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Compositional variations in the Vestan Rheasilvia basin

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ABSTRACT

We present and describe the maps of spectral parameters such as pyroxene band centers and depths, reflectance at 1.4 μm and 2.8 μm band depth in the Rheasilvia quadrangle. We found a broad anti-correlation between pyroxene band centers and depths while the reflectance is not correlated with the pyroxene spectral parameters. In addition, we found that the Rheasilvia quadrangle is free of OH absorption signatures. We also derived lithological maps with improvements in the spatial resolution with respect to previous lithological maps of the same region. We confirm that the central mound is dominated by eucritic/howarditic pyroxene while diogenitic lithology has been found mainly in a region delineated by Tarpeia, Severina and Mariamne craters. We found small scale variations in the composition of pyroxene. These variations identify lithological units that extend for tens of km, although small units of less than 1 km have also been found. We consider this fact as an indication of a high level of compositional heterogeneity within the Vestan crust.

1. Introduction

Asteroid 4/Vesta has been intensively studied since its discovery in 1807 by Heinrich Wilhelm Matthias Olbers. Telescopic observations (ground-based and Hubble Space Telescope (HST)), revealed that this asteroid exhibits pyroxene absorption bands similar to the howardite–eucrite–diogenite (HED) meteorites (McCord et al., 1970). It was also revealed that there are longitudinal variations in albedo and surficial composition (Gaffey, 1997; Binzel et al., 1997; Vernazza et al., 2005; Carry et al., 2010; Li et al., 2010; Reddy et al., 2010). In addition, the existence of a large basin at the Vestan South Pole was identified (Thomas et al., 1997). The discovery of a family of small asteroids dynamically and compositionally linked to Vesta – the Vestoids (Binzel and Xu, 1993) – provided the missing link in the interpretation of the Vesta–HED connection: Vestoids are likely samples of the missing mass ejected from Vestan South Polar basin during the cratering event, while the HEDs are small fragments of Vestoids that have reached the inner Solar System and the Earth (Marzari et al., 1996). In this scenario, the HEDs are considered to be excavated samples of a stratified internal structure (McSween et al., 2011).

Petrologic and geochemical studies of HEDs, and thermal evolution models, have generated a hypothesis to explain the internal structure of Vesta, called the magma ocean model (Righter and Drake, 1997; Ruzicka et al., 1997; Mandler and Elkins-Tanton, 2013; Toplis et al., 2013). According to this picture, a body with an initial chondritic composition experienced widespread or global melting induced by the heat produced by decay of ^{26}Al and possibly other minor short-lived radionuclides. Crystallization of this magma ocean generated a layered structure. Metals (Fe, Ni) concentrated in the central core, while olivine and orthopyroxene formed a mantle of harzburgite and orthopyroxenite (diogenite). If melting were incomplete, an olivine-rich (dunite) lower mantle may have formed (Neumann et al., 2014) below harzburgite and orthopyroxenite. Continuing crystallization formed a crust of gabbro and basalt (sampled respectively by cumulate and basaltic eucrites). The most external layer is composed of regolith breccias (sampled by polymict eucrite and howardite). Although the magma ocean model remains popular, another scenario envisions continuous melt extraction from the mantle, so that a global scale magma ocean never formed (Wilson and Keil, 2012).

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The Dawn spacecraft accomplished a major step forward in understanding Vesta. From July 2011 to August 2012, the spacecraft orbited Vesta (Russell et al., 2013), and during this time the Visible InfraRed Mapping Spectrometer (VIR) acquired spectra of its surface from 0.2 to 5 μm (De Sanctis et al., 2011). The instrument operated during Survey (VSS), High Altitude Mapping (VSH) and Low Altitude Mapping (VSL) orbits as well as during Approach and Departure phases, providing an almost global coverage of the surface. Data from VSL have the highest spatial resolution. 70 m/px is the nominal resolution in this orbit, in comparison with 170 m/px and 700 m/px that are the typical resolutions during the VSH and VSS orbits, respectively. While VSL coverage is limited to less than 1% of the total surface, that dataset provides a detailed view of some localized areas.

The Dawn spacecraft confirmed the existence of an approximately circular basin in the South Pole, named Rheasilvia, superimposed on an older basin called Veneneia (Russell et al., 2012; Jaumann et al., 2012; Marchi et al., 2012; Schenk et al., 2012). In addition, spectroscopic measurements confirmed that the spectrum of Vesta is dominated by pyroxene absorption bands with variations of band center position, band depth and other band parameters at both large and small scales (De Sanctis et al., 2012a, 2013; Ammannito et al., 2013a; McSween et al., 2013). In particular, there is a strong indication that the Rheasilvia basin has its own spectral characteristics: the pyroxene absorption bands are deeper and wider, and center positions are shifted toward shorter wavelengths with respect to the average values. Rheasilvia's central mound has a relatively low spectral diversity (McSween et al., 2013). These spectral behaviors indicate the presence of Mg-pyroxene-rich terrains in Rheasilvia, an occurrence confirmed by the Gamma-Ray and Neutron Detector (GRaND) (Prettyman et al., 2012) and the Framing Camera (FC) color data (Reddy et al., 2012), the other two instruments on the Dawn spacecraft.

The Rheasilvia basin has attracted considerable interest because its diameter (500 ± 20 km; Jaumann et al., 2012) with respect to the size of Vesta (rotational ellipsoid with semi-axes of 280.9 km and 226.2 km with the origin at the center of mass of the body; Ermakov et al., 2014) is such that in a magma ocean scenario, ultramafic rocks from the upper mantle should have been exposed (Ivanov and Melosh, 2013; Jutzi et al., 2013). Therefore, this particular location has been considered as a potential window into the internal structure (Pieters et al., 2011). Interestingly, Dawn has found no evidence so far of the presence of olivine within the Rheasilvia basin (Ammannito et al., 2013b; Ruesch et al., 2014; Clenet et al., 2014). It is worth noting that the identification of olivine, when combined with pyroxene, by reflectance spectroscopy in the VIS/NIR range has always been controversial (Beck et al., 2013). Both minerals have a diagnostic feature at about 1 μm, but the crystal structure of olivine has a lower absorption coefficient relative to that of pyroxene. The direct consequence is that it is difficult to detect olivine in concentrations <25% in the presence of abundant orthopyroxene (Beck et al., 2013). However, also the locations with pure diogenitic-like terrains, thought to be lower crust material, are concentrated in only a few spots, and do not correspond to the uplifted central mound, which is instead dominated by howarditic and eucritic compositions (McSween et al., 2013; Ammannito et al., 2013a). The lack of both olivine detections and widespread ultramafic minerals within Rheasilvia has implications for the Vestan internal structure.

2. Maps of the Rheasilvia basin

Here we describe the characteristics of the distribution of spectral parameters in the Rheasilvia quadrangle, which includes all latitudes below 65°S (Roatsch et al., 2012). Details of the map production process, as well as the computation of spectral parameters, are provided in Frigeri et al. (2015) and Combe at al. (2015). In this paper, all the maps and coordinates are given using the Claudia Prime Meridian Reference System (Russell et al., 2012; Reddy et al., 2013). Products in this paper can be converted in the IAU Reference System by adding 150° from longitudes values (Li, 2013b).

The spectral position of the centers of the two major absorption bands in the VIR sensitivity range, at 1 μm (BI) and 2 μm (BII), are especially useful for identifying variations in pyroxene chemical composition (Burns, 1993). We computed the pyroxene band centers following the method described by Ammannito et al. (2013a). The values obtained are shown in the maps in Fig. 1.

In these maps, some regions have both BI and BII centers shifted to shorter wavelengths (blue in the map) with respect to the average values on Vesta which are 0.926 μm for BI center and 1.971 μm for BII center. This implies the presence in these locations of pyroxenes with higher Mg versus Fe concentration (Adams, 1974; Klima et al., 2007). For both BI and BII, there is a general trend that longitudes between 0°E and 100°E have shorter spectral position of the centers of the two pyroxene bands. In addition, there are localized regions with particularly short values of band centers. These regions are associated with some of the lowest topography on the Vestan surface (Jaumann et al., 2012). These are presumably outcrops of the deep crust or upper mantle exposed at the base of Rheasilvia's central uplift (Reddy et al., 2012). Another characteristic of BI and BII centers is that their values are correlated, meaning that spectra with particularly high or low values of BI center position also have a high or low BII center position. This is an indication that the mineralogy in this region is dominated by a pyroxene chemical composition with a minor or absent influence of other components such as carbonaceous chondrites, which tend to increase the values of the BII center (De Sanctis et al., 2015).

Projected maps of the values of pyroxene band depth are shown in Fig. 2.

The values in the maps have been corrected for photometric effects using a method described by Longobardo et al. (2014). In analogy with the band centers, the band depths of BI and BII have the same trend, meaning that low values of BI depth correspond to low values of BII depth, and the same for high values. However, the distributions of band centers and depths do not have a clear correlation. In general, the region below 65°S has deeper bands when compared with the average Vestan surface. This distribution seems to correlate with the pyroxene band centers that, as noticed earlier, have shorter values in the same latitude range. However, this broad correlation is not supported when we analyze the distribution at smaller scale (tens of km and below). In particular, there is a region in the middle of the map with deeper bands that roughly corresponds to the central mound (topographic high). This may be a consequence of additional photometric effects not completely taken into account in the correction applied or of a different physical state, such as grain size distribution, in the mound.

Fig. 3 (left) shows a map of the reflectance generated at 1.4 μm, as described in Combe et al. (2015). The photometrically-corrected 1.4 μm reflectance provides a contextual view of the surface optical properties. Although in the map there are some residual artifacts, mainly due to poor illumination conditions in the polar areas, it is possible to identify a hemispherical dichotomy with the region roughly from 135°E to 315°E longitude, showing generally lower values in comparison to the opposite region. This dichotomy does not correlate with either pyroxene band centers or depths, indicating that it is not associated with pyroxene chemical composition. This is particularly clear when we notice that the highest values in reflectance are in the region of longitudes between 335°E and 20°E, while minimum values of band centers are between 0°E and 100°E, and the depths increase closer to the South Pole.