Spectral Analysis of the Quadrangles Av-13 and Av-14 on Vesta

F. Zambon[a], A. Frigeri[a], J.-P. Combe[b], F. Tosi[a], A. Longobardo[a], E. Ammannito[c], M. C. De Sanctis[a], D. T. Blewett[c],J. Scully[d], E. Palomba[a], , B. Denevi[d], A. Yingst[g], C. T. Russell[c] and C. A. Raymond[e]

[a]*INAF-IAPS Istituto di Astrofisica e Planetologia Spaziali, Via del Fosso del Cavaliere, 100, 00133 Rome, Italy*
[b] *Bearfight Institute, 22 Fiddler's Road, Winthrop, WA 98862*
[c]*The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland 20723, USA*
[d]*Institute of Geophysics and Planetary Physics, University of California at Los Angeles, 3845 Slichter Hall, 603 Charles E. Young Drive, East, Los Angeles, CA 90095-1567, USA*
[e]*NASA/Jet Propulsion Laboratory and California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA*

* Corresponding author: Francesca Zambon
INAF-IAPS Istituto di Astrofisica e Planetologia Spaziali
Via del Fosso del Cavaliere, 100, 00133 Rome, Italy
Phone: +39-06-45488760
Fax: +39-06-45488188
Email: francesca.zambon@iaps.inaf.it

Abstract

The Av-13 (Tuccia) and Av-14 (Urbinia) quadrangles are located in the south-west region of Vesta. They are characterized by a large topographic variability, from the highest (Vestalia terra highlands) to the lowest (Rheasilvia basin). Many geological units in these quadrangle are not associated with mineralogical variability, as shown by the color-composite maps. Maps of mafic absorption band-center position reveal that the principal lithology is eucrite-rich howardite, but diogenite-rich howardite areas also are present, corresponding to particular features such as Antonia and Justina craters, which are also characterized by strong mafic absorptions. These quadrangles, especially Urbinia, are characterized by many bright ejecta, such as those of Tuccia crater, which are the highest reflectance materials on Vesta (Zambon et al., 2014). Dark areas are also present and correspond with regions with deeper OH-signature. The two quadrangle also contain many vertical ridge crests associated with the Rheasilvia impact. These ridges do not show mineralogical differences with respect to their surroundings, but have a distinctive appearance in color-ratio composite images.

1. Introduction

Vesta, the second most massive body in the main asteroid belt (Thomas et al., 1997; Zuber et al., 2011), can be considered a relic of the protoplanetary disk, revealing the history of the early solar system (Coradini et al., 2011). Dawn, the NASA discovery mission devoted to the study of Vesta and Ceres, covered a large part of Vesta's surface during the orbital phase. Dawn has three instruments: the Framing Camera (FC), the Visible and InfraRed Spectrometer (VIR), and the Gamma Ray and Neutron Detector (GRaND) (Sierks et al., 2011; De Sanctis et al., 2011; Prettyman et al., 2011). Before the arrival of Dawn, Vesta's surface was divided into fifteen quadrangles which were later named for their respective individual features (Fig. 1) (Russell and Raymond, 2011). For each quadrangle geological (Williams et al., 2014) and mineralogical maps (Frigeri et al. (2015b) this special issue) have been produced. In this paper, we discuss the mineralogy of two contiguous quadrangles, Av-13 (Tuccia) and Av-14 (Urbinia), located in the southern hemisphere (Fig. 1). These quadrangles contain several geological units, and part of the Rheasilvia basin (McSween et al. (2013); Ammannito et al. (2015), this issue), the Vestal Terra highlands (Frigeri et al., 2015a), and enigmatic "orange" materials (Le Corre et al., 2011; Garry et al., 2014; Tosi et al., 2015, this issue). Moreover Av-13 and Av-14 contain numerous ridges and grooves also present in other quadrangles (see Longobardo et al., 2015; McFadden et al., 2015). Kneissl et al. (2014) and Mest et al. (2012) performed the geological analysis of the quadrangles mapping a variety of geological units. In this paper, we analyzed the general mineralogy of the

Tuccia and Urbinia quadrangles, as well as specific features, using several tools, such as spectral parameters, temperature maps and spectral unmixing. Ground-based observations (Gaffey, 1997) and Hubble Space Telescope (HST) data (Li et al., 2010) of Vesta have previously revealed the ubiquitous presence of pyroxenes but also mineralogical variations on Vesta's surface. The Dawn mission provided many high-resolution observations of Vesta, allowing for the derivation of the distribution of global and local lithologies (De Sanctis et al., 2012a; Ammannito et al., 2013a). VIR, the Dawn visible and infrared spectrometer, acquired more than 20 million spectra at different spatial resolutions during Dawn's orbit around Vesta, providing a large coverage of Vesta's surface. VIR confirmed the presence of pyroxenes (McCord et al., 1970) associated with the howardite, eucrite and diogenite (HED) meteorites at global scale (Drake, 1979; Feierberg and Drake, 1980; De Sanctis et al., 2012a, 2013), but other minerals have also been found in localized areas. Olivine has been discovered in the northern hemisphere, in correspondence with Bellicia and Arruntia craters (Ammannito et al., 2013b; Ruesch et al., 2014) (see also Combe et al. (2015b) this issue), while opaque hydrated material, likely associated with carbonaceous chondrite impactors, has been detected in dark units (Jaumann et al., 2012; McCord et al., 2012;

Palomba et al., 2014) and in the region of the Marcia crater (De Sanctis et al., 2015b, De Sanctis et al., 2015a this issue). The VIR spectra of Vesta are characterized by the two pyroxenes bands at 0.9 (band I) and 1.9μm (band II) typical of Fe-bearing pyroxenes (McCord et al., 1970; De Sanctis et al., 2012a). Spectral parameters, such as the band center, reveal lithologies from diogenite to eucrite. The center position of the two bands are associated with iron content (Adams, 1974). A band center shifted toward longer wavelengths is indicative of a higher content of Fe^{2+} and vice versa (Klima et al., 2007, 2011). The depth of a band gives an indication of the abundance of the absorbing minerals, the grain size and the presence of other materials (Clark, 1999). The signature at 2.8-μm is related to the abundance of OH, and reveals the existence of hydrated areas in association with dark material (Jaumann et al., 2012; McCord et al., 2012; De Sanctis et al., 2013; Palomba et al., 2014). A color composite map is very useful in emphasizing spectral slope differences. The spectral slope gives information on the composition and maturity of the soil, and each color indicates a particular terrain type on Vesta's surface (see section 3.2). Lithological variation on Vesta can also be analyzed by application of a spectral linear unmixing algorithm. We select a plausible laboratory spectra sample of Vesta's analogue (called endmembers), we found the best linear combination of these endmembers for each VIR spectrum. This technique allows for identifying the lithologies present in some interesting regions and the relative abundance of each endmember, providing a quantitative information of the abundance of the lithologies on Vesta (for more detail see section 3.5 and Zambon et al., 2015, submitted). All these tools are very useful in performing an in-depth spectral analysis of the two quadrangles.

FIGURE 1

2. Data

Dawn acquired data at different spatial resolution based on the altitude of the spacecraft from the surface (Russell et al., 2007; Russell and Raymond, 2011; Russell et al., 2012, 2013). The mission at Vesta consisted of five principal phases. The mission phases are summarized in Table 1.

VIR is made up of two spectral distinct detectors, or "channels". The visible channel covers the wavelengths ranging between 0.25μm to 1.07μm, and the infrared channel is sensitive from 1.02μm to 5.10μm (De Sanctis et al., 2011). Each channel has 432 bands, which defines the spectral resolution of the two detectors. The average spectral sampling is 1.8 nm/band for the visible channel and 9.8 nm/band for the infrared channel (De Sanctis et al., 2011).

The VIR spectral range allows for a mineralogical and a thermal analysis of Vesta surface. VIR data, in units of calibrated reflectance factor (I/F) from 0.4μm to 3μm, are fundamental for the characterization of the two pyroxene bands, and for analysis of the OH-signature at 2.8μm. Bridging between the two VIR channels is performed in post-processing. A gap in the spectra near 1.1μm is due to the junction between the visible and infrared channels. To reduce the noise, we removed recurrent spikes due to damaged pixels or calibration residuals, and we smoothed the spectra before deriving the spectral parameters. The spectra have been smoothed with a boxcar average of 3 spectral channels (supplementary online material of De Sanctis et al. 2012). The Dawn Framing Camera obtains images through a broad-band clear filter and seven narrow-band filters (center wavelengths in the range 0.4 to 1.0 μm) (Sierks et al., 2011). With these filters color-ratio composite maps have been produced using band ratios similar to those often adopted for Clemetine ratio maps of the Moon (e.g. Pieters et al., 1994).

3. Tools and techniques

For the mineralogical analysis of Av-13 and Av-14, we used several techniques. Below we describe in detail the tools used for our analysis.

3.1. Albedo maps at 1.4μm

Albedo maps have been obtained from FC data that were photometrically corrected with the Akimov disk function (Shkuratov et al., 1999; Eq. (29), Li et al., 2013, Longobardo et al., 2014). Av-13 and Av-14 present large variations in albedo, highlighting localized dark and bright units, principally associated with the ejecta of impact craters. Fig. 2 presents albedo maps at 1.4-μm for both the quadrangles.

FIGURE 2

3.2. Color composite maps

In Fig. 3, color composite maps of Tuccia and Urbinia quadrangles are shown. These maps have been derived from FC data, using red-green-blue (RGB) color assignments similar to those used for the Clementine maps of the Moon: RED = R(0.75μm)/R(0.45μm), GREEN = R(0.75μm)/R(0.92μm), and BLUE = R(0.45μm)/R(0.75μm). These maps highlight regions with differing spectral characteristics (Fig. 3). Many regions have been identified. Yellow areas typically represent high-reflectance material and blue areas indicate low-reflectance material. Red and blue ratios are indicative of the spectral slope. Green areas represent regions with deeper pyroxene absorption bands, and red areas have steeper visible slopes relative to bluer areas. The orange/red regions are those with the steepest visible slopes (Reddy et al., 2012; Le Corre et al., 2013).

FIGURE 3

3.3. Spectral parameters

The spectral parameters that are most useful in analyzing Vesta's mineralogy are band centers and band depths (Figs 4, 5). To derive these, we use the method described in the supplementary material of De Sanctis et al. (2012a) and by Ammannito et al. (2013a). The position of the two pyroxene bands allows for determination of the principal lithologies present on Vesta. A band center at longer wavelengths indicates a larger abundance of eucrite, while a band center at shorter wavelengths highlights a higher content of diogenite. In addition, band depths are useful in determining the abundance of absorbing minerals, the grain size, and the presence of other materials (Clark, 1999). On Vesta, deeper bands are associated with the high-reflectance regions, which represent pristine material (Zambon et al., 2014). Shallower bands have been observed in the presence of dark material (Jaumann et al., 2012; Palomba et al., 2014). In Figs. 4 and 5, band centers and band depth maps of the Av-13 and Av-14 quadrangles are shown. Unlike band centers, band depth values are affected by the illumination and observation geometry, hence a photometric correction is required to allow a proper interpretation. Such a correction has been applied according to the procedure described in Longobardo et al. (2014), which first removes the local topography effects by means of the Akimov disk function (Akimov, 1975; Shkuratov et al., 1999) and then removes the reflectance variations due to the different observation geometry by means of the phase function retrieved by Longobardo et al. (2014). In particular, in this work we consider values corrected to a phase angle of 0°. Band centers do not depend on the photometric conditions, but are a function of the temperature. Large temperature variations lead to significant shift of the band centers (e.g., Roush and Singer, 1986; Hinrichs et al., 1999; Moroz et al., 2000; Hinrichs and Lucey, 2002; Burbine et al., 2009). Vesta's surface temperature, retrieved from VIR infrared data, ranges from 198 to 269K (Tosi et al., 2014). Limiting the analysis only to the period of maximum daily insolation, the average temperatures of bright material (BM) units are between 252 and 265 K with maximum values between 255 and 266K (Tosi et al., 2014). In the present case, the small temperature variation does not substantially affect band center position, and a band center temperature correction is not necessary.

FIGURE 4, 5

3.4. OH distribution maps

VIR spectra of Vesta are characterized by the presence of the OH signature at 2.8-μm. Generally, dark material appears rich in OH and is associated with carbonaceous chondrite (CC) (Jaumann et al., 2012; Palomba et al., 2014), while bright units are OH poor (De Sanctis et al., 2012b; Zambon et al., 2014). Vibrations of OH-cation bonds produce a narrow absorption band centered at 2.8μm. The 2.8μmm band depth measured in VIR spectra (De Sanctis et al., 2012b; Combe et al., 2015a, this issue), is the ratio between the reflectance at the center of the absorption (average in the range 2.7895 - 2.8087μm) and the average reflectance of its shoulders (in the range 2.6476 - 2.6668μmm and 2.9031 - 2.9222μmm respectively). The 2.8μmm band depth data shown in this article make use of the entire VIR infrared dataset from Approach to HAMO-2 (Combe et al., 2015a). In Fig. 6 the band depth maps of the OH signature at 2.8μm for Tuccia and Urbinia quadrangles are shown.

FIGURE 6

3.5. Linear spectral unmixing

Linear spectral unmixing is useful for deriving the principal lithologies of Vesta as well as their relative abundances (Zambon et al. 2015, submitted). Unmixing methods are useful for understanding the composition of a surface (e.g. Pieters and Englert, 1993; Keshava and Mustard, 2002; Bioucas-Dias et al., 2012). Linear mixing assumes that multiple scattering is negligible and the observed spectrum is a linear combination of the spectra of a number of representative endmembers. In this regards, Vesta analogues have been selected, from RELAB database (`http://www.planetary.brown.edu/relabdocs/relab_disclaimer.htm`), considering their spectral characteristics. We selected endmembers with a particle size compatible with that suggested for Vesta ($< 25\mu m$) (Hiroi et al., 1994; Palomba et al., 2014; Zambon et al., 2014). We consider nine plausible endmembers: four eucrite, two diogenite, two olivine, and a straight line which represents a possible featureless component (Table 2). We calculate all the possible combinations of three endmembers chosen from the endmembers sample, and we select the spectrum corresponding to the minimum χ^2. We do not consider spectral slope, which involves nonlinear processes. Hence by excluding this variable from our analysis we reduce the uncertainty due to the application of the linear method. To remove the slope, we find the best-fit line between the first point (0.6μm) and the last point (2.5μm) of the spectrum, then divide the spectrum by this line. To be consistent, the slope was removed from both the VIR and the endmember spectra. Since we do not consider the albedo we use a generic line which represents a generic featureless endmember. Taking in to account the information derived by the albedo map (Schröder et al., 2013), we can infer if the featureless endmember represents a low-reflectance or a high-reflectance featureless phase.

Tests on laboratory mixtures of olivine and low- and high-calcium pyroxene indicate that olivine abundances are underestimated at low olivine abundances, and with an accuracy within 10% for olivine amount $> 50\%$. For plagioclase and low and high calcium pyroxene mixtures, plagioclase content is underestimated within 11% for plagioclase content $> 40\%$, while the CC is overestimated within 26% for CC and Millbillillie mixtures. Further details are presented by Zambon et al. 2015, submitted.

4. Description of the quadrangles

Av-13 and Av-14 are located in the southwest part of Vesta (Tuccia: 180°-270° E; 21°, 66° S, Urbinia: 270°-360° E; 21°, 66° S). These quadrangles contain a diversity of terrain types as well as several features of particular interest. Both Tuccia and Urbinia quadrangles include part of the Rheasilvia basin. The northern region of Av-13 covers part of Vestalia Terra and the Veneneia basin, while Av-14 contains a portion of Oppia's orange ejecta (Le Corre et al. (2013); Tosi et al. (2015) this issue). Urbinia and Tuccia are characterized by substantial topographic relief: the southern parts of the quadrangles, within the Rheasilvia basin, have some of the lowest elevations on Vesta, while the northern parts are home to the Vestalia Terra highlands, the highest areas on the entire asteroid (Jaumann et al., 2012; Frigeri et al., 2015a, this issue). According to the geologic maps of Kneissl et al. (2014) and Mest et al. (2012), Av-13 and Av-14 are dominated by Rheasilvia ridge and groove material (Rrg), as well as Rheasilvia smooth (Rs) material, and bright crater (bc) material. Bright crater ray (bcr) material is among the most widespread of the geological units. Some units of undifferentiated crater material (uc) and undifferentiated lobate (ul) material are also present. In this paper, we focus on the mineralogy of Av-13 and Av-14, investigating if this large variety of geological units corresponds to an equally varied mineralogy. The Tuccia quadrangle and most of the Urbinia quadrangle are characterized by a extensive ridge, similar to Gegania and Lucaria quadrangles (See Longobardo et al. (2015) this issue). Moreover, the vertical structure of the ridge in Av-14 has not been observed in other quadrangles, which suggests a different formation mechanism. Prominent impact craters of the Marcian period (Williams et al., 2014) include the relatively young craters Galeria and Eusebia, showing diffuse ejecta blankets (Kneissl et al., 2014), and the two young craters Vibidia and Antonia (Kneissl et al., 2014).

5. General mineralogy of Av-13 and Av-14

Tuccia and Urbinia quadrangle band centers distribution indicate that these quadrangles are dominated by eucrite-rich howardite, although some localized regions are more diogenitic. From the band center maps shown in Fig. 4, it is possible to derive the mineralogy of these quadrangle. Areas characterized by shorter wavelengths (blue) are more diogenitic, while area dominated by longer wavelengths are more eucritic (red); the yellow regions in the band center maps are howarditic areas. Plots in Fig. 7 show the band centers distribution for the whole quadrangle compared with those of different HED. Mineralogy of the two quadrangle is dominated by howardite and eucrite, although different band centers distribution between the two quadrangle are present. Diogenite has been detected corresponding to the Antonia and Justina craters (see section 7), which is expected based on their location within the Rheasilvia basin. The most diogenitic areas of Vesta (De Sanctis et al., 2012a; Ammannito et al., 2013a; McSween et al., 2013), is contained in these quadrangles. The impacts that formed the Antonia and Justina craters exposed the underlying diogenite observed in their ejecta. Tuccia presents a more heterogeneous mineralogy with respect to Urbinia quadrangle (Fig 7). Lithologies from diogenite-rich howardite to eucrite are present in Tuccia, while Urbinia is principally composed of eucrite-rich howardite and eucrite. In both quadrangles, the band center are compatible with cumulate eucrite, implying different evolution scenarios with respect to basaltic eucrite. Cumulate and basaltic eucrite are generally characterized by a similar composition with a different texture. Despite the compositional analogies the 1 and 2μm bands of the basaltic eucrite are shifted towards longer wavelengths, allowing them to be distinguished from cumulate eucrites (Fig. 7). Cumulate eucrites are similar to gabbros, in that they are formed in deep layers and are thought to have undergone relatively slow crystallization. The basaltic eucrites have been formed near Vesta's surface and cooled relatively quickly (Mittlefehldt et al., 1998; McSween et al., 2011). Plots in Fig. 8 show that reflectance at 1.4μm and band centers are not correlated. A similar distribution between the band centers and the reflectance has been observed, except for the band II center of Av-13, which is widespread, underlining again the larger mineralogical variability of Tuccia quadrangle. The spectral homogeneity of the Av-14 quadrangle is also observed in the band depths, which have lower range variability as shown in Fig. 9. A better correlation between reflectance and band depths has been found, in the case of the Tuccia quadrangle, the correlation index R^2 (0.281 for the band I and 0.341 for the band II) is higher than for the case of Urbinia, where R^2 is close to 0. This is probably due to a lower variability of the band depths with respect to the reflectance. The histogram in Fig. 10 summarize the band depths variability of both the quadrangle, confirming the larger heterogeneity of Av-13 relative to that of Av-14. As expected from the typical spectral profile of pyroxenes, BDI is greater than BDII, with most common values in the range 0.26-0.44 (average value 0.35) for BI and 0.08-0.24 (average value 0.16) for BII in quadrangle

Av-13 Tuccia, and in the range 0.28-0.43 (average value 0.36) for BI and 0.10-0.24 (average value 0.17) for BII in quadrangle Av-14 Urbinia. Furthermore, the BD histograms do not have a gaussian shape, unlike other quadrangles of Vesta (also adjacent to Av-13 and AV-14) where the observed statistics is closer to a Gaussian fit (e.g., Tosi et al., 2015 this issue). Because the band depth values are a function of the reflectance, with bright materials displaying deeper pyroxene bands than dark materials, a non-Gaussian distribution in the band depths reveals that the Tuccia and Urbinia quadrangles present an unbalanced budget between these two categories of materials, unlike other quadrangles where the abundance of bright or dark material may be substantially balanced.

FIGURE 7,8,9,10

The color-ratio composite maps in Fig. 3 exhibit a variety of color units. Yellow areas are associated with high-reflectance crater ejecta, orange corresponds to the Oppia ejecta (see Le Corre et al., 2013; Garry et al., 2014; Tosi et al., 2015, this issue), violet highlights low-reflectance areas, and blue is associated with the ridges. As mentioned above, green intensity is controlled by the strength of band I, while red-to-blue variations correspond with steeper-to-shallower visible spectral slope. Yellow areas are those with a deeper band I, in agreement with the typical behavior of the bright units (De Sanctis et al. (2015a)). The red/orange regions are those with a steeper visible spectral slope, which on the Moon is related to the maturity index of the soil. The blue areas indicate younger terrains. Av-13 and Av-14 quadrangles appear to lack the OH signature, with the exception of the dark area in Veneneia basin and the region corresponding to the orange material in the Urbinia quadrangle (Fig. 6). A relatively strong OH signature is often associated with dark material (Jaumann et al., 2012; Palomba et al., 2014). In Fig. 11 scatter plots of the OH-signature band depth vs 1.4-μm reflectance are shown. A better correlation between reflectance and OH-signature is found for the Tuccia quadrangle than in Urbinia quadrangle. Maps in Fig. 12 indicate that low-reflectance (blue areas) and especially high-reflectance (yellow areas) regions have more differences with the linear model with respect to the intermediate albedo regions.

FIGURE 11,12

We have also assessed surface temperatures within the two quadrangles, seeking to identify areas that have temperatures that are unusually high or low relative to the surroundings. Comparing temperature and incidence angle maps, we can exclude areas for which temperature extremes are directly linked to the illumination conditions from our identified hot and cold regions. Generally, high-reflectance material is colder than low-reflectance material (Tosi et al., 2014). A prominent low temperature area is the bright ejecta from Antonia and Tuccia craters. On Vesta, bright materials have a strong correlation with the temperature with respect to the dark units. They are characterized by a lower thermal emissivity, indicating material that is more consolidated than the dark areas (Tosi et al., 2014).

FIGURE 13

6. Geology and mineralogy

The principal geological units within Tuccia and Urbinia quadrangles are: bright crater material (bc) in the Tuccia quadrangle, which covers the entire strip from Antonia to Eusebia; dark crater material (dc), which corresponds to the Antonia crater; Rheasilvia ridge-and-groove material (Rrg); dark lobate material (dl), which corresponds to the groove in the Urbinia quadrangle; and cratered highland material (ch) (Kneissl et al., 2014; Mest et al., 2012). Mineralogical variation does not always correspond with specific geological units. A correspondence between short band II center and the Rhealsilvia basin is observed in Fig. 14, confirming the presence of diogenite in this region. In general, we cannot associate a particular mineralogy with a specific geological unit, e.g. bright crater ejecta material (bc) has lithologies that range from diogenite to eucrite.

FIGURE 14

7. Main Geological units and other relevant features

Here we describe in detail the principal features present in the Tuccia and Urbinia quadrangles.

Antonia crater. Antonia crater, whose geological characteristics are described by Kneissl et al. (2014), is located in the southern part of the Tuccia quadrangle at 60°S and 200°E with a diameter of approximately 14.8-15.6 km (Kneissl et al., 2014). It is situated inside the Rheasilvia basin close to the lowest elevation region of Vesta, with depths of $\sim$21 km below the reference ellipsoid (Kneissl et al., 2014), while the floor of Antonia itself is approximately 17.6 km below the reference ellipsoid (Kneissl et al., 2014). The Antonia region contains two geological units: bright crater material and dark crater material. As explained by (Kneissl et al., 2014) bc material on the western part of Antonia's crater floor is relatively smooth, and contains high-albedo deposits, partly extending to the crater rim, and partly covered by a strip of dark material moving down-slope. This material is asymmetrical; bright ejecta material of Antonia likely represent pristine surface regolith. Dc material on the eastern part of Antonia's crater floor is rougher and darker than unit bcf. This area is characterized by lobe-shaped margins and lobate linear features on the deposit's surface (Kneissl et al., 2014). The dark material present in this area is likely a mixture of dark material deposited in that region with pristine surface regolith, originally emplaced on the crater wall but subsequently moved downward (Kneissl et al., 2014). The dark strip is likely due to an impact on a steep slope (Krohn et al., 2013).

Antonia is a relatively young crater belonging to the Marcian period (Kneissl et al., 2014; Williams et al., 2014) (Fig. 2). Band centers in the Antonia region, in Tuccia quadrangle, are at shorter wavelengths than in the rest of the quadrangle, revealing a predominantly diogenite-like mineralogy (Fig. 7). Antonia's ejecta blanket has the largest band depth in this quadrangle (Fig. 5). Material present in this area is the freshest in the quadrangle. Antonia ejecta also contains a unique example of OH-poor dark material (Fig. 6). In

Fig. 15 (left) we select areas with different 2.8μm band depths. We compare bright and dark regions in the Antonia crater area with other regions of the Tuccia quadrangle. Plot in Fig. 15 (right) shows the typical trend of the reflectance at 1.4μm as a function of the 2.8μm band depth. The plot confirms that lower-albedo regions correspond with greater 2.8μm band depth (yellow areas inside the Veneneia basin) and vice-versa (bright material in Tuccia, Vibidia and Antonia craters). However an exception is represented by the red area in the dark ejecta of Antonia crater, which is relatively dark with a shallow 2.8μm band depth. The red area has a reflectance variation at 1.4μm between 0.27 and 0.30 which corresponding with a 2.8μm band depth between 0.014 and 0.019. Veneneia basin has the typical behavior of the dark material to low reflectance range variation (0.023-0.025) correspond to 2.8μm band depth larger than the rest of the quadrangles (0.034-0.039). Dark exogenic material on Vesta is interpreted to have been derived from carbonaceous chondritic impactors. The lack of OH signature in these particular dark areas may be due to several reasons: dark impactors poor in OH, evaporated volatiles due to the dynamics of the impact, or endogenic OH-poor dark material. Since dark material on Vesta is generally considered to be exogenic and the Antonia dark material corresponds to crater ejecta, an endogenic origin is unlikely. A linear unmixing model allows for mapping the relative abundances of the principal lithologies. In this region, we found eucrite, diogenite and a large distribution of the featureless component, which can be associated with opaque material. Diogenite exceeds 50% while a concentration of dark material around 35-40% has been found in the dark stripe (red area in Fig. 15). The RGB image in Fig. 16 highlights the combination of the different lithologies modeled; a combination of the featureless component with eucrite emerges from the diogenitic background.

FIGURE 15, 16

Justina ejecta. The ejecta of Justina ejecta is one of the brighter units present in Urbinia quadrangle. Unlike the other bright units present in Urbinia, it has diogenitic ejecta. The linear unmixing map in Fig. 17 and band center maps in Fig. 4 show the distribution of diogenite in a part of the ejecta; moreover, a quite homogeneous distribution of featureless material, with abundances $\sim 10\%$, is present in all these areas.

FIGURE 17

Ridge crest. A large distribution of ridges are present in Tuccia, especially in Urbinia quadrangle (see geological map in Fig. 14). These structures formed as a result of the Rheasilvia impact, and are present also in other quadrangles, in particular in Lucaria and Gegania and in Pinaria (see Longobardo et al., 2015; McFadden et al., 2015, this issue). Unlike the Lucaria and Gegania ridges, the Tuccia and Urbinia ridges are vertical and shorter, but in both cases they do not show large variation in composition with respect to their surroundings. Differences have been detected in the color-ratio composite maps (Fig. 3, Longobardo et al., 2015, this issue): the ridge are blue, indicating less maturity of the soil in the crest with respect to the valley, which is compatible with the ridge formation. Longobardo et al. (2015), this issue, observed that ridges in Gegania and Lucaria quadrangle have more diogenitic composition, even if this is not observed in our quadrangle. Maps in Fig. 4 do not show any band centers variation in correspondence with the ridge, indicating that they are not related to a mineralogical variation with respect to surrounding regions.

8. Conclusion

Although Tuccia and Urbinia quadrangles contain a variety of geological units, analysis of VIR data does not reveal an association between mineralogy and the specific units. We found only a connection between the Rheasilvia basin and diogenitic composition, as expected from prior work. The mineralogy of these two quadrangles is different: in Urbinia we found principally eucrite-rich howardite, whereas in Tuccia all the lithologies are represented. The range of variation for pyroxene band I is quite similar for the two quadrangles, while band II depth for the Tuccia quadrangle shows a wider interval with respect to the range found in the Urbinia quadrangle (see, Fig. 5 and Fig. 6). This could be related to the varied mineralogy of Tuccia. Tuccia and Urbinia are also poor in OH, with some exceptions for the Oppia ejecta in Av-13 areas and parts of the Veneneia basin in Av-14. Dark ejecta in Antonia exhibits peculiar behavior with respect to the other dark ejecta on Vesta. The Antonia dark ejecta, in fact, poor in OH, implying an OH-poor impactor or a different dynamic of the impact. One of the principal features of these quadrangle are the vertical ridges, which are largely distributed. The ridges appear blue in the color-ratio composite map, and are consistent with the presence of less mature soil, while no mineralogical variation have been observed for these areas.

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Figure captions

Figure 1: Vesta's surface divided into quadrangles. Tuccia (Av-13) and Urbinia (Av-14) quadrangle are indicated in the red rectangle.

Figure 2: VIR maps at 1.4μm of Tuccia (top) and Urbinia (bottom) quadrangles. The data are photometrically corrected by Akimov method.

Figure 3: Color composite map of obtained from FC data using the following color combination: RED = R(0.75)/R(0.45), GREEN = R(0.75)/R(0.92), and BLUE = R(0.45)/R(0.75).

Figure 4: Band centers maps of Tuccia and Urbinia quadrangles. Shorter wavelengths (blue) indicate a larger diogenite content, longer wavelengths

(red) indicate eucrite-rich areas, while yellow regions are associated with howardite.

Figure 5: Band depth maps of Tuccia and Urbinia quadrangles. Band depth are photometrically corrected using the value of the Akimov disk function for i=0°, e=0°, ϕ=0° (Longobardo et al., 2014).

Figure 6: Band depth map of the OH-signature at 2.8μm for Av-13 Tuccia (top) and Av-14 Urbinia (bottom).

Figure 7: Band centers distribution of Tuccia (left) and Urbinia (right) quadrangle compared with those of different HED meteorites. The red rectangle indicates the diogenite region, green corresponds to howardite, and blue encloses the eucrite region.

Figure 8: Plots showing the relationship between band centers and reflectance at 1.4μm. Red line represent the best fit.

Figure 9: Analogous plots to Fig. 8 for the bands depths. Red line represent the best fit. Green points refer to band II depth, while black points to band I depth.

Figure 10: Histograms illustrating the frequency of the band I depth and band II depth (hereafter BDI and BDII) values measured across the Tuccia and Urbinia quadrangle, sampled with a 0.01 bin width.

Figure 11: Plots show the relation between the reflectance at 1.4-μm and the depth of the OH-signature at 2.8-μm. Red line represent the best fit, the blue dots refer to the measured values of the whole maps. The small $R^2$and large χ^2 values indicates that a linear model is not appropriate, even if a better correlation is observed for the quad Av13.

Figure 12: Ratio between the measured reflectance at 1.4μm and the 1.4μm/2.8μm linear fit model. The maps highlight the difference between the measured reflectance and the linear model. Dark blue areas are OH-poor regions, green color represent less hydrated areas than average units of the same reflectance, while red/yellow region represent more hydrated areas. A perfect anti-correlation between reflectance at 1.4μm and the 2.8μm signature would be represented in gray.

Figure 13: Temperatures map of Tuccia (left) and Urbinia (right) quadrangle compared with the corresponding incidence angle maps and the albedo maps previously shown in Fig. 2. Red circles indicate the region in which temperature is affected by instantaneous illumination condition.

Figure 14: Comparison between Tuccia (top) and Urbinia band II center map with the corresponding geological maps derived by Kneissl et al. (2014) and Mest et al. (2012) respectively.

Figure 15: 2.8 μm band depth distribution for the Antonia crater area within Tuccia quadrangle, compared with other regions. Red and green areas contain portions of the dark ejecta Antonia crater, while the blue region the bright one. The cyan region corresponds to Tuccia's proximal ejecta, the magenta region is Vibidia ejecta, and the yellow area is the Veneneia basin.

Figure 16: Results of linear unmixing for Antonia region. The panels show the abundances and the distribution of the single lithologies found in this areas. χ^2 is an indication of the quality of the results.

Figure 17: Panel analogous to that shown in Fig. 16 for Justina area.

Table 1: Characteristics of Dawn's principal mission phases at Vesta.

Table 2: Spectral characteristics of the endmembers selected for the linear spectral unmixing. **References**

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