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Vesta's north pole quadrangle Av-1 (Albana): Geologic map and the nature of the south polar basin antipodes

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A B S T R A C T

As part of systematic global mapping of Vesta using data returned by the *Dawn* spacecraft, we have produced a geologic map of the north pole quadrangle, Av-1 Albana. Extensive seasonal shadows were present in the north polar region at the time of the *Dawn* observations, limiting the ability to map morphological features and employ color or spectral data for determination of composition. The major recognizable units present include ancient cratered highlands and younger crater-related units (undivided ejecta, and mass-wasting material on crater floors). The antipode of Vesta's large southern impact basins, Rheasilvia and Veneneia, lie within or near the Av-1 quadrangle. Therefore it is of particular interest to search for evidence of features of the kind that are found at basin antipodes on other planetary bodies. Albedo markings known as lunar swirls are correlated with basin antipodes and the presence of crustal magnetic anomalies on the Moon, but lighting conditions preclude recognition of such albedo features in images of the antipode of Vesta's Rheasilvia basin. "Hilly and lineated terrain," found at the antipodes of large basins on the Moon and Mercury, is not present at the Rheasilvia or Veneneia antipodes. We have identified small-scale linear depressions that may be related to increased fracturing in the Rheasilvia and Veneneia antipodal areas, consistent with impact-induced stresses (Buczkowski, D. et al. [2012b]. Analysis of the large scale troughs on Vesta and correlation to a model of giant impact into a differentiated asteroid. Geol. Soc. of America Annual Meeting. Abstract 152-4; Bowling, T.J. et al. [2013]. J. Geophys. Res. – Planets, 118. http://dx.doi.org/10.1002/jgre.20123). The general high elevation of much of the north polar region could, in part, be a result of uplift caused by the Rheasilvia basin-forming impact, as predicted by numerical modeling (Bowling, T.J. et al. [2013]. J. Geophys. Res. – Planets, 118. http://dx.doi.org/10.1002/jgre.20123). However, stratigraphic and crater size–frequency distribution analysis indicate that the elevated terrain predates the two southern basins and hence is likely a remnant of the ancient vestan crust. The lack of large-scale morphological features at the basin antipodes can be attributed to weakened antipodal constructive interference of seismic waves caused by an oblique impact or by Vesta's non-spherical shape, or by attenuation of seismic waves because of the physical properties of Vesta's interior. A first-order analysis of the *Dawn* global digital elevation model for Vesta indicates that areas of permanent shadow are unlikely to be present in the vicinity of the north pole.

1. Introduction

The existence of a large impact basin near Vesta's south pole was discovered through imaging with the *Hubble Space Telescope*

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(Thomas et al., 1997; Binzel et al., 1997; Kattoum and Dombard, 2009). Mapping by the *Dawn* spacecraft in orbit around Vesta confirmed that the south polar basin, now named Rheasilvia, is ~500 km in diameter and ~19 km deep (Jaumann et al., 2012; Schenk et al., 2012; Marchi et al., 2012). The basin's diameter is about 88% of the length of the asteroid's major axis. *Dawn* also discovered a second, older, large southern basin (Veneneia, 400 km diameter). Approximately half of Veneneia was destroyed by the Rheasilvia basin-forming event (Jaumann et al., 2012; Schenk et al., 2012; Marchi et al., 2012). The age of Rheasilvia has been estimated using the observed crater size–frequency distribution and a lunar-like production function to be ~3.53 byr (Schmedemann et al., 2013); a separate estimate obtained by scaling the average Main Belt asteroid size–frequency distribution to vestan crater sizes yields an age of ~1 byr (Marchi et al., 2012; Schenk et al., 2012). The model ages of Veneneia are ~3.75 Ga (lower limit, Schmedemann et al., 2013) and ~2 Ga (Marchi et al., 2012; Schenk et al., 2012).

On other Solar System bodies, unusual features are sometimes found near the antipode (point diametrically opposite) to large impact basins (see summary in Table 1). "Hilly and lineated" material (Murray et al., 1974; Melosh and McKinnon, 1988) located at the antipode of Mercury's Caloris basin may have been formed by converging seismic waves (Schultz and Gault, 1975; Hughes et al., 1977; Lü et al., 2011) or ejecta (Moore et al., 1974) from the Caloris impact. The regions antipodal to Mercury's other large basins (Tolstoj, Beethoven, Rembrandt) have been resurfaced by volcanic plains or by formation of other basins, thus it is not known if hilly and lineated terrain was formed there (Blewett et al., 2010).

Grooved and broken-up terrain like that at the Caloris antipode occurs at the antipodes of the lunar Imbrium, Serenitatis, Orientale, and Crisium basins (Moore et al., 1974; Schultz and Gault, 1975; Stuart-Alexander, 1978; Wilhelms, 1987), suggesting that similar processes accompanied the formation of these basins (Table 1). The South Pole-Aitken (SPA) basin is the largest recognized impact basin on the Moon (e.g., Schultz, 1976; Stuart-Alexander, 1978; Belton et al., 1992), with a diameter of ~2500 km. The SPA antipode lies within the younger Imbrium basin, therefore any hilly and lineated terrain that may have been formed by SPA was destroyed by the Imbrium basin-forming event. However, Schultz and Crawford (2011) used evidence from laboratory impact experiments and numerical hydrocode simulations to conclude that the SPA collision caused extensive antipodal fracturing in the mantle and lower crust that provided pathways for later mare volcanism, explaining the nearside–farside asymmetry in the distribution of the maria. Schultz and Crawford (2011) also suggest that a system of nearside structural elements, attributed by others to the proposed Procellarum basin (e.g., Whitaker, 1981), are radial and concentric to the SPA antipode and can be explained by SPA antipodal effects.

On Mars, the Alba Patera shield volcano is antipodal to the center of the 2300 km diameter Hellas basin. Williams and Greeley (1994) used numerical modeling to show that the Hellas impact was energetic enough to fracture the crust at the Hellas antipode, resulting in potential conduits for later volcanism that formed Alba Patera (Williams and Greeley, 1994; Peterson, 1978). The extensive volcanism related to Alba Patera would have buried any hilly and lineated terrain that may have existed.

Large impact basins have formed on icy satellites of the outer Solar System (e.g., Schenk, 2010; Schenk et al., 2012, 2013). Hilly and lineated type terrain has not been recognized on these bodies. On Mimas, craters in the area antipodal to the Herschel basin are unusually shallow, possibly a result of antipodal focusing of ejecta or seismic energy (Schenk, 2010).

A correlation between areas of magnetized crust, swirl-like albedo anomalies, and basin antipodes is found on the Moon (Lin et al., 1988; Richmond et al., 2005). The creation of an antipodal magnetic anomaly may involve the amplification of existing magnetic fields by the expanding vapor-melt cloud in a large impact (Hood and Artemieva, 2008), or shock effects of converging ejecta (Hood et al., 2013). Lunar swirls (e.g., El-Baz, 1972; Schultz, 1976; Hood and Schubert, 1980; Schultz and Srnka, 1980; Hood and Williams, 1989; Blewett et al., 2011; Garrick-Bethell et al., 2011; Kramer et al., 2011a,b) are high-reflectance markings with diffuse edges and no measurable topographic expression. According to the solar-wind standoff model for lunar swirls (Hood and Schubert, 1980), the presence of a crustal magnetic anomaly leads to deflection of solar-wind ions, thus protecting the surface from the normal lunar space-weathering process that causes darkening and reddening of freshly exposed material (see Hapke, 2001 for a review of the effects and causes of lunar-style space weathering).

It is clear that Vesta's Rheasilvia and Veneneia impacts produced global effects in the form of the Divalia Fossae and Saturnalia Fossae tectonic troughs (Buczkowski et al., 2012a,b; Jaumann et al., 2012; Scully et al., 2014). Thus, an interesting question is whether unusual terrain texture or albedo patches occur at the antipodes of Vesta's large basins. Inspection of Table 1 would lead to a simple prediction that any crater with a diameter greater than ~0.2 of its target body size should have produced disrupted terrain at the antipode. Bowling et al. (2012, 2013) carried out numerical modeling of the Rheasilvia impact and predicted that antipodal focusing of the impact stress wave would cause large extensional radial strains at the antipode, resulting in uplifted topography and deformed terrain (discussed further in Section 4). Also, Buczkowski et al. (2012b) reported that hydrocode modeling of a Rheasilvia-like impact produced large differential stresses at the antipode. Impact modeling by Jutzi and Asphaug (2011) suggested that the formation of the Rheasilvia basin would have deposited ejecta in the northern hemisphere.

The presence or absence of antipodal terrain on Vesta thus will provide clues to the role of gravity and internal structure (e.g., seismic velocity, porosity, crust–mantle density contrast, and core size/strength) in the formation of basin-related units. Identification of swirl-like albedo or color anomalies near the antipodes of Vesta's large basins could imply that (1) an antipodal magnetization process (Hood and Artemieva, 2008; Hood et al., 2013) took place and produced a crustal magnetic anomaly, and (2) that the solar wind contributes to space-weathering on Vesta, as it does on the Moon and S-type asteroids.

Table 1
Characteristics of large impact basins on Mercury, the Moon, Mars, and Mimas, with Vesta's large basins Rheasilvia and Veneneia.

Basin name[a]	Basin diameter, km	Basin diam./target body diam.
Caloris [y]	1550	0.32
Rembrandt [ob]	715	0.15
Beethoven [ob]	625	0.13
Tolstoj [ob]	510	0.10
South Pole-Aitken [ob]	2500	0.72
Imbrium [y]	1160	0.33
Orientale [y]	930	0.27
Serenitatis [y]	920	0.26
Crisium [y]	740	0.21
Hellas [ob]	2300	0.34
Herschel [n]	139	0.35
Rheasilvia [n]	500	0.88
Veneneia [n]	400	0.70

[a] "Hilly and lineated" terrain at antipode: yes, no, obscured by later activity. Table updated from Blewett et al. (2010). Herschel, Rheasilvia and Veneneia, while lacking hilly and lineated antipodal terrain, do possess other, more subtle morphologic features that could be related to antipodal effects, and flood volcanism at the South Pole-Aitken and Hellas antipodes could have been facilitated by fracturing induced by the formation of these basins (see text).