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

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Abstract

The Av-13 (Tuccia) and Av-14 (Urbina) 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 (Rheasil-

28 via basin). Many geological units in these quadrangle are not associated with
 29 mineralogical variability, as shown by the color-composite maps. Maps of
 30 mafic absorption band-center position reveal that the principal lithology is
 31 eucrite-rich howardite, but diogenite-rich howardite areas also are present,
 32 corresponding to particular features such as Antonia and Justina craters,
 33 which are also characterized by strong mafic absorptions. These quadran-
 34 gles, especially Urbinia, are characterized by many bright ejecta, such as
 35 those of Tuccia crater, which are the highest reflectance materials on Vesta
 36 (Zambon et al., 2014). Dark areas are also present and correspond with
 37 regions with deeper OH-signature. The two quadrangle also contain many
 38 vertical ridge crests associated with the Rheasilvia impact. These ridges do
 39 not show mineralogical differences with respect to their surroundings, but
 40 have a distinctive appearance in color-ratio composite images.

41 **1. Introduction**

42 Vesta, the second most massive body in the main asteroid belt (Thomas
 43 et al., 1997; Zuber et al., 2011), can be considered a relic of the protoplan-
 44 etary disk, revealing the history of the early solar system (Coradini et al.,
 45 2011). Dawn, the NASA discovery mission devoted to the study of Vesta

46 and Ceres, covered a large part of Vesta’s surface during the orbital phase.
 47 Dawn has three instruments: the Framing Camera (FC), the Visible and
 48 InfraRed Spectrometer (VIR), and the Gamma Ray and Neutron Detector
 49 (GRaND) (Sierks et al., 2011; De Sanctis et al., 2011; Prettyman et al., 2011).
 50 Before the arrival of Dawn, Vesta’s surface was divided into fifteen quadran-
 51 gles which were later named for their respective individual features (Fig.
 52 1) (Russell and Raymond, 2011). For each quadrangle geological (Williams
 53 et al., 2014) and mineralogical maps (Frigeri et al. (2015b) this special is-
 54 sue) have been produced. In this paper, we discuss the mineralogy of two
 55 contiguous quadrangles, Av-13 (Tuccia) and Av-14 (Urbina), located in the
 56 southern hemisphere (Fig. 1). These quadrangles contain several geological
 57 units, and part of the Rheasilvia basin (McSween et al. (2013); Ammannito
 58 et al. (2015), this issue), the Vestal Terra highlands (Frigeri et al., 2015a),
 59 and enigmatic ”orange” materials (Le Corre et al., 2011; Garry et al., 2014;
 60 Tosi et al., 2015, this issue). Moreover Av-13 and Av-14 contain numerous
 61 ridges and grooves also present in other quadrangles (see Longobardo et al.,
 62 2015; McFadden et al., 2015). Kneissl et al. (2014) and Mest et al. (2012)
 63 performed the geological analysis of the quadrangles mapping a variety of
 64 geological units. In this paper, we analyzed the general mineralogy of the

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

84 Palomba et al., 2014) and in the region of the Marcia crater (De Sanctis
 85 et al., 2015b, De Sanctis et al., 2015a this issue). The VIR spectra of Vesta
 86 are characterized by the two pyroxenes bands at 0.9 (band I) and $1.9\mu\text{m}$
 87 (band II) typical of Fe-bearing pyroxenes (McCord et al., 1970; De Sanctis
 88 et al., 2012a). Spectral parameters, such as the band center, reveal lithologies
 89 from diogenite to eucrite. The center position of the two bands are associ-
 90 ated with iron content (Adams, 1974). A band center shifted toward longer
 91 wavelengths is indicative of a higher content of Fe^{2+} and vice versa (Klima
 92 et al., 2007, 2011). The depth of a band gives an indication of the abundance
 93 of the absorbing minerals, the grain size and the presence of other materials
 94 (Clark, 1999). The signature at $2.8\text{-}\mu\text{m}$ is related to the abundance of OH,
 95 and reveals the existence of hydrated areas in association with dark material
 96 (Jaumann et al., 2012; McCord et al., 2012; De Sanctis et al., 2013; Palomba
 97 et al., 2014). A color composite map is very useful in emphasizing spectral
 98 slope differences. The spectral slope gives information on the composition
 99 and maturity of the soil, and each color indicates a particular terrain type on
 100 Vesta’s surface (see section 3.2). Lithological variation on Vesta can also be
 101 analyzed by application of a spectral linear unmixing algorithm. We select
 102 a plausible laboratory spectra sample of Vesta’s analogue (called endmem-

bers), 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 $0.25\mu\text{m}$ to $1.07\mu\text{m}$, and the infrared channel is sensitive from $1.02\mu\text{m}$ to $5.10\mu\text{m}$ (De Sanctis et al., 2011). Each channel has 432 bands, which defines the spectral resolution of the two

121 detectors. The average spectral sampling is 1.8 nm/band for the visible
122 channel and 9.8 nm/band for the infrared channel (De Sanctis et al., 2011).

123 The VIR spectral range allows for a mineralogical and a thermal analysis
124 of Vesta surface. VIR data, in units of calibrated reflectance factor (I/F) from
125 $0.4\mu\text{m}$ to $3\mu\text{m}$, are fundamental for the characterization of the two pyroxene
126 bands, and for analysis of the OH-signature at $2.8\mu\text{m}$. Bridging between
127 the two VIR channels is performed in post-processing. A gap in the spectra
128 near $1.1\mu\text{m}$ is due to the junction between the visible and infrared channels.
129 To reduce the noise, we removed recurrent spikes due to damaged pixels
130 or calibration residuals, and we smoothed the spectra before deriving the
131 spectral parameters. The spectra have been smoothed with a boxcar average
132 of 3 spectral channels (supplementary online material of De Sanctis et al.
133 2012). The Dawn Framing Camera obtains images through a broad-band
134 clear filter and seven narrow-band filters (center wavelengths in the range
135 0.4 to $1.0\mu\text{m}$) (Sierks et al., 2011). With these filters color-ratio composite
136 maps have been produced using band ratios similar to those often adopted
137 for Clementine ratio maps of the Moon (e.g. Pieters et al., 1994).

138 3. Tools and techniques

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

141 3.1. Albedo maps at $1.4\mu\text{m}$

142 Albedo maps have been obtained from FC data that were photometrically
143 corrected with the Akimov disk function (Shkuratov et al., 1999; Eq. (29),
144 Li et al., 2013, Longobardo et al., 2014). Av-13 and Av-14 present large
145 variations in albedo, highlighting localized dark and bright units, principally
146 associated with the ejecta of impact craters. Fig. 2 presents albedo maps at
147 $1.4\text{-}\mu\text{m}$ for both the quadrangles.

148 FIGURE 2

149

150 3.2. Color composite maps

151 In Fig. 3, color composite maps of Tuccia and Urbinia quadrangles are
152 shown. These maps have been derived from FC data, using red-green-blue
153 (RGB) color assignments similar to those used for the Clementine maps of the
154 Moon: $\text{RED} = R(0.75\mu\text{m})/R(0.45\mu\text{m})$, $\text{GREEN} = R(0.75\mu\text{m})/R(0.92\mu\text{m})$,

155 and $\text{BLUE} = R(0.45\mu\text{m})/R(0.75\mu\text{m})$. These maps highlight regions with dif-
 156 fering spectral characteristics (Fig. 3). Many regions have been identified.
 157 Yellow areas typically represent high-reflectance material and blue areas in-
 158 dicate low-reflectance material. Red and blue ratios are indicative of the
 159 spectral slope. Green areas represent regions with deeper pyroxene absorp-
 160 tion bands, and red areas have steeper visible slopes relative to bluer areas.
 161 The orange/red regions are those with the steepest visible slopes (Reddy
 162 et al., 2012; Le Corre et al., 2013).

163 FIGURE 3

165 3.3. Spectral parameters

166 The spectral parameters that are most useful in analyzing Vesta’s min-
 167 eralogy are band centers and band depths (Figs 4, 5). To derive these, we
 168 use the method described in the supplementary material of De Sanctis et al.
 169 (2012a) and by Ammannito et al. (2013a). The position of the two pyrox-
 170 ene bands allows for determination of the principal lithologies present on
 171 Vesta. A band center at longer wavelengths indicates a larger abundance
 172 of eucrite, while a band center at shorter wavelengths highlights a higher
 173 content of diogenite. In addition, band depths are useful in determining the

174 abundance of absorbing minerals, the grain size, and the presence of other
175 materials (Clark, 1999). On Vesta, deeper bands are associated with the
176 high-reflectance regions, which represent pristine material (Zambon et al.,
177 2014). Shallower bands have been observed in the presence of dark material
178 (Jaumann et al., 2012; Palomba et al., 2014). In Figs. 4 and 5, band cen-
179 ters and band depth maps of the Av-13 and Av-14 quadrangles are shown.
180 Unlike band centers, band depth values are affected by the illumination and
181 observation geometry, hence a photometric correction is required to allow a
182 proper interpretation. Such a correction has been applied according to the
183 procedure described in Longobardo et al. (2014), which first removes the lo-
184 cal topography effects by means of the Akimov disk function (Akimov, 1975;
185 Shkuratov et al., 1999) and then removes the reflectance variations due to
186 the different observation geometry by means of the phase function retrieved
187 by Longobardo et al. (2014). In particular, in this work we consider values
188 corrected to a phase angle of 0° . Band centers do not depend on the photo-
189 metric conditions, but are a function of the temperature. Large temperature
190 variations lead to significant shift of the band centers (e.g., Roush and Singer,
191 1986; Hinrichs et al., 1999; Moroz et al., 2000; Hinrichs and Lucey, 2002; Bur-
192 bine et al., 2009). Vesta’s surface temperature, retrieved from VIR infrared

193 data, ranges from 198 to 269K (Tosi et al., 2014). Limiting the analysis
 194 only to the period of maximum daily insolation, the average temperatures of
 195 bright material (BM) units are between 252 and 265 K with maximum val-
 196 ues between 255 and 266K (Tosi et al., 2014). In the present case, the small
 197 temperature variation does not substantially affect band center position, and
 198 a band center temperature correction is not necessary.

199 FIGURE 4, 5

200

201 3.4. OH distribution maps

202 VIR spectra of Vesta are characterized by the presence of the OH signa-
 203 ture at 2.8- μ m. Generally, dark material appears rich in OH and is associated
 204 with carbonaceous chondrite (CC) (Jaumann et al., 2012; Palomba et al.,
 205 2014), while bright units are OH poor (De Sanctis et al., 2012b; Zambon
 206 et al., 2014). Vibrations of OH-cation bonds produce a narrow absorption
 207 band centered at 2.8 μ m. The 2.8 μ mm band depth measured in VIR spectra
 208 (De Sanctis et al., 2012b; Combe et al., 2015a, this issue), is the ratio between
 209 the reflectance at the center of the absorption (average in the range 2.7895 -
 210 2.8087 μ m) and the average reflectance of its shoulders (in the range 2.6476 -
 211 2.6668 μ mm and 2.9031 - 2.9222 μ mm respectively). The 2.8 μ mm band depth

212 data shown in this article make use of the entire VIR infrared dataset from
213 Approach to HAMO-2 (Combe et al., 2015a). In Fig. 6 the band depth maps
214 of the OH signature at $2.8\mu\text{m}$ for Tuccia and Urbinia quadrangles are shown.

215 FIGURE 6

216

217 3.5. *Linear spectral unmixing*

218 Linear spectral unmixing is useful for deriving the principal lithologies
219 of Vesta as well as their relative abundances (Zambon et al. 2015, sub-
220 mitted). Unmixing methods are useful for understanding the composition
221 of a surface (e.g. Pieters and Englert, 1993; Keshava and Mustard, 2002;
222 Bioucas-Dias et al., 2012). Linear mixing assumes that multiple scattering is
223 negligible and the observed spectrum is a linear combination of the spectra
224 of a number of representative endmembers. In this regards, Vesta analogues
225 have been selected, from RELAB database ([http://www.planetary.brown.](http://www.planetary.brown.edu/relabdocs/relab_disclaimer.htm)
226 [edu/relabdocs/relab_disclaimer.htm](http://www.planetary.brown.edu/relabdocs/relab_disclaimer.htm)), considering their spectral charac-
227 teristics. We selected endmembers with a particle size compatible with that
228 suggested for Vesta ($< 25\mu\text{m}$) (Hiroi et al., 1994; Palomba et al., 2014; Zam-
229 bon et al., 2014). We consider nine plausible endmembers: four eucrite, two
230 diogenite, two olivine, and a straight line which represents a possible fea-

231 tureless component (Table 2). We calculate all the possible combinations of
 232 three endmembers chosen from the endmembers sample, and we select the
 233 spectrum corresponding to the minimum χ^2 . We do not consider spectral
 234 slope, which involves nonlinear processes. Hence by excluding this variable
 235 from our analysis we reduce the uncertainty due to the application of the
 236 linear method. To remove the slope, we find the best-fit line between the
 237 first point ($0.6\mu\text{m}$) and the last point ($2.5\mu\text{m}$) of the spectrum, then divide
 238 the spectrum by this line. To be consistent, the slope was removed from both
 239 the VIR and the endmember spectra. Since we do not consider the albedo we
 240 use a generic line which represents a generic featureless endmember. Taking
 241 in to account the information derived by the albedo map (Schröder et al.,
 242 2013), we can infer if the featureless endmember represents a low-reflectance
 243 or a high-reflectance featureless phase.

244 Tests on laboratory mixtures of olivine and low- and high-calcium pyroxene
 245 indicate that olivine abundances are underestimated at low olivine abun-
 246 dances, and with an accuracy within 10% for olivine amount $> 50\%$. For
 247 plagioclase and low and high calcium pyroxene mixtures, plagioclase content
 248 is underestimated within 11% for plagioclase content $> 40\%$, while the CC is
 249 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

268 material (uc) and undifferentiated lobate (ul) material are also present. In
 269 this paper, we focus on the mineralogy of Av-13 and Av-14, investigating if
 270 this large variety of geological units corresponds to an equally varied miner-
 271 alogy. The Tuccia quadrangle and most of the Urbinia quadrangle are char-
 272 acterized by a extensive ridge, similar to Gegania and Lucaria quadrangles
 273 (See Longobardo et al. (2015) this issue). Moreover, the vertical structure
 274 of the ridge in Av-14 has not been observed in other quadrangles, which
 275 suggests a different formation mechanism. Prominent impact craters of the
 276 Marcian period (Williams et al., 2014) include the relatively young craters
 277 Galeria and Eusebia, showing diffuse ejecta blankets (Kneissl et al., 2014),
 278 and the two young craters Vibidia and Antonia (Kneissl et al., 2014).

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

280 Tuccia and Urbinia quadrangle band centers distribution indicate that
 281 these quadrangles are dominated by eucrite-rich howardite, although some
 282 localized regions are more diogenitic. From the band center maps shown in
 283 Fig. 4, it is possible to derive the mineralogy of these quadrangle. Areas
 284 characterized by shorter wavelengths (blue) are more diogenitic, while area
 285 dominated by longer wavelengths are more eucritic (red); the yellow regions

286 in the band center maps are howarditic areas. Plots in Fig. 7 show the band
 287 centers distribution for the whole quadrangle compared with those of differ-
 288 ent HED. Mineralogy of the two quadrangle is dominated by howardite and
 289 eucrite, although different band centers distribution between the two quad-
 290 rangle are present. Diogenite has been detected corresponding to the Antonia
 291 and Justina craters (see section 7), which is expected based on their location
 292 within the Rheasilvia basin. The most diogenitic areas of Vesta (De Sanctis
 293 et al., 2012a; Ammannito et al., 2013a; McSween et al., 2013), is contained in
 294 these quadrangles. The impacts that formed the Antonia and Justina craters
 295 exposed the underlying diogenite observed in their ejecta. Tuccia presents a
 296 more heterogeneous mineralogy with respect to Urbinia quadrangle (Fig 7).
 297 Lithologies from diogenite-rich howardite to eucrite are present in Tuccia,
 298 while Urbinia is principally composed of eucrite-rich howardite and eucrite.
 299 In both quadrangles, the band center are compatible with cumulate eucrite,
 300 implying different evolution scenarios with respect to basaltic eucrite. Cumu-
 301 late and basaltic eucrite are generally characterized by a similar composition
 302 with a different texture. Despite the compositional analogies the 1 and $2\mu\text{m}$
 303 bands of the basaltic eucrite are shifted towards longer wavelengths, allowing
 304 them to be distinguished from cumulate eucrites (Fig. 7). Cumulate eucrites

305 are similar to gabbros, in that they are formed in deep layers and are thought
 306 to have undergone relatively slow crystallization. The basaltic eucrites have
 307 been formed near Vesta's surface and cooled relatively quickly (Mittlefehldt
 308 et al., 1998; McSween et al., 2011). Plots in Fig. 8 show that reflectance
 309 at $1.4\mu\text{m}$ and band centers are not correlated. A similar distribution be-
 310 tween the band centers and the reflectance has been observed, except for the
 311 band II center of Av-13, which is widespread, underlining again the larger
 312 mineralogical variability of Tuccia quadrangle. The spectral homogeneity of
 313 the Av-14 quadrangle is also observed in the band depths, which have lower
 314 range variability as shown in Fig. 9. A better correlation between reflectance
 315 and band depths has been found, in the case of the Tuccia quadrangle, the
 316 correlation index R^2 (0.281 for the band I and 0.341 for the band II) is higher
 317 than for the case of Urbinia, where R^2 is close to 0. This is probably due to
 318 a lower variability of the band depths with respect to the reflectance. The
 319 histogram in Fig. 10 summarize the band depths variability of both the
 320 quadrangle, confirming the larger heterogeneity of Av-13 relative to that of
 321 Av-14. As expected from the typical spectral profile of pyroxenes, BDI is
 322 greater than BDII, with most common values in the range 0.26-0.44 (average
 323 value 0.35) for BI and 0.08-0.24 (average value 0.16) for BII in quadrangle

324 Av-13 Tuccia, and in the range 0.28-0.43 (average value 0.36) for BI and 0.10-
 325 0.24 (average value 0.17) for BII in quadrangle Av-14 Urbinia. Furthermore,
 326 the BD histograms do not have a gaussian shape, unlike other quadrangles
 327 of Vesta (also adjacent to Av-13 and AV-14) where the observed statistics
 328 is closer to a Gaussian fit (e.g., Tosi et al., 2015 this issue). Because the
 329 band depth values are a function of the reflectance, with bright materials
 330 displaying deeper pyroxene bands than dark materials, a non-Gaussian dis-
 331 tribution in the band depths reveals that the Tuccia and Urbinia quadrangles
 332 present an unbalanced budget between these two categories of materials, un-
 333 like other quadrangles where the abundance of bright or dark material may
 334 be substantially balanced.

335 FIGURE 7,8,9,10

336
 337 The color-ratio composite maps in Fig. 3 exhibit a variety of color units.
 338 Yellow areas are associated with high-reflectance crater ejecta, orange corre-
 339 sponds to the Oppia ejecta (see Le Corre et al., 2013; Garry et al., 2014; Tosi
 340 et al., 2015, this issue), violet highlights low-reflectance areas, and blue is as-
 341 sociated with the ridges. As mentioned above, green intensity is controlled by
 342 the strength of band I, while red-to-blue variations correspond with steeper-

343 to-shallower visible spectral slope. Yellow areas are those with a deeper band
 344 I, in agreement with the typical behavior of the bright units (De Sanctis et al.
 345 (2015a)). The red/orange regions are those with a steeper visible spectral
 346 slope, which on the Moon is related to the maturity index of the soil. The
 347 blue areas indicate younger terrains. Av-13 and Av-14 quadrangles appear
 348 to lack the OH signature, with the exception of the dark area in Veneneia
 349 basin and the region corresponding to the orange material in the Urbinia
 350 quadrangle (Fig. 6). A relatively strong OH signature is often associated
 351 with dark material (Jaumann et al., 2012; Palomba et al., 2014). In Fig.
 352 11 scatter plots of the OH-signature band depth vs $1.4\text{-}\mu\text{m}$ reflectance are
 353 shown. A better correlation between reflectance and OH-signature is found
 354 for the Tuccia quadrangle than in Urbinia quadrangle. Maps in Fig. 12 indi-
 355 cate that low-reflectance (blue areas) and especially high-reflectance (yellow
 356 areas) regions have more differences with the linear model with respect to
 357 the intermediate albedo regions.

358 FIGURE 11,12

359

360 We have also assessed surface temperatures within the two quadrangles,
 361 seeking to identify areas that have temperatures that are unusually high

362 or low relative to the surroundings. Comparing temperature and incidence
 363 angle maps, we can exclude areas for which temperature extremes are directly
 364 linked to the illumination conditions from our identified hot and cold regions.
 365 Generally, high-reflectance material is colder than low-reflectance material
 366 (Tosi et al., 2014). A prominent low temperature area is the bright ejecta
 367 from Antonia and Tuccia craters. On Vesta, bright materials have a strong
 368 correlation with the temperature with respect to the dark units. They are
 369 characterized by a lower thermal emissivity, indicating material that is more
 370 consolidated than the dark areas (Tosi et al., 2014).

371 **FIGURE 13**

372 **6. Geology and mineralogy**

373 The principal geological units within Tuccia and Urbinia quadrangles
 374 are: bright crater material (bc) in the Tuccia quadrangle, which covers the
 375 entire strip from Antonia to Eusebia; dark crater material (dc), which cor-
 376 responds to the Antonia crater; Rheasilvia ridge-and-groove material (Rrg);
 377 dark lobate material (dl), which corresponds to the groove in the Urbinia
 378 quadrangle; and cratered highland material (ch) (Kneissl et al., 2014; Mest
 379 et al., 2012). Mineralogical variation does not always correspond with spe-

380 cific geological units. A correspondence between short band II center and the
 381 Rheasilvia basin is observed in Fig. 14, confirming the presence of diogenite
 382 in this region. In general, we cannot associate a particular mineralogy with a
 383 specific geological unit, e.g. bright crater ejecta material (bc) has lithologies
 384 that range from diogenite to eucrite.

385 FIGURE 14

386

387 **7. Main Geological units and other relevant features**

388 Here we describe in detail the principal features present in the Tuccia and
 389 Urbina quadrangles.

390 *Antonia crater.* Antonia crater, whose geological characteristics are de-
 391 scribed by Kneissl et al. (2014), is located in the southern part of the Tuccia
 392 quadrangle at 60°S and 200°E with a diameter of approximately 14.8-15.6
 393 km (Kneissl et al., 2014). It is situated inside the Rheasilvia basin close
 394 to the lowest elevation region of Vesta, with depths of ~ 21 km below the
 395 reference ellipsoid (Kneissl et al., 2014), while the floor of Antonia itself is
 396 approximately 17.6 km below the reference ellipsoid (Kneissl et al., 2014).
 397 The Antonia region contains two geological units: bright crater material and

398 dark crater material. As explained by (Kneissl et al., 2014) bc material on the
399 western part of Antonia’s crater floor is relatively smooth, and contains high-
400 albedo deposits, partly extending to the crater rim, and partly covered by
401 a strip of dark material moving down-slope. This material is asymmetrical;
402 bright ejecta material of Antonia likely represent pristine surface regolith. Dc
403 material on the eastern part of Antonia’s crater floor is rougher and darker
404 than unit bcf. This area is characterized by lobe-shaped margins and lobate
405 linear features on the deposit’s surface (Kneissl et al., 2014). The dark mate-
406 rial present in this area is likely a mixture of dark material deposited in that
407 region with pristine surface regolith, originally emplaced on the crater wall
408 but subsequently moved downward (Kneissl et al., 2014). The dark strip is
409 likely due to an impact on a steep slope (Krohn et al., 2013).

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

417 Fig. 15 (left) we select areas with different $2.8\mu\text{m}$ band depths. We compare
 418 bright and dark regions in the Antonia crater area with other regions of the
 419 Tuccia quadrangle. Plot in Fig. 15 (right) shows the typical trend of the
 420 reflectance at $1.4\mu\text{m}$ as a function of the $2.8\mu\text{m}$ band depth. The plot con-
 421 firms that lower-albedo regions correspond with greater $2.8\mu\text{m}$ band depth
 422 (yellow areas inside the Veneneia basin) and vice-versa (bright material in
 423 Tuccia, Vibidia and Antonia craters). However an exception is represented
 424 by the red area in the dark ejecta of Antonia crater, which is relatively dark
 425 with a shallow $2.8\mu\text{m}$ band depth. The red area has a reflectance variation
 426 at $1.4\mu\text{m}$ between 0.27 and 0.30 which corresponding with a $2.8\mu\text{m}$ band
 427 depth between 0.014 and 0.019. Veneneia basin has the typical behavior of
 428 the dark material to low reflectance range variation (0.023-0.025) correspond
 429 to $2.8\mu\text{m}$ band depth larger than the rest of the quadrangles (0.034-0.039).
 430 Dark exogenic material on Vesta is interpreted to have been derived from
 431 carbonaceous chondritic impactors. The lack of OH signature in these par-
 432 ticular dark areas may be due to several reasons: dark impactors poor in
 433 OH, evaporated volatiles due to the dynamics of the impact, or endogenic
 434 OH-poor dark material. Since dark material on Vesta is generally considered
 435 to be exogenic and the Antonia dark material corresponds to crater ejecta,

436 an endogenic origin is unlikely. A linear unmixing model allows for map-
437 ping the relative abundances of the principal lithologies. In this region, we
438 found eucrite, diogenite and a large distribution of the featureless compo-
439 nent, which can be associated with opaque material. Diogenite exceeds 50%
440 while a concentration of dark material around 35-40% has been found in the
441 dark stripe (red area in Fig. 15). The RGB image in Fig. 16 highlights
442 the combination of the different lithologies modeled; a combination of the
443 featureless component with eucrite emerges from the diogenitic background.

444 FIGURE 15, 16

445 *Justina ejecta*. The ejecta of Justina ejecta is one of the brighter units present
446 in Urbinia quadrangle. Unlike the other bright units present in Urbinia, it has
447 diogenitic ejecta. The linear unmixing map in Fig. 17 and band center maps
448 in Fig. 4 show the distribution of diogenite in a part of the ejecta; moreover,
449 a quite homogeneous distribution of featureless material, with abundances
450 $\sim 10\%$, is present in all these areas.

451 FIGURE 17

452

453 *Ridge crest*. A large distribution of ridges are present in Tuccia, especially
454 in Urbinia quadrangle (see geological map in Fig. 14). These structures

455 formed as a result of the Rheasilvia impact, and are present also in other
456 quadrangles, in particular in Lucaria and Gegania and in Pinaria (see Lon-
457 gobardo et al., 2015; McFadden et al., 2015, this issue). Unlike the Lucaria
458 and Gegania ridges, the Tuccia and Urbinia ridges are vertical and shorter,
459 but in both cases they do not show large variation in composition with re-
460 spect to their surroundings. Differences have been detected in the color-ratio
461 composite maps (Fig. 3, Longobardo et al., 2015, this issue): the ridge are
462 blue, indicating less maturity of the soil in the crest with respect to the valley,
463 which is compatible with the ridge formation. Longobardo et al. (2015), this
464 issue, observed that ridges in Gegania and Lucaria quadrangle have more
465 diagenetic composition, even if this is not observed in our quadrangle. Maps
466 in Fig. 4 do not show any band centers variation in correspondence with the
467 ridge, indicating that they are not related to a mineralogical variation with
468 respect to surrounding regions.

469 8. Conclusion

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

488 observed for these areas.

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495 **Figure captions**

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

498 **Figure 2:** VIR maps at $1.4\mu\text{m}$ of Tuccia (top) and Urbinia (bottom) quad-
499 rangles. The data are photometrically corrected by Akimov method.

500 **Figure 3:** Color composite map of obtained from FC data using the follow-
501 ing color combination: RED = $R(0.75)/R(0.45)$, GREEN = $R(0.75)/R(0.92)$,
502 and BLUE = $R(0.45)/R(0.75)$.

503 **Figure 4:** Band centers maps of Tuccia and Urbinia quadrangles. Shorter
504 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 $i=0^\circ$, $e=0^\circ$, $\phi=0^\circ$ (Longobardo et al., 2014).

Figure 6: Band depth map of the OH-signature at $2.8\mu\text{m}$ 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 $1.4\mu\text{m}$. 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.

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

529 **Figure 12:** Ratio between the measured reflectance at $1.4\mu\text{m}$ and the $1.4\mu\text{m}/2.8\mu\text{m}$
 530 linear fit model. The maps highlight the difference between the measured
 531 reflectance and the linear model. Dark blue areas are OH-poor regions,
 532 green color represent less hydrated areas than average units of the same
 533 reflectance, while red/yellow region represent more hydrated areas. A per-
 534 fect anti-correlation between reflectance at $1.4\mu\text{m}$ and the $2.8\mu\text{m}$ signature
 535 would be represented in gray.

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

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

543 **Figure 15:** 2.8 μm band depth distribution for the Antonia crater area
 544 within Tuccia quadrangle, compared with other regions. Red and green ar-
 545 eas contain portions of the dark ejecta Antonia crater, while the blue region
 546 the bright one. The cyan region corresponds to Tuccia’s proximal ejecta, the
 547 magenta region is Vibidia ejecta, and the yellow area is the Veneneia basin.

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

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

552 **Table 1:** Characteristics of Dawn’s principal mission phases at Vesta.

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

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