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Geologic mapping of Vesta

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A B S T R A C T

We report on a preliminary global geologic map of Vesta, based on data from the Dawn spacecraft's High-Altitude Mapping Orbit (HAMO) and informed by Low-Altitude Mapping Orbit (LAMO) data. This map is part of an iterative mapping effort; the geologic map has been refined with each improvement in resolution. Vesta has a heavily-cratered surface, with large craters evident in numerous locations. The south pole is dominated by an impact structure identified before Dawn's arrival. Two large impact structures have been resolved: the younger, larger Rheasilvia structure, and the older, more degraded Veneneia structure. The surface is also characterized by a system of deep, globe-girdling equatorial troughs and ridges, as well as an older system of troughs and ridges to the north. Troughs and ridges are also evident cutting across, and spiraling arcuately from, the Rheasilvia central mound. However, no volcanic features have been unequivocally identified. Vesta can be divided very broadly into three terrains: heavily-cratered terrain; ridge-and-trough terrain (equatorial and northern); and terrain associated with the Rheasilvia crater. Localized features include bright and dark material and ejecta (some defined specifically by color); lobate deposits; and mass-wasting materials. No obvious volcanic features are evident. Stratigraphy of Vesta's geologic units suggests a history in which formation of a primary crust was followed by the formation of impact craters, including Veneneia and the associated Saturnalia Fossae unit. Formation of Rheasilvia followed, along with associated structural deformation that shaped the Divalia Fossae ridge-and-trough unit at the equator. Subsequent impacts and mass wasting events subdued impact craters, rims and portions of ridge-and-trough sets, and formed slumps and landslides, especially within crater floors and along crater rims and scarps. Subsequent to the formation of Rheasilvia, discontinuous low-albedo deposits formed or were emplaced; these lie stratigraphically above the equatorial ridges that likely were formed by Rheasilvia. The last features to be formed were craters with bright rays and other surface mantling deposits. Executed progressively throughout data acquisition, the iterative mapping process provided the team with geologic proto-units in a timely manner. However, interpretation of the resulting map was hampered by the necessity to provide the team with a standard nomenclature and symbology early in the process. With regard to mapping and interpreting units, the mapping process was hindered by the lack of calibrated mineralogic information. Topography and shadow played an important role in discriminating features and terrains, especially in the early stages of data acquisition.

1. Introduction

Geologic mapping is a comprehensive investigative process that organizes disparate datasets into geologic units with the goal of revealing the underlying geologic processes and placing those

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processes into a global, contextual framework. The arrival of the Dawn spacecraft at the asteroid Vesta provides a first opportunity for this approach to be utilized for Vesta at the sub-km scale, at which features such as impact craters, local landslides and tectonic structures can be resolved. The inner main belt asteroid Vesta is a particularly compelling target for this traditional investigative process because of long-standing evidence for its basaltic surface and longitudinal mineralogic heterogeneity gathered first through Earth-based polarimetric and spectroscopic measurements (Degewij et al., 1979; Gaffey, 1997, 1983; McCord et al., 1970; Reddy et al., 2010). Such a surface indicated a differentiated crust and, potentially, volcanic activity in Vesta's past.

Prior to the arrival of the Dawn spacecraft, the highest-resolution images of the surface of Vesta (38 km/pixel) were provided by the Hubble Space Telescope (HST; Li et al., 2010). During favorable approach conditions in 1994 and 1996, the HST provided reflectance data at 0.439, 0.673, 0.953 and 1.042 μm, and from these data, albedo, elevation and mineralogical data were derived, from which maps of mineralogic composition and lithology were produced (Binzel et al., 1997; Gaffey, 1997; Li et al., 2008, 2006) These data revealed a surface dominated by regionally distinct units interpreted to be impact-excavated pyroxene-rich plutonic material, results that agreed generally with mineralogic maps created from Earth-based spectroscopy (Degewij et al., 1979; Gaffey, 1997, 1983; Reddy et al., 2010). Though necessarily generated from images with a resolution no better than 38.5–52 km/pixel (Binzel et al., 1997; Li et al., 2010, 2008; Zellner et al., 1997), these maps represented first steps in understanding Vesta's geologic history.

NASA's Dawn spacecraft entered Vestan orbit on July 16, 2011, and spent one year in orbit to characterize its geomorphology, elemental and mineralogical composition, topography, shape, and internal structure before departing to asteroid Ceres on September 5, 2012. Three orbital phases of the mission returned images at successively higher resolutions; the highest of these was 20–25 m/pixel. Preliminary geologic results from the initial orbital phase ("Survey orbit") are reported by Russell et al. (2012) and Jaumann et al. (2012).

During the pre-encounter phase of the mission, the Dawn science team followed the recommendations of Batson (1990) for planetary geologic mapping and divided the asteroid into 15 quadrangles for geologic mapping. Preliminary global geologic maps were also produced in an iterative fashion as new data became available (Yingst et al., 2012, 2011). These iterations of the global geologic map were utilized by the science team during the active phases of the mission to inform evolving hypotheses, correlate crater size-frequency statistics, mineralogic data and other products with preliminary geologic units, and place new data within a baseline geologic context. This work represents the compilation and analysis of these iterative efforts.

2. Approach

A geologic map is a visual representation of the distribution and sequence of rock types and other geologic information. It allows observations to be organized and represented in an intuitive format, unifies observations of heterogeneous surfaces made at different localities into a comprehensive whole, and provides a framework for science questions to be answered. A geologic map defines boundaries for the extent and overlap of important characteristics such as mineralogy, topography, morphology and elemental abundance. This information can then be used to analyze relationships between these characteristics; this, in turn, can inform models of thermal and structural evolution. In the case of Vesta, a geologic map also would allow the HED (howardite, eucrite and diogenite) meteorites (a family of meteorites believed to have originated from Vesta (Binzel and Xu, 1993; Consolmagno and Drake, 1977; McCord et al., 1970) and discussed in more detail in Section 3) to be placed in geologic context, should the sources be located.

The goals in creating any geologic map determine the level of detail at which the map is created, and thus the required spatial resolution of data selected for the base map. Where the goal is to summarize the current state of knowledge for a region for archiving, the presented map will differ from one where the purpose is to provide a preliminary overview of geologic context in a setting where data collection is in process, or where the amount or type of data available varies across the mapped region. These latter maps are often iterative – that is, multiple versions are created because each iteration is refined as data become available. An example of such a situation is the geologic mapping that may occur during field work, where a sketch map of local units or layers is created first to inform the choice of future sampling locations, and is updated as those samples are collected and analyzed. The more comprehensive geologic map is generated later, when all the available data has been acquired, refined and analyzed in detail.

An orbital mission to another planetary body is analogous to this scenario of field work followed by data analysis, where time in the field mirrors the period of spacecraft data acquisition. A detailed geologic map is often generated after the mission ends, once all the data are acquired and have been fully calibrated and refined. However, as in field work, analysis of data begins as soon as it is acquired. Iterative mapping is a process that provides the geologic context for, and reveals the interrelationships of, geologic characteristics revealed by each emerging dataset. Further, it can do so within a timeframe that allows the map to inform data analysis of other team members on the mission timeline.

The global geologic maps presented here demonstrate the progression of lessons learned from generating each iteration (Yingst et al., 2012, 2011). Where possible, we have referred back to units and surface features identified by mapping efforts that predate the Dawn mission (Binzel et al., 1997; Gaffey, 1997); we note that because the spatial resolution available for these mapping efforts was ~500 times coarser than that available here, there are previously named and mapped regions that are not included because they do not exist as geologically defined features. This includes Olbers Regio, identified in HST images as a dark ovoid region approximately 200 km across. For the final iteration of the map we include type examples of units and landforms, and descriptions and interpretations of primary units; we also attempt to deconvolve and interpret the basic stratigraphy in a relative sense utilizing stratigraphic relationships. We intend for the map to provide a contextual framework for more advanced compositional and/or geomorphological mapping at large scales (smaller regions). However, because the process of data analysis is still in its early stages as of this writing, we expect the concepts for the units and structures presented to evolve as analysis and understanding mature. Our goals for this work are thus twofold: firstly, to provide the community with a preliminary assessment of the geology of Vesta, using traditional geologic mapping methods as a primary tool to perform this assessment; and secondly, to report on and analyze the mapping process as it was conducted during an active mission, where iterative products were fed directly to the team to inform subsequent data acquisition and analysis.

3. Geologic setting

Vesta is an ellipsoidal asteroid with dimensions estimated at $286.3 \times 278.6 \times 223.2 \pm 0.1$ km (Russell et al., 2012). Efforts by