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

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24 **Abstract**

25 The Av-13 (Tuccia) and Av-14 (Urbinia) quadrangles are located in the
26 south-west region of Vesta. They are characterized by a large topographic
27 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 quadrangles
51 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 μ 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- μ 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: RED = $R(0.75\mu\text{m})/R(0.45\mu\text{m})$, GREEN = $R(0.75\mu\text{m})/R(0.92\mu\text{m})$,

155 and 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

164

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- μm . 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 μm . The 2.8 μmm 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 μm) and the average reflectance of its shoulders (in the range 2.6476 -
211 2.6668 μmm and 2.9031 - 2.9222 μmm respectively). The 2.8 μmm 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

250 are presented by Zambon et al. 2015, submitted.

251 **4. Description of the quadrangles**

252 Av-13 and Av-14 are located in the southwest part of Vesta (Tuccia:
253 180°-270° E; 21°, 66° S, Urbinia: 270°-360° E; 21°, 66° S). These quadrang-
254 gles contain a diversity of terrain types as well as several features of particular
255 interest. Both Tuccia and Urbinia quadrangles include part of the Rheasil-
256 via basin. The northern region of Av-13 covers part of Vestalia Terra and
257 the Veneneia basin, while Av-14 contains a portion of Oppia's orange ejecta
258 (Le Corre et al. (2013); Tosi et al. (2015) this issue). Urbinia and Tuccia
259 are characterized by substantial topographic relief: the southern parts of the
260 quadrangles, within the Rheasilvia basin, have some of the lowest elevations
261 on Vesta, while the northern parts are home to the Vestalia Terra highlands,
262 the highest areas on the entire asteroid (Jaumann et al., 2012; Frigeri et al.,
263 2015a, this issue). According to the geologic maps of Kneissl et al. (2014)
264 and Mest et al. (2012), Av-13 and Av-14 are dominated by Rheasilvia ridge
265 and groove material (Rrg), as well as Rheasilvia smooth (Rs) material, and
266 bright crater (bc) material. Bright crater ray (bcr) material is among the
267 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 Urbinia 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 diogenitic 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

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

507 **Figure 5:** Band depth maps of Tuccia and Urbinia quadrangles. Band depth
508 are photometrically corrected using the value of the Akimov disk function
509 for $i=0^\circ$, $e=0^\circ$, $\phi=0^\circ$ (Longobardo et al., 2014).

510 **Figure 6:** Band depth map of the OH-signature at $2.8\mu\text{m}$ for Av-13 Tuccia
511 (top) and Av-14 Urbinia (bottom).

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

516 **Figure 8:** Plots showing the relationship between band centers and re-
517 flectance at $1.4\mu\text{m}$. Red line represent the best fit.

518 **Figure 9:** Analogous plots to Fig. 8 for the bands depths. Red line repre-
519 sent the best fit. Green points refer to band II depth, while black points to
520 band I depth.

521 **Figure 10:** Histograms illustrating the frequency of the band I depth and
522 band II depth (hereafter BDI and BDII) values measured across the Tuccia
523 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) quadrangle
537 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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