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- Evidence of Vesta magmatic activity
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Compositional evidence of magmatic activity on Vesta

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Abstract Like the Earth and other terrestrial planets, the asteroid Vesta has a basaltic crust and a large iron core; its surface is dominated by impact craters of all sizes and has tectonic features. The presence of basaltic compositions, olivine, howardite-eucrite-diogenite meteorites, and models of Vesta's formation, suggests that volcanic and/or magmatic activity could have occurred on Vesta. A global search for lobate structures did not find unequivocal evidence of volcanic features. Nevertheless, several morphological properties of Brumalia Tholus on Vestalia Terra suggest that this topographic high most likely formed as a magmatic intrusion. The presence of more orthopyroxene-rich material relative to surrounding terrain in the ejecta of Teia, a fresh impact crater on the northern face of Brumalia Tholus, supports the hypothesis of magmatic intrusions on Vesta.

1. Introduction

Clear evidence for ancient volcanism, based on basaltic material in meteorite collections, exists only for the parent asteroid of the howardite-eucrite-diogenite (HED) meteorites [e.g., *Wilson and Keil*, 1996, 2012; *Drake*, 1979]. This asteroid was commonly assumed to be Vesta (*McCord et al.* [1970] and many subsequent articles, e.g., *Feierberg et al.* [1980], *Gaffey* [1997], and *Binzel et al.* [1997]) and Dawn mission confirmed this early assumption [*Russell et al.*, 2012, *De Sanctis et al.*, 2012, *McSween et al.*, 2013]. However, widespread volcanism in the early solar system has also been inferred through the occurrence of other basaltic meteorites of asteroidal origin [e.g., *Greenwood et al.*, 2005; *McCoy et al.*, 1996; *Goodrich et al.*, 2001]. The Dawn observations of the only certain differentiated asteroid, Vesta, deserve a reconsideration of the factors controlling volcanism on asteroidal bodies. Different types of volcanic deposits have been hypothesized on Vesta, including basaltic lava flows, channelized flows on steeper slopes, and shallow and deep intrusions (dikes) [*Righter and Drake*, 1997; *Ruzicka et al.*, 1997]. No unequivocal morphologic evidence of ancient lava flows has thus far been identified on Vesta [*Williams et al.*, 2013] probably because of the early cessation of volcanism [*Schiller et al.*, 2010] and the following intense crustal disruption due to bombardment by impactors [*Marchi et al.*, 2012, 2103].

Vesta shows large topographic features with highlands and hills. Vestalia Terra is a topographic high, bounded by steep scarps [*Jaumann et al.*, 2012; *Buczkowski et al.*, 2014 ; *Yingst et al.*, 2014] located between ~25°N to 35°S and ~200°E to 300°E (Claudia coordinate system). Crater counting indicates that Vestalia Terra is older than the surrounding units, and it is possibly the oldest feature on Vesta [*Marchi et al.*, 2012]. It seems to consist of a more resistant material than the rest of Vesta [*Buczkowski et al.*, 2012, 2014]. The southern plateau of Vestalia Terra may be underlain by high-density material more typical of Vesta's mantle than its crust [*Raymond et al.*, 2013]. Brumalia Tholus is an elongate hill on Vestalia Terra (Figure 1a), characterized by steep slopes and its orientation relative to a series of merged pits called Albalonga Catena (Figure 1a) that are thought to represent a steep subsurface fault and are visible to both the east and west of the hill [*Buczkowski et al.*, 2014]. The morphology of Brumalia Tholus suggests that this topographic high most likely formed as some form of magmatic intrusion [*Buczkowski et al.*, 2014]. Brumalia Tholus is not correlated with impact basin rims. There is also no evidence for building such a high-standing dome-like feature by accumulation of ejecta of several smaller craters. However, a way to assess whether this hypothesis is correct is to analyze the geology and composition of this region, searching for features that indicate volcanic/magmatic activity.

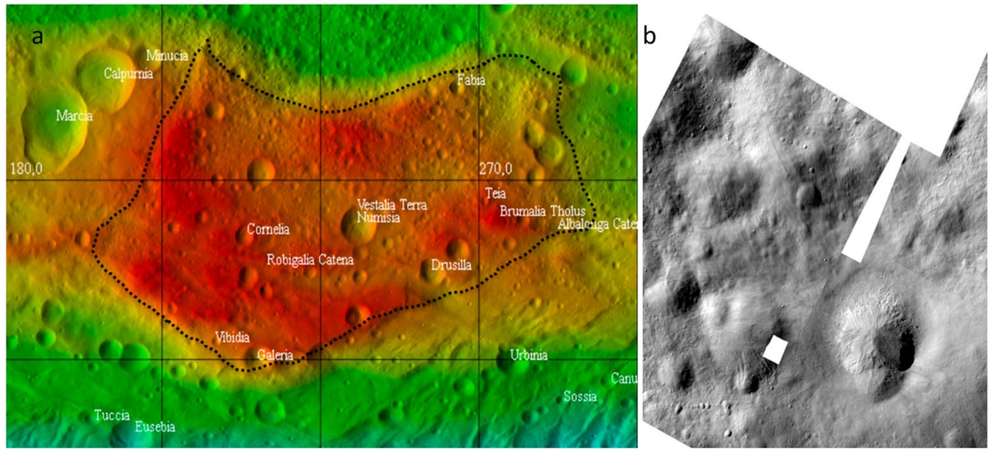

Figure 1. (a) Topographic context image of Vestalia Terra (black dashed line); major features are named, including Brumalia Tholus and Teia crater; the map is in Claudia coordinate system. (b) Framing camera Low Altitude Mapping Orbit mosaic of Teia crater.

The basaltic nature of the surface is confirmed by the visible and infrared imaging spectrometer (VIR) [*De Sanctis et al.*, 2011, 2012, 2013; *Ammannito et al.*, 2013a, 2013b] indicating that Vesta has experienced planetary-scale differentiation that produced a crust, mantle, and a core [*Russell et al.*, 2012]. The HED meteorite link with Vesta [*Russell et al.*, 2012; *De Sanctis et al.*, 2012, 2013 ; *Ammannito et al.*, 2013a, 2013b; *McSween et al.*, 2011; *McCord et al.*, 1970] was reinforced by the mapping of pyroxene mineralogy from Dawn's orbit [*Russell et al.*, 2012; *De Sanctis et al.*, 2012; *Ammannito et al.*, 2013b] that yielded the locations of the diogenite-rich and eucrite-rich regions and by Gamma Ray and Neutron Detector measurements that confirm a compositional match between howardite and the Vestan surface [*Prettyman et al.*, 2012]. VIR's mapping provides regional and local geologic context for Vesta's HED lithologies [*Ammannito et al.*, 2013a, 2013b]; the spectra obtained by VIR indicate that Vesta is generally covered by a howarditic regolith [*De Sanctis et al.*, 2012, 2013] but that some areas, such as the floor of the south polar Rheasilvia basin, have a higher than average diogenitic component, while some others, dominantly in the equatorial regions, display a higher eucritic component in the regolith [*De Sanctis et al.*, 2012; *Ammannito et al.*, 2013a, 2013b; *McSween et al.*, 2013].

2. Data Analysis

NASA's Dawn spacecraft orbited and observed Vesta for slightly more than a year permitting detailed study of Vesta's surface and interior [*Russell et al.*, 2012; *De Sanctis et al.*, 2012; *Ammannito et al.*, 2013a; *Jaumann et al.*, 2012]. Rheasilvia impact basin is deep enough to have sampled the lower crust and possibly the upper mantle of Vesta, as confirmed by the presence of diogenite on its floor and in the rimming ejecta deposits [*De Sanctis et al.*, 2012; *Ammannito et al.*, 2013a, 2013b; *McSween et al.*, 2013]. In contrast, the equatorial highland Vestalia Terra shows quite uniform howarditic mineralogy [*De Sanctis et al.*, 2012; *Ammannito et al.*, 2013a, 2013b] with a few exceptions, such as Teia crater (Figure 1b). The impact crater Teia (271°E, 3.4°S, 6.6 km diameter) is located on the northwest flank of Brumalia Tholus (Figure 1a). Its ejecta, mapped as lineated crater material (unit lc) by *Buczkowski et al.* [2014], exhibit a distinctive striation pattern; the material extends in a fan-like pattern about 40 km wide and 30 km long to the north, down the slope of Brumalia Tholus (Figure 1). To the southeast this pattern is much more subdued and extends only a few kilometers from the crater rim because of the upslope position of the crater rim in this direction. The northwest ejecta pattern is particularly distinct when viewed in the infrared spectral data (Figures 1a and 1b).

The different composition of the asymmetric ejecta is clear in the color composite images. The ejecta also display an unusual morphology in the VIR color image (Figures 2a and 2b). The unusual pattern of the Teia ejecta is even stronger in the color composite normalized image, obtained scaling to 1 the values of the reflectance of each spectrum at a 1.2 μm. Normalization is a way to eliminate the difference

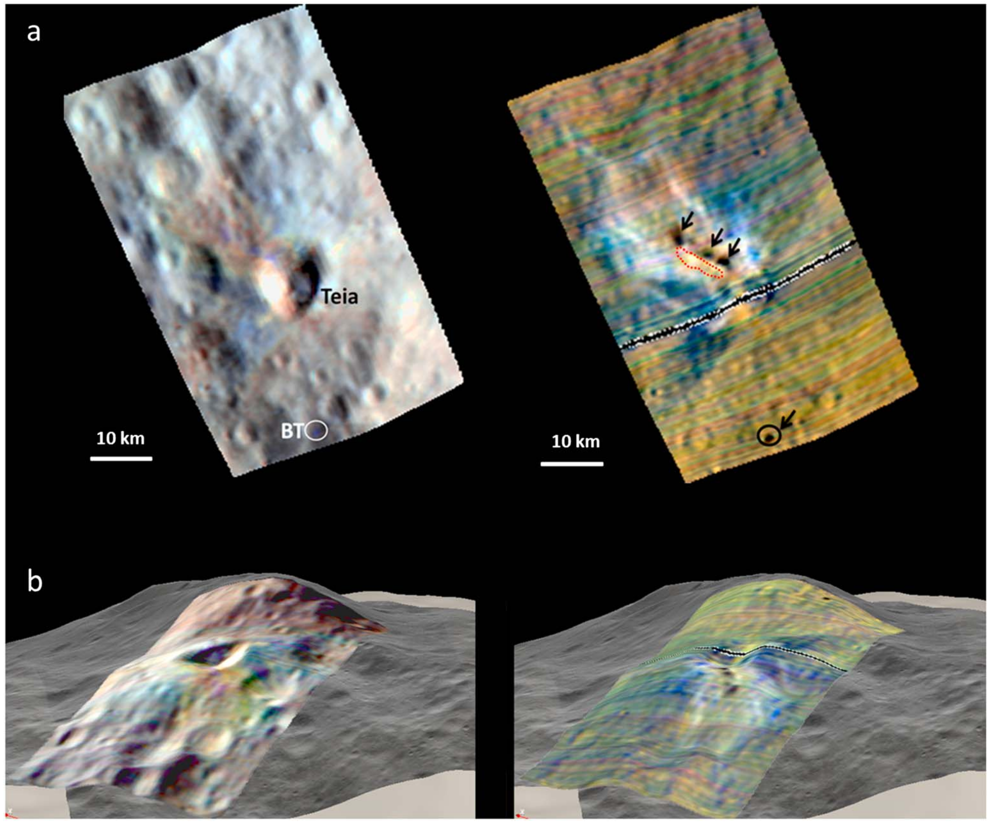

Figure 2. (a) Color composite (red (R): 2.00 μm, green (G): 1.66 μm, and blue (B): 1.15 μm) image of Teia crater and Brumalia Tholus (BT) obtained by VIR data with a nominal pixel size of 186 m (left); color composite (B: 1.54 μm, G: 1.76 μm, and R: 1.91 μm) image of Teia crater and Brumalia Tholus obtained by VIR data normalized at 1.2 μm (right). The central material in the ejecta is indicated by black arrows while the red lines indicate adjacent ejecta with different spectral characteristics. (b) VIR color composite as in Figure 2a draped over Vesta shape model.

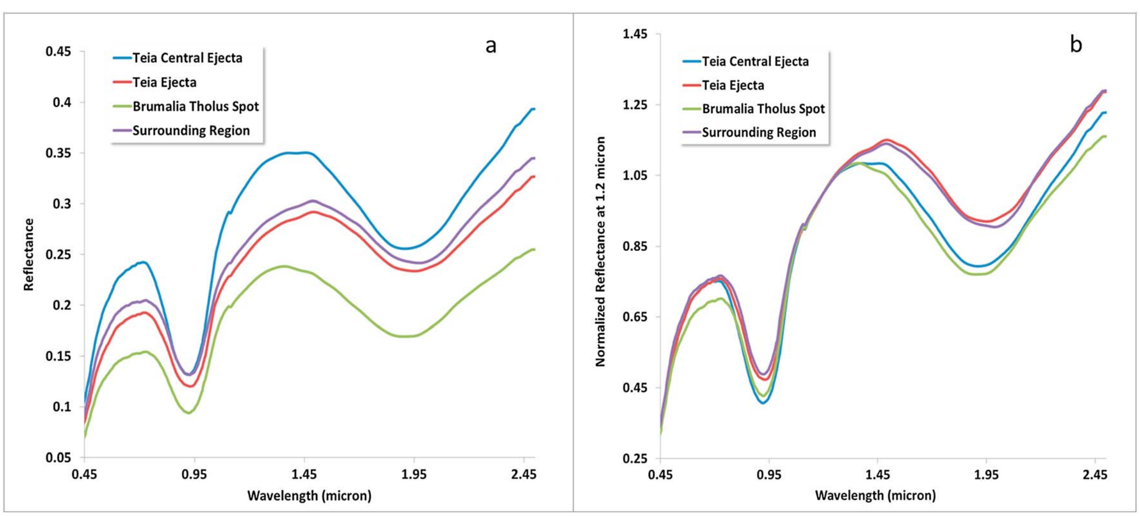

Figure 3. Spectra of Teia ejecta and Brumalia Tholus terrains. (a) Visible and infrared spectra representative of the Teia central ejecta (black arrows in Figure 2b), the adjacent ejecta (material within the red line in Figure 2b), the background material, and the small spot on top of Brumalia Tholus (BT circle in Figures 2a and 2b). (b). Spectra of Figure 3a normalized at 1.2 μm. The small bands around 1.05 μm are instrumental artifacts. The spectra were smoothed to reduce noise; the calibration details and data analysis procedure are describe in *Ammannito et al.* [2013a].

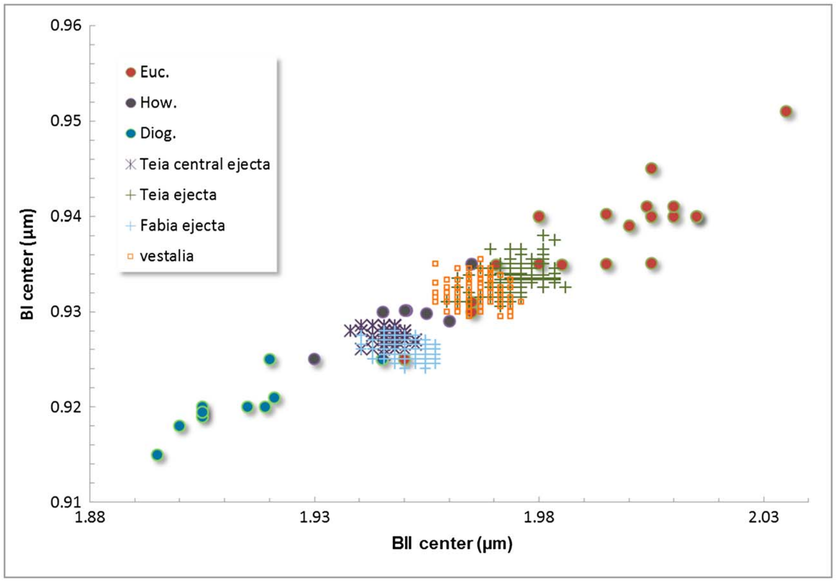

Figure 4. Scatterplot of band centers. HED data[21] are represented as colored circles and lie on a linear correlation trend: eucrites and diogenites plot in well-separated locations, while the howardite field lies in the middle of eucrites and diogenites. Data of Teia ejecta and Fabia ejecta are represented as crosses. The central ejecta (black arrows in Figure 2b) are indicated by black crosses and show shorter values of band centers with respect the background Vestalia Terra material (orange squares) and adjacent ejecta (green crosses) that, conversely, have longer values of BI and BII centers. Fabia ejecta (cyan crosses) have similar values to Teia central ejecta.

in illumination and albedo in order to enhance spectral differences. The normalized image reveals copious compositionally distinct ejecta that flowed downhill, following the steep slopes of Brumalia Tholus. A distinct color with respect the background is also seen in a very small spot on the top of Brumalia Tholus (BT in Figure 2a).

Analysis of the spectra of this area (Figure 3) demonstrates that Teia's ejecta have a different proportion of diogenite and eucrite as compared to the howarditic regolith that constitutes the background material. Similarly, the small spot on Brumalia Tholus shows a spectral difference with respect to the surrounding terrains. The central outflow in the Teia ejecta (black arrows in Figure 2a) and the spot on Brumalia Tholus (BT circle in Figure 2a) show similar spectra (Figure 2), with prominent pyroxene bands, indicating that the ejecta is likely sampling Brumalia's interior material.

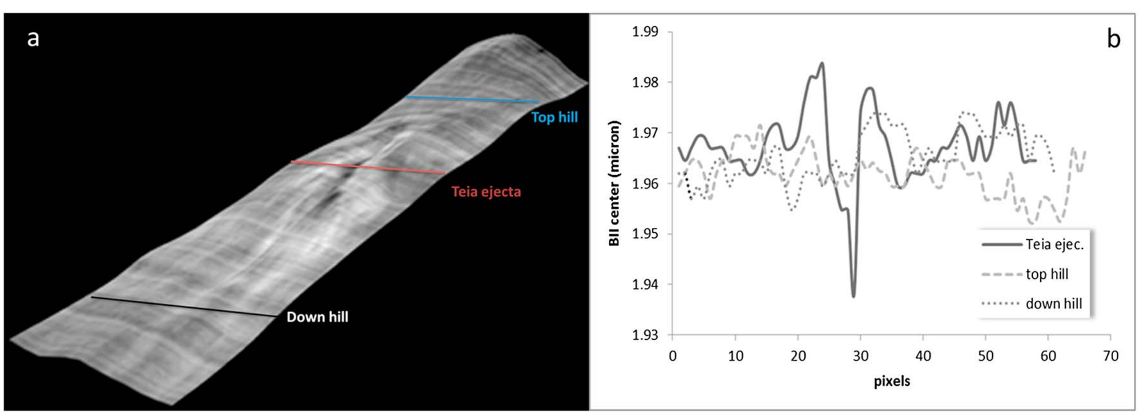

Figure 5. Distribution of BII center in Brumalia Tholus. (a) Locations of the different transects (top hill, downhill, and one cutting Teia ejecta) on BII center distribution. (b) Plot of the values of BII for the different transects. The central ejecta (black arrows in Figure 2b) shows the minimum value of BII, and it is embedded in ejecta with BII center larger than the background material.

Spectral data of HEDs indicate that band centers for 0.9 μm (hereafter BI) and 1.9 μm (hereafter BII) pyroxene absorptions are systematically different for diogenites and eucrites [*De Sanctis et al.*, 2013]. Thus, a plot of BI versus BII centers can distinguish different lithologies. In such a band center diagram, diogenites and eucrites cluster in distinct areas: BI and BII centers are at shorter wavelengths for diogenites than for eucrites, and howardites lie between but partially overlap the fields of diogenites and eucrites (Figure 4). The plot of the values of BI and BII of the Brumalia Tholus and Teia area is shown in Figure 4.

The distribution of the band centers indicates that Teia central ejecta are composed of howardite enriched in diogenitic material surrounded by a larger region of ejecta enriched in eucritic material. The distribution of material can be also seen in Figure 5 where transections of BII centers are plotted. It is clear that Teia's ejecta differ from the background material in that they show more extreme compositions: the central ejecta (black arrows in Figure 2a) show minimum values of BII (more diogenitic), and they are embedded in ejecta (red line in Figure 2a) with BII centers greater (more eucritic) than that of the background material.

VIR also identified diogenite-enriched material in a small crater on the top of Brumalia Tholus (BT in Figure 2b). The spectrum of this spot (Figure 3) shows strong band depths with relatively short band centers, and it is very similar to the spectra of Teia's central ejecta. Its mineralogy, derived from the values of pyroxenes band centers, indicates howardite that is enriched in diogenite, similar to that of Teia central ejecta.

3. Discussion

Considering the ejecta pattern and the distinct spectral signature, it seems most likely that the Teia ejecta consist of different subsurface materials, reflecting differences in composition and physical properties that were mixed by impact processes. This is supported by the fact that Brumalia Tholus is a positive surface feature that should at least partially contain more competent material than the rest of the vestan regolith. Impacts that occur on geological boundaries between rocks of different strengths, densities, and competence result in variations in the accelerations of the ejected material. Friction and turbulence in the ejected material that results from the inhomogeneous velocities could result in the striation pattern of the deposited material that is observed. The specific on-slope impact geometry of Teia crater will enhance this ejecta pattern, particularly downslope.

Although Teia crater appears almost circular, it shows the asymmetric crater shape of a sharp uphill rim and a subdued ejecta covered downhill rim [*Buczkowski et al.*, 2014, Figure 6], as is expected for impacts on slopes on Vesta [*Krohn et al.*, 2013]. This is consistent with the asymmetric butterfly distribution of the striation pattern, which is indicative of being formed by an oblique impact. Meanwhile the melty looking striated ejecta pattern is consistent with there being a geological boundary in the subsurface hit by the impact.

Teia crater is only 900 m deep, but this must be considered a minimum depth as the crater shows signs of considerable infilling [*Buczkowski et al.*, 2014]. Given the crater diameter, it is reasonable to assume that the maximum excavation depth is a couple of kilometers [*Melosh*, 1989; *Osinski and Pierazzo*, 2013; *Vincent et al.*, 2012] and the diogentic material of Brumalia Tholus is no more than a kilometer from the surface of Vesta.

Taking into account the compositional structure in the ejecta and the geomorphology of Brumalia Tholus, it appears that the central part of the rise is composed of competent diogenite rather than the eucritic ejecta in the surrounding regions. Differences in material properties in the central ejecta is also confirmed by the different temperature retrieved in the thermal infrared [*Tosi et al.*, 2014; *Keihm et al.*, 2012]. Temperatures derived from VIR infrared data indicate that the central ejecta are cooler than the surrounding material suggesting a different thermal inertia of the ejecta with respect the background.

Compositional and thermal evidence indicate that the subsurface of Brumalia Tholus is most likely composed of different material than the surrounding regolith. There are two possibilities for a geological boundary in the subsurface of this region: (i) Brumalia Tholus is a large block of lower crust or upper mantle that was excavated by a giant low velocity impact such as Rheasilvia or Veneneia and deposited on Vestalia Terra or (ii) Brumalia Tholus is the top of an intrusive plutonic body such as a dike or laccolith.

In the first hypothesis, low velocity giant impacts may disrupt large parts of the lower crust and excavate coherent blocks that would, in some cases, be deposited upside down or in more or less vertical position simulating a hill or even mountain when covered by ejecta of subsequent nearby impacts. However, Brumalia Tholus is not close to the rim of Rheasilvia, where the largest blocks of material should be deposited. Moreover, this requires that Vestalia Terra is covered by a significant amount of Rheasilvia ejecta. There are three major arguments against this assumption. First, Vestalia Terra is a highland region whose southern portion shows a strong positive Bouguer gravity anomaly, indicting denser than average material. Second, the spectral signature of Vestalia Terra is distinct from that of Rheasilvia ejecta, where diogenitic-rich lithologies are recognized [*De Sanctis et al.*, 2012; *Ammannito et al.*, 2013a, 2013b]. The mineralogy of Vestalia Terra central region, where Teia is located, is mainly eucritic-rich howardites. No other crater on this region, except for Teia, shows diogenite in the ejecta, indicating a quite uniform mineralogy of the shallow subsurface. In addition, the orientation of Brumalia Tholus relative to Albalonga Catena strongly suggests that the formation of the two features are related [*Buczkowski et al.*, 2014], which would not be true if Brumalia simply represented a Rheasilvia ejecta block.

In the second hypothesis, Teia crater excavates the northern face of Brumalia Tholus and thus its ejecta samples Brumalia's interior material. The identification of howardite enriched in diogenite on the top of Brumalia Tholus and in the ejecta of Teia crater is consistent with the presence of a subsurface magmatic intrusion. Moreover, an enrichment in eucritic material in some of the Teia ejecta seems to indicate that the eucritic old crust also has been sampled by the Teia impact.

4. Conclusion

The morphology and composition of Teia ejecta are very peculiar and different from most of the other crater ejecta on Vestalia Terra, with exception of Fabia crater. This crater, on the northern border of Vestalia Terra, has also ejecta with distinct composition with respect the background, showing an enrichment of diogenitic material with respect the rest of Vestalia Terra. However, Fabia is at much lower elevation with respect to Teia and could sample material that is below the Vestalia Terra crust.

Vestalia Terra is a distinct region of Vesta: it has been suggested that part of this region is composed of a denser material than the rest of Vesta's crust [*Raymond et al.*, 2013]. The greater density, associated with the high topography, suggests the possible presence of mantle material at shallow depth under the plateau. In this case, the small Fabia impact could have excavated material with lower crustal or upper mantle lithologies. The detailed compositional information presented here, indicating an enrichment in orthopyroxene in the Teia and also the Fabia ejecta, supports the hypothesis of sill-like intrusions or shallow mantle beneath Vestalia Terra. The identification of magmatic activity on Vesta provides long-awaited confirmation that Vesta formed and evolved in a similar manner to the terrestrial planets.

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