Icarus 240 (2014) 3–19

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

The geological nature of dark material on Vesta and implications for the subsurface structure

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ARTICLE INFO

Article history:
Received 1 July 2013
Revised 17 April 2014
Accepted 17 April 2014
Available online 2 May 2014

Keywords:
Asteroid Vesta
Geological processes
Cratering

ABSTRACT

Deposits of dark material appear on Vesta's surface as features of relatively low-albedo in the visible wavelength range of Dawn's camera and spectrometer. Mixed with the regolith and partially excavated by younger impacts, the material is exposed as individual layered outcrops in crater walls or ejecta patches, having been uncovered and broken up by the impact. Dark fans on crater walls and dark deposits on crater floors are the result of gravity-driven mass wasting triggered by steep slopes and impact seismicity. The fact that dark material is mixed with impact ejecta indicates that it has been processed together with the ejected material. Some small craters display continuous dark ejecta similar to lunar dark-halo impact craters, indicating that the impact excavated the material from beneath a higher-albedo surface. The asymmetric distribution of dark material in impact craters and ejecta suggests non-continuous distribution in the local subsurface. Some positive-relief dark edifices appear to be impact-sculpted hills with dark material distributed over the hill slopes. Dark features inside and outside of craters are in some places arranged as linear outcrops along scarps or as dark streaks perpendicular to the local topography. The spectral characteristics of the dark material resemble that of Vesta's regolith. Dark material is distributed unevenly across Vesta's surface with clusters of all types of dark material exposures. On a local scale, some craters expose or are associated with dark material, while others in the immediate vicinity do not show evidence for dark material. While the variety of surface exposures of dark material and their different geological correlations with surface features, as well as their uneven distribution, indicate a globally inhomogeneous distribution in the subsurface, the dark material seems to be correlated with the rim and ejecta of the older Veneneia south polar basin structure. The origin of the dark material is still being debated, however, the geological analysis suggests that it is exogenic, from carbon-rich low-velocity impactors, rather than endogenic, from freshly exposed mafic material or melt, exposed or created by impacts.

1. Introduction

Albedo differences on 4 Vesta's surface were observed in multispectral images obtained by the Hubble Space Telescope (Zellner et al., 1997; Binzel et al., 1997; Gaffey, 1997). However, regions of very low albedo on Vesta's surface were first discovered by the Dawn mission (Jaumann et al., 2012a; Russell et al., 2012; McCord et al., 2012; Reddy et al., 2012). These dark material deposits are non-randomly distributed over the surface and often associated with geological/morphological features (Jaumann et al., 2012b; McCord et al., 2012). Dark material occurs most conspicuously in small, well-defined deposits. These are often but not always directly associated with impact structures and occur in

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http://dx.doi.org/10.1016/j.icarus.2014.04.035

crater walls or are excavated by the impact process and mixed into the ejecta. Alternatively, it may occur as blocky or layered outcrops in crater walls and as mass-wasting deposits on crater flanks and floors. One apparent conclusion from these observations (Jaumann et al., 2012b; McCord et al., 2012; Reddy et al., 2012) is that the nature of the dark material deposits, whatever their sources, is strongly influenced by impact mixing, gardening and mass-wasting. In addition to the small, well-defined dark material deposits, there are also large regions of low albedo surface material, often with indistinct boundaries, that appear to include dark material. Intermediate-scale evidence of mixing also exists in the form of wispy and mottled dark material deposits. Data from the Dawn visible and infrared imaging spectrometer (VIR) (De Sanctis et al., 2012a, 2013; Stephan et al., 2014; Palomba et al., 2014) show that the reflectance spectrum of dark material is similar to, but more muted than, the average Vesta spectrum, and contains no obvious additional spectral features. The pyroxene absorptions near 1 and 2 μm are present, but attenuated compared to average Vesta surfaces. Typically, dark material deposits show a lower visual to near-IR albedo, with stronger thermal emission because of higher temperatures due to lower albedo (De Sanctis et al., 2012a, 2013; Capria et al., 2014). Dark material may be present as intimate and/or macroscopic mixtures with other Vesta materials. Most regions on Vesta can be modeled as a linear mixture of just two materials, i.e. a bright, pyroxene-rich soil and a generic darker, reddish material (McCord et al., 2012). The dark component does not change the main spectral parameter values, as indicated by the analysis of the band centers and the band depths (Stephan et al., 2014; Palomba et al., 2014).

The main hypotheses formulated so far for the origin of dark material are: (1) low velocity infall from objects containing dark material, (2) basalt flows, dikes or sills on/in Vesta that were broken and redistributed by impacts, and (3) impact melt from major cratering events (McCord et al., 2012; Jaumann et al., 2012a). Dawn images provide no conclusive evidence of basaltic lava flows (Jaumann et al., 2012a; Yingst et al., 2014; Williams et al., 2013), and the evidence of basaltic intrusions is equivocal. In addition, it is difficult to understand how a Vesta-like object could retain sufficient heat to create secondary melting and near-surface extrusions of lava late enough in Vesta's evolution for the flows or major parts of them to survive impact battering into the present day (e.g. Zuber et al., 2011; McSween et al., 2011; Russell et al., 2012, 2013). On the other hand, there is morphological evidence of impact melt deposits on Vesta that have low reflectance (Denevi et al., 2012; Yingst et al., 2014; Williams et al., 2013). Although this is consistent, with the apparent active impact history of Vesta, which must have included some higher-velocity impactors (O'Brien et al., 2011) only one impact melt deposit in crater Marcia could be identified while possible melt deposits in Rheasilvia basin and Cornelia crater are still debated (Denevi et al., 2012; Williams et al., 2013). However, the small mass of Vesta and its location at a solar distance of 2.3 AU are likely to result in a significantly greater percentage of low-velocity impacts than on the inner planets and the Moon, resulting in the preservation of major fractions of the projectile (O'Brien et al., 2011). Thus it is probable that dark material might have been introduced by impacts as remnants of impactor material (McCord et al., 2012). Dark material originating from carbonaceous chondrite-rich (CC) objects, especially from the outer parts of the asteroid belt and perhaps from comets, must have impacted Vesta's surface. Further, the spectrum of the dark material end member, as modeled by McCord et al. (2012), is similar to that of CC and organic-rich material in the outer Solar System. Exogenic infall is also supported by certain HED (howardites, eucrite, diogenite) meteorites, originating from Vesta (e.g. Russell et al., 2013), that contain clasts of carbonaceous chondrite material within a matrix of pyroxene-rich basaltic material (Cloutis et al., 2013; Herrin et al., 2011; McCoy and Reynolds, 2007). Moreover, the broad correlation between dark material and OH signature, detected by VIR, and H abundance, detected by GRanD, (De Sanctis et al., 2012b; Prettyman et al., 2012) is a further indication of carbonaceous chondrite as darkening agent of the Vestan regolith. Carbonaceous chondritic clasts are the main xenolithic clasts in howardites and exhibit varying degrees of aqueous alteration. These chondritic clasts can contain H_2O in the form of hydrated, hydroxylated, or oxyhydroxylated mineral phases (Zolensky et al., 1996; Lorenz et al., 2007; Prettyman et al., 2012).

The major objective of this study is to investigate the subsurface layering of the dark material, their excavation and distribution process by impacts and, if the source is exogenic, whether it is due to multiple impacts or to only one or a few events.

2. Data base and methods

The Dawn mission orbited Vesta from July 16, 2011 until September 5, 2012, using three instruments to observe the surface (Russell and Raymond, 2011). The Visual and Infrared Spectrometer (VIR) detects surface mineralogical compositions by measuring spectral variations in the range from ~0.4 to 5.0 μm and corresponding absorption features (De Sanctis et al., 2010). The Gamma Ray and Neutron Detector (GRaND) provides information on the elemental composition of the surface (Prettyman et al., 2011). The Dawn Framing Camera (FC) observes the surface in seven colors in the visible to near-infrared wavelength range. FC also provides stereo coverage by systematically changing observation geometries (Sierks et al., 2011; Raymond et al., 2011). Calibrated Dawn Framing Camera data (Schröder et al., 2013a) as well as the digital terrain model (DTM) obtained during the Dawn High Altitude Mapping Orbits (HAMO 1 and 2) (Jaumann et al., 2012a; Preusker et al., 2012) were used in our geological analysis of the dark material on Vesta. During the orbital phases, the FC mapped the surface at image scales of ~260 m/pixel (FC) in the survey phase, ~60 m/pixel in HAMO and ~20 m/pixel in the Low Altitude Mapping Orbit (LAMO). The stereo-photogrammetric processing of Dawn images is based on a software suite that has been applied successfully to several planetary stereo image data sets (Jaumann et al., 2007; Gwinner et al., 2009; Preusker et al., 2011). There are five steps to gain Dawn stereo-photogrammetry: photogrammetric block adjustment; multi-image matching; surface point triangulation; digital terrain model (DTM) generation; and base map generation (Raymond et al., 2011). Elevations refer to a best approximation of Vesta's irregular shape – a biaxial ellipsoid with a semi-major axis of 285 km and a semi-minor axis of 229 km. The resulting DTM covers ~90% of Vesta's surface and has a grid spacing of 48 pixels per degree (~92 m/pixel, with a vertical resolution of <10 m) (Jaumann et al., 2012a; Preusker et al., 2012). Based on the DTM, a global HAMO (60 m/pixel spatial resolution) and a LAMO (20 m/pixel spatial resolution) mosaic were derived (Roatsch et al., 2012). To correct for brightness changes due to local topography within the image and brightness changes due to differences in phase angle between images, we used a photometric adjustment based on the disk function for the former and a phase function for the latter (Li et al., 2013; Schröder et al., 2013b). Schröder et al. (2013b) used an approach based on models in which the explicit dependence of reflectance on phase angle is decoupled from the effects of local topography (Kaasalainen et al., 2001; Shkuratov et al., 2011). Their approach separates the disk function from the phase function, and is well suited to facilitate photometric correction by combining the best-fit disk function of Vesta with a polynomial to describe the phase function. Radiometric and photometric correction has been applied to the entire HAMO and