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Mineralogical and spectral analysis of Vesta's Gegania and Lucaria quadrangles and comparative analysis of their key features

Andrea Longobardo [a,*], Ernesto Palomba [a], Maria Cristina De Sanctis [a], Angelo Zinzi [b,c], Jennifer E.C. Scully [d], Fabrizio Capaccioni [a], Federico Tosi [a], Francesca Zambon [a], Eleonora Ammannito [d], Jean-Philippe Combe [e], Carol A. Raymond [f], Cristopher T. Russell [d]

[a] INAF Istituto di Astrofisica e Planetologia Spaziali (IAPS), via Fosso del Cavaliere, 00133 Rome, Italy
[b] ASI – ASI Science Data Center (ASDC), 00133 Rome, Italy
[c] INAF Osservatorio Astronomico di Roma (OAR), 00040 Monte Porzio Catone (RM), Italy
[d] UCLA, Los Angeles, CA 90095 , USA
[e] Bear Fight Institute, Winthrop, WA 98862, USA
[f] California Institute Technology JPL, Pasadena, CA 91109, USA

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A B S T R A C T

This work is aimed at developing and interpreting infrared albedo, pyroxene and OH band depths, and pyroxene band center maps of Vesta's Gegania and Lucaria quadrangles, obtained from data provided by the Visible and InfraRed (VIR) mapper spectrometer on board NASA's Dawn spacecraft.

The Gegania and Lucaria quadrangles span latitudes from 22°S to 22°N and longitudes from 0°E to 144°E. The mineralogical and spectral maps identify two large-scale units on this area of Vesta, which extend eastwards and westward of about 60°E, respectively. The two regions are not associated to large-scale geological units, which have a latitudinal distribution rather than longitudinal, but are defined by different contents of carbonaceous chondrites (CC): the eastern region, poor in CCs, is brighter and OH-depleted, whereas the western one, rich in CCs, is darker and OH-enriched.

A detailed analysis of the small-scale units in these quadrangles is also performed. Almost all the units show the typical correspondence between high albedo, deep pyroxene bands, short band centers and absence of OH and vice versa. Only a few exceptions occur, such as the ejecta from the Aelia crater, where dark and bright materials are intimately mixed.

The most characteristic features of these quadrangles are the equatorial troughs and the Lucaria tholus.

The equatorial troughs consist of graben, i.e. a depression limited by two conjugate faults. The graben do not present their own spectral signatures, but spectral parameters similar to their surroundings, in agreement to their structural origin. This is observed also in graben outside the Gegania and Lucaria quadrangles. However, it is possible to observe other structural features, such as tectonic grooves, characterized by a changing composition and hence an albedo variation. This result is confirmed not only by mineralogical maps of Vesta, but also by analyzing the VIRTIS-Rosetta observations of Lutetia. The albedo change is instead a typical behavior of geomorphic grooves. Finally, ridges are characterized by a bluer color and, in some cases, shorter band centers than their surroundings, suggesting that they are composed of fresher materials.

We also performed a comparative analysis between the three tholi of Vesta, i.e. Lucaria (which gives the name to its quadrangle), Aricia (in the Marcia quadrangle) and Brumalia (Numisia quadrangle). Whereas Brumalia tholus is a young magmatic intrusion, the absence of diogenites, the low albedo, and the orientation of Aricia and Lucaria tholi suggest that they are older features, which are covered by dark materials and therefore experienced a different geological history than Brumalia.

1. Introduction

Vesta is the second largest and the second most massive asteroid in the Main asteroid belt, as well as the only surviving

* Corresponding author. Fax: +39 0649934384.
E-mail address: andrea.longobardo@iaps.inaf.it (A. Longobardo).

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protoplanet (Thomas et al., 1997; Keil et al., 2002; McSween et al., 2011). Ground-based and Hubble Space Telescope observations of Vesta (e.g. McCord et al., 1970; Gaffey, 1997; Binzel et al., 1997) identified Vesta as the parent body of the howardite–eucrite–dio genite (HED) suite of basaltic achondrite meteorites (e.g., Consolmagno and Drake, 1977; Feierberg and Drake, 1980), which are mainly composed of plagioclase and pyroxenes.

The NASA-Dawn mission orbited the Asteroid (4) Vesta from 16 July 2011 to 5 September 2012 (Russell et al., 2012, 2013) and greatly improved our knowledge of the asteroid. The Dawn science is based on the color and hyperspectral images provided by the Framing Camera (FC, e.g. Sierks et al., 2011), and by the Visible and InfraRed spectrometer (VIR, e.g. De Sanctis et al., 2011), respectively, and on the surface elemental composition maps obtained by the Gamma Ray and Neutron Detector (GRaND, e.g. Prettyman et al., 2011). In particular the FC and VIR data allowed us to derive mineralogical maps of the surface of Vesta (e.g. Ammannito et al., 2013a).

The Vesta visible and near-infrared spectra provided by VIR are dominated by the two pyroxene bands, centered at approximately 0.9 μm and 1.9 μm (hereafter referred to as BI and BII), respectively. This confirms the HED composition of the surface of Vesta (De Sanctis et al., 2012a, 2013).

Moreover, the Dawn mission revealed that Vesta is the asteroid with the largest variation of albedo and color (Reddy et al., 2012a). This is due to the different mineralogical units and to the presence of dark patches on its surface.

Vesta surface is covered by fine regolith (granulometry between 25 and 50 μm, e.g. Palomba et al., 2014), which is mostly howardite-like but has a composition spanning the range from diogenitic to eucritic. Diogenites are mainly concentrated in the Southern hemisphere, in particular in the Rheasilvia basin (McSween et al., 2013; Ammannito et al., 2015). This is the youngest region of Vesta, generated about 1 Gyr ago (Kneissl et al., 2014; Williams et al., 2014a) by a large impact which excavated the surface and exposed diogenites from the sub-surface.

However, spectral analysis also revealed lithologies that are different to the HEDs. For example, some regions in the Northern hemisphere host olivine deposits. The clearest detection is in the Bellicia and Arruntia regions, located at 40°N latitude and at about 40°E and 70°E longitude, respectively (Ammannito et al., 2013b; Ruesch et al., 2014a; Palomba et al., 2015), but other recent robust detections have been found poleward of 60°N, i.e. in the Albana and Pomponia regions (Palomba et al., 2015). Local olivine enrichment could also be present in equatorial and Southern regions (Ruesch et al., 2014a; Palomba et al., 2015).

Vesta is also characterized by the presence of dark and bright units (hereafter referred as DU and BU, respectively). The DU are defined as regions presenting a 15% albedo decrease, at least, with respect to the surroundings and are labelled by the "D" letter followed by a cardinal number. If the albedo decrease is larger than 30%, the unit is considered as "very dark" and labelled by "VD" followed by a cardinal number (Palomba et al., 2014). The BU are also defined basing on a relative criterion: the spectral analysis by Zambon et al. (2014) considers as bright the regions with an albedo 20% larger than the surroundings.

Spectral analysis of VIR data (McCord et al., 2012) revealed that BU are composed of Vestan unaltered soil (Zambon et al., 2014), whereas DU are contaminated by carbonaceous chondrites (CCs), most likely delivered by low-velocity impacts that occurred since the Late Heavy Bombardment (McCord et al., 2012; Turrini et al., 2014). This interpretation comes from two strong spectral signatures in the DU. The first one is the BI and BII depth reduction, due to mixing between the HEDs and the spectrally featureless CC (e.g. McCord et al., 2012; Palomba et al., 2014). The other is the detection of the OH absorption band, observed in CCs (De Sanctis et al., 2012b; Palomba et al., 2014). Another recently found CC effect on the HED spectra is how the BII center shifts toward longer wavelengths (De Sanctis et al., 2015), which could lead to misinterpreting a DU as an eucritic region.

Only optical differences have been found between Vesta BU and DU (i.e. different role of single and multiple scattering), whereas physical properties such as regolith grain size and surface roughness are substantially similar (Longobardo et al., 2014).

In order to obtain a more complete and detailed geological and mineralogical characterization, Vesta's surface has been divided into fifteen quadrangles (Frigeri et al., 2015): the two poles, four quadrangles in the Northern hemisphere, four in the Southern hemisphere, and five at equatorial latitudes.

In this work, mineralogical and spectral maps of the Gegania and Lucaria quadrangles are discussed. The Gegania and Lucaria quadrangles span latitudes from 22°S to 22°N and extend from 0°E to 72°E and from 72°E to 144°E longitude, respectively (Frigeri et al., 2015). They take their name from their largest features, i.e. the Gegania crater and Lucaria Tholus, respectively.

Schafer et al. (2014) produced a geological map of these quadrangles. Their study, based on analysis of FC images, revealed three substantial main geological macro-regions: (a) cratered highland regions, the oldest of the quadrangles, extending to northern latitudes; (b) the Divalia Fossae formation, spanning the equatorial latitudes (down to 15–20°S) and characterized by the linear features generated from the Rheasilvia impact (Buczkowski et al., 2012); and (c) Rheasilvia ejecta, lightly cratered and younger terrain extending poleward of 15–20°S.

Other small-scale geological units are also found in these quadrangles. The equatorial troughs are the most prominent feature of the Gegania and Lucaria quadrangles. Lucaria Thouls is one of the three tholi on the Vestan surface (Aricia and Brumalia being the other two). Moreover, many impact craters and the presence of diffuse material are also observed.

In addition, previous studies on dark (Palomba et al., 2014) and bright (Zambon et al., 2014) materials revealed the presence of 16 DU and 3 BU in these quadrangles.

After presenting the VIR spectrometer (Section 2) and the spectral parameters defined for this study (Section 3), a mineralogical overview of Gegania and Lucaria Vesta regions is given (Section 4). Then, a spectral and mineralogical analysis of the geological units identified by Schafer et al. (2014), and of the DU and BU included in these quadrangles, is performed in Sections 5 and 6, respectively. The most characteristic features, i.e. the linear features and the tholus, are analyzed in more detail. Since these features are also found within other Vestan quadrangles, we compare their spectral properties in the Gegania and Lucaria quadrangles with their spectral properties on the rest of Vesta's surface. This comparative analysis (Section 7) also takes into account linear features observed in other asteroids. In particular, the Lutetia features are studied by means of hyperspectral maps provided by the Visible and InfraRed Thermal Imaging Spectrometer (VIRTIS), onboard the ESA Rosetta mission (presented in Section 2).

Finally, conclusions are given in Section 8.

2. The VIR-Dawn and VIRTIS-Rosetta instruments and strategy of observation

The VIR (De Sanctis et al., 2011) and VIRTIS-M (Coradini et al., 1999) imaging spectrometers are two similar instruments, on-board the NASA-Dawn and the ESA-Rosetta spacecraft, respectively.

They include two spectral channels, working in the visible (0.25–1.05 μm) and near-infrared (1.0–5.1 μm) range, respectively. Each channel includes 432 bands; therefore the spectral resolution