able to return different spectral indicators (continuum levels, absorption bands properties, spectral slopes and their mutual correlations) from Vesta's observations and from laboratory spectra of HED meteorites (Ammannito et al., 2013a,b). The VMT allows us to map the spatial distribution of each spectral indicator across Vesta's surface. The description of the details of how BI and BII have been defined in the VMT and how the band parameters have been computed is reported in Ammannito et al. (2013a), De Sanctis et al. (2013), Frigeri et al. (2015a), and Combe et al. (2015a). For the specific purpose of this study, we use the distribution of BI and BII center positions and depths, as well as the reflectance and 2.8-μm band depth.

The spectral positions of the two major absorption bands of pyroxenes derived from VIR data provide indications of the distribution of different mineralogical units across Vesta's surface, since the exact locations of these bands vary with pyroxene crystal chemistry. Laboratory studies indicate that band centers for BI and BII pyroxene absorptions are systematically different for diogenites and eucrites (Gaffey, 1976; De Sanctis et al., 2013; Beck et al., 2011): BI and BII centers are at slightly shorter wavelengths for diogenites than for eucrites, a consequence of more Mg-rich pyroxenes with lower Ca concentrations in the former. Howardites, because of their intermediate nature, lie between, but partially overlap the fields of diogenites and eucrites.

The depth of an absorption band is mainly determined by the abundance of the absorbing minerals, the grain size distribution, and the abundance of opaque phases; thus it is a useful parameter to be used in mineralogical mapping. The band depths analyzed here have been corrected for geometrical effects. In fact, it has been