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Olivine or impact melt: Nature of the "Orange" material on Vesta from Dawn

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ABSTRACT

NASA's Dawn mission observed a great variety of colored terrains on asteroid (4) Vesta during its survey with the Framing Camera (FC). Here we present a detailed study of the orange material on Vesta, which was first observed in color ratio images obtained by the FC and presents a red spectral slope. The orange material deposits can be classified into three types: (a) diffuse ejecta deposited by recent medium-size impact craters (such as Oppia), (b) lobate patches with well-defined edges (nicknamed "pumpkin patches"), and (c) ejecta rays from fresh-looking impact craters. The location of the orange diffuse ejecta from Oppia corresponds to the olivine spot nicknamed "Leslie feature" first identified by Gaffey (Gaffey, M.J. [1997]. Icarus 127, 130–157) from ground-based spectral observations. The distribution of the orange material in the FC mosaic is concentrated on the equatorial region and almost exclusively outside the Rheasilvia basin. Our in-depth analysis of the composition of this material uses complementary observations from FC, the visible and infrared spectrometer (VIR), and the Gamma Ray and Neutron Detector (GRaND). Several possible options for the composition of the orange material are investigated including, cumulate eucrite layer exposed during impact, metal delivered by impactor, olivine–orthopyroxene mixture and impact melt. Based on our analysis, the orange material on Vesta is unlikely to be metal or olivine (originally proposed by Gaffey (Gaffey, M.J. [1997]. Icarus 127, 130–157)). Analysis of the elemental composition of Oppia ejecta blanket with GRaND suggests that its orange material has ~25% cumulate eucrite component in a howarditic mixture, whereas two other craters with orange material in their ejecta, Octavia and Arruntia, show no sign of cumulate eucrites. Morphology and topography of the orange material in Oppia and Octavia ejecta and orange patches suggests an impact melt origin. A majority of the orange patches appear to be related to the formation of the Rheasilvia basin. Combining the interpretations from the topography, geomorphology, color and spectral parameters, and elemental abundances, the most probable analog for the orange material on Vesta is impact melt.

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1. Introduction

Vesta is the largest differentiated asteroid with a basaltic surface that is mostly intact today. Since 1929, Vesta's surface has been extensively studied using ground-based telescopes in the ultraviolet, visible and infrared wavelength ranges (Bobrovnikoff, 1929; McFadden et al., 1977; Blanco and Catalano, 1979; Taylor et al., 1985; Festou et al., 1991; Gaffey, 1997; Hendrix et al., 2003; Zellner et al., 2005; Rivkin et al., 2006; Reddy et al., 2010) and using Hubble Space Telescope (HST) data (Thomas et al., 1997; Li et al., 2010, 2011). All these studies led to a better understanding of the mineralogy, space weathering effects and the global shape of Vesta. Especially, visible and near-infrared spectroscopy suggested that Vesta is one of the most diverse objects in the asteroid belt in terms of its surface composition and HST imagery showed its large-scale variations in albedo. In the meantime, laboratory analyses of reflectance spectra of meteorite samples and observations of Vesta have strengthened the idea of a genetic link between the Howardite–Eucrite–Diogenite suite of meteorites and Vesta itself (McCord et al., 1970; Binzel and Xu, 1993; Burbine et al., 2001; McSween et al., 2011; Reddy et al., 2011a). However, some HEDs might originate from catastrophic impact on Vestoids as well (Moskovitz et al., 2010). These Vestoids correspond to fragments of Vesta excavated by previous impacts and ejected into space that are forming the majority of objects in the Vesta family of asteroids.

After a cruise of less than four years, NASA's Dawn spacecraft placed itself in orbit around Vesta on July 16, 2011 for a yearlong global characterization. The Framing Camera (FC) (Sierks et al., 2011) is one of three instruments onboard the Dawn spacecraft and mapped the asteroid through a clear filter and seven narrow-band filters from 0.4 to 1.0 μm. Dawn FC color data have confirmed several ground-based and HST observations of Vesta including its hemispherical dichotomy, rotational color variations (Reddy et al., 2012b; Reddy et al., 2013; Li et al., 2013a) and the presence of dark carbonaceous chondrite xenoliths (Reddy et al., 2012d). The high-resolution color images obtained by the FC allowed the discrimination of a variety of color units and provided data to study their distribution on the vestan surface. We also use the visible and infrared spectrometer (VIR) an imaging spectrometer combining two data channels: the visible-infrared (VIS) from 0.25 to 1.07 μm, and the infrared (IR) from 0.95 to 5.1 μm (DeSanctis et al., 2011).

Finally, we use data from Dawn's Gamma Ray and Neutron Detector (GRaND), which measured the elemental composition of Vesta's regolith (Prettyman et al., 2011). Global Fe/O and Fe/Si ratios measured by GRaND show that Vesta's regolith is howarditic, strengthening the link between Vesta and the HEDs; and, measurements of the abundance and distribution of H by GRaND reveal the presence of H-rich materials likely delivered by the infall of carbonaceous chondrites (Prettyman et al., 2012). Recently, the GRaND team has completed global mapping of the abundance of total Fe (w_{Fe}), the thermal neutron absorption cross section (Σ_A), high energy gamma rays (HEGR), and the effective atomic mass of the regolith (Lawrence et al., in press; Peplowski et al., 2013; Prettyman et al., 2013; Yamashita et al., 2013). A subset of these elemental parameters (Fe, neutron absorption, and HEGR) will be used to characterize selected, broad regions containing orange materials identified in FC data. Since GRaND is omnidirectional, the spatial resolution of elemental maps depends on altitude. Data acquired in Dawn's Low Altitude Mapping Orbit (LAMO) with a mean altitude of about 210 km are used. Maps determined from LAMO data have a spatial resolution of about 300 km (full-width-at-half-maximum of arc length on the surface). At this scale, distinct compositional regions can be distinguished. GRaND is further sensitive to bulk-regolith composition to depths of about 1 m.

Several color ratios and color parameters have been developed to map the distribution of HED terrains on Vesta (Le Corre et al., 2011). Reddy et al. (2012b) applied color ratios from the Clementine mission (Pieters et al., 1994) to distinguish color units using Dawn FC images. Clementine color ratio images are RGB color composites in which $C_R = R(0.75)/R(0.45)$, $C_G = R(0.75)/R(0.92)$, and $C_B = R(0.45)/R(0.75)$; where $R(\lambda)$ is the reflectance in a filter centered at λ(μm) and C_R, C_G, C_B are the red, green and blue channels respectively. Greener areas in this color composite have deeper pyroxene absorption bands (typical of diogenites) and redder areas have steeper visible slopes relative to bluer areas. Reddy et al. (2012b) observed two large impact craters (Oppia and Octavia) that showed prominent red/orange ejecta in Clementine color ratio images. They also noted several brighter orange patches around Oppia. The orange/red color of these craters and patches appears to come from a steeper visible slope ($R(0.75)/R(0.45)$) compared to surrounding areas.

Gaffey (1997) noticed a drop in pyroxene band area ratio (BAR) between 60°E and 120°E longitude in rotationally resolved spectra of Vesta. He interpreted this drop in BAR as an indicator for the presence of olivine. Gaffey (1997) informally named this feature the "Leslie formation" and suggested it to be exposed olivine mantle material due to a large impact. A low albedo feature (#15) corresponds to this possible olivine unit in HST maps of Vesta (Binzel et al., 1997; Li et al., 2010). HST color spectra showed that this unit had the reddest visible spectral slope compared to any other unit on the surface of Vesta (Li et al., 2010). This feature also had weaker 1-μm band depth compared to the average surface. Li et al. (2010) interpreted this red slope and weaker band depth as an indicator of lunar-style space weathering. Comparing HST albedo maps, ground-based compositional maps and Dawn FC data, Reddy et al. (2013) suggested that "Leslie formation", and feature #15 correspond to Oppia crater and its orange ejecta. This link is remarkable in the sense that orange material on Vesta was first detected by ground-based telescopes prior to the arrival of Dawn at Vesta, however its spatial context remained nebulous.

Here we present a detailed study of the nature of this orange material on Vesta. Combining multiple data sets from the suite of instruments on the Dawn spacecraft we provide a detailed geological description of the orange material, constrain its mineralogy, mineral chemistry, and meteorite affinities within the HED suite. Using this information, we test multiple hypotheses for the origin/formation of orange material on Vesta.

2. Data description and processing

2.1. Orbits and resolution of FC and VIR data

The FC dataset examined in this study spans a range of resolution from 487 to 16 m/pixel. It consists of FC color images, corresponding to filters F2 to F8 (Table 1) acquired from the approach phase at a distance of 5200 km from Vesta, to the High Altitude Mapping Orbit (HAMO) phase (Table 2). We also used clear filter images from the LAMO phase at the closest from the surface. The approach and orbital phases are summarized in Table 2. During the approach phase, there were three rotational characterizations (RC) consisting of the first observations of Vesta using the color filters (F2 to F8). In between each set of color images the FC also acquired clear filter (F1) frames, which have a much broader wavelength band pass. Next, the survey phase encompasses seven cycles of observations (one cycle per orbit) with the first, fourth and the seventh comprising color mapping