

VESTA'S ELEMENTAL COMPOSITION. T.H. Prettyman,¹ A.W. Beck,² W.C. Feldman,¹ D.J. Lawrence,³ T.J. McCoy,² H.Y. McSween,⁴ D.W. Mittlefehldt,⁵ P.N. Peplowski,³ C.A. Raymond,⁶ R.C. Reedy,¹ C.T. Russell,⁷ T.N. Titus,⁸ M.J. Toplis,⁹ N. Yamashita,¹ ¹Planetary Science Institute (1700 East Fort Lowell, Suite 106, Tucson, AZ 85719-2395, prettyman@psi.edu), ²Smithsonian Institution, ³Johns Hopkins University Applied Physics Laboratory, ⁴University of Tennessee, ⁵NASA Johnson Space Center, ⁶Jet Propulsion Laboratory, Caltech, Pasadena, CA, ⁷University of California, Los Angeles, ⁸USGS Astrogeology Science Center, ⁹University of Toulouse.

Introduction: Many lines of evidence (e.g. common geochemistry, chronology, O-isotope trends, and the presence of different HED rock types in polymict breccias) indicate that the howardite, eucrite, and diogenite (HED) meteorites originated from a single parent body.[1] Meteorite studies show that this protoplanet underwent igneous differentiation to form a metallic core, an ultramafic mantle, and a basaltic crust.[1] A spectroscopic match between the HEDs and 4 Vesta [2] along with a plausible mechanism for their transfer to Earth, perhaps as chips off V-type asteroids ejected from Vesta's southern impact basin, supports the consensus view that many of these achondritic meteorites are samples of Vesta's crust and upper mantle.[3]

The HED-Vesta connection was put to the test by the NASA Dawn mission, which spent a year in close proximity to Vesta.[4] Measurements by Dawn's three instruments, redundant Framing Cameras (FC), a Visible-Infrared (VIR) spectrometer, and a Gamma Ray and Neutron Detector (GRaND), along with radio science have strengthened the link. Gravity measurements by Dawn are consistent with a differentiated, silicate body, with a dense Fe-rich core.[4] The range of pyroxene compositions determined by VIR overlaps that of the howardites.[5] Elemental abundances determined by nuclear spectroscopy are also consistent with HED-compositions.[6] Observations by GRaND provided a new view of Vesta inaccessible by telescopic observations. Here, we summarize the results of Dawn's geochemical investigation of Vesta and their implications.

A GRaND View of Vesta. Dawn's nuclear spectrometer (GRaND) was originally intended to be a "carbon-copy" of the Lunar Prospector Gamma-Ray Spectrometer (LP-GRS); however, the placement of the instrument on the deck of the spacecraft necessitated some design changes.[7] Like LP-GRS, GRaND contains a large-volume bismuth-germanate (BGO) scintillator, which serves as the primary gamma ray detector; however, unlike LP-GRS, GRaND's boron-loaded plastic (BLP) anti-coincidence shield and neutron spectrometer is segmented to enable contributions from Vesta (and Ceres) to be separated from spacecraft background. In addition, Li-loaded glass scintillators and Gd metal were strategically-added to the faces of the downward- and upward-facing BLP segments to enable separation of thermal and epithermal neutron

components. Finally, an array of room-temperature semiconductors (CdZnTe), with better gamma-ray energy-resolution than BGO, was flown as a demonstration technology. The selected arrangement of sensors enables gamma ray spectroscopy up to ~10 MeV, a range that includes signatures for major elements such as Fe, Si, Mg, and O and radioelements K, Th, and U. GRaND's neutron measurements are sensitive to moderation by H, neutron absorption, and the average atomic mass of Vesta's regolith.

Close proximity and long integration times are required for nuclear spectroscopy. Thus, Dawn spent ~5 months in a low altitude circular, polar mapping orbit (about 1.79 body radii from center), which enabled full global mapping of selected elemental signatures. Despite similarities in spectrometer design, the sensitivity of these measurements was lower than that of Lunar Prospector, which flew much closer to the Moon (1.02 body radii from center). For Vesta, the intrinsic spatial resolution of map products was on the order of 300 km, somewhat smaller in scale than the Rheasilvia impact basin. The measurements are sensitive to regolith composition to depths of several decimeters.

The global regolith. The Fe/O and Fe/Si mass ratios for Vesta's global regolith, determined by gamma ray spectroscopy (BGO), are consistent with HED compositions (howardite).[6] The error ellipses exclude most other achondrite compositions, all chondrites and stony-iron meteorites. These observations indicate that Vesta's howarditic regolith does not contain significant exogenic Fe-Ni metal, beyond that observed in howardite, which implies that Vesta is not the source of the mesosiderites. The detection limit for the radioelement K (<1 mg/g),[6] abundant in glass spherules found in some howardites,[8] is consistent with the low concentrations found in HEDs,[6] ruling out evolved, K-rich lithologies as a major crustal component.

Exogenic hydrogen. Vesta's regolith contained unexpectedly high concentrations of hydrogen, as determined by measurements of epithermal neutrons [6] and confirmed by an analysis of fast neutron counting data.[9] The range of hydrogen on Vesta is about 400 $\mu\text{g/g}$, with the highest concentrations found in Vesta's dark hemisphere near the equator.[6] In these locations, water ice is not stable within the depths sensed

by GRaND. Furthermore, the global maximum is much higher than for lunar soils, which contain solar-wind hydrogen (typically $<100 \mu\text{g/g H}$). [6] Comparative analyses of Ne isotope ratios in lunar samples and regolithic howardites show that hydrogen content of Vesta's regolith that is derived from the solar wind must be much smaller than that of the Moon. [6] Although Vesta's magmas incorporated some water, [10] the source of surficial H seen by GRaND is not likely endogenic as Vesta formed from volatile-poor materials. [6] Rather, the observed anticorrelation of H with albedo points to the infall of exogenic carbonaceous chondrite material as the probable source. [6]

This hypothesis is supported by additional observations. The distribution of H is correlated with the $2.8 \mu\text{m}$ absorption band areas mapped by VIR, which is sensitive to OH content. [11] Carbonaceous chondrites contain hydrated phyllosilicates, which could serve as a stable reservoir of hydrogen. Some howardites contain clasts of carbonaceous chondrite, which have not undergone significant dewatering by impacts. C-type asteroids, some of which are located nearby, likely contributed hydrogen-rich material to Vesta. Finally, Vesta is the only asteroid for which evidence of surface alteration by volatiles has been found. [12] Pitted terrain found in the floors of young impact craters such as Marcia may have formed in high-velocity impacts that released volatiles from a regolith containing exogenic, hydrated minerals. [12, 13]

Elemental variegation. Vesta has long been known as a "colorful" asteroid, [14, 15] and GRaND's measurements reveal broad, spatial patterns that track with those seen by optical spectroscopy. A suite of elemental maps was recently published [6, 9, 16-18] and is now available from the NASA Planetary Data System Small Bodies Node. The archive includes maps of H, Fe, the effective thermal neutron macroscopic absorption cross section (Σ_{eff}), contributions of fast neutrons to average atomic mass ($\langle A \rangle$), and the high-energy gamma ray (HEGR) continuum. The latter three quantities are weighted averages of elemental abundances and are sensitive to different aspects of Vesta's composition. For example, Σ_{eff} is sensitive to Fe, which is primarily found in pyroxene, as well as Ca and Al, which are components of plagioclase. [18] Together, Fe and Σ_{eff} constrain the proportion of pyroxene and plagioclase in Vesta's surface.

The maps can be interpreted in terms of howardite petrology (e.g. see Fig 1). The Rheasilvia basin is diogenite-rich; whereas, the older terrane within Vesta's dark hemisphere is eucrite-rich. A lobe of diogenite-rich material extending northward from the Rheasilvia basin in the eastern hemisphere may be part of the

ejecta blanket, perhaps diagnostic of an oblique impact. A similar lobe is seen in compositional indices derived from FC and VIR data. The impact that formed Rheasilvia may have excavated portions of Vesta's harzburgitic mantle [19]; however, an elemental signature for olivine-rich lithologies within the basin is lacking. [18] A region of low-Fe and intermediate neutron absorption has been interpreted as a possible signature for cumulate eucrites [16]; however, the range of compositions sensed by GRaND is consistent with howardite. Vesta's pristine, ancient crust has been pulverized by impacts to produce a howarditic regolith.

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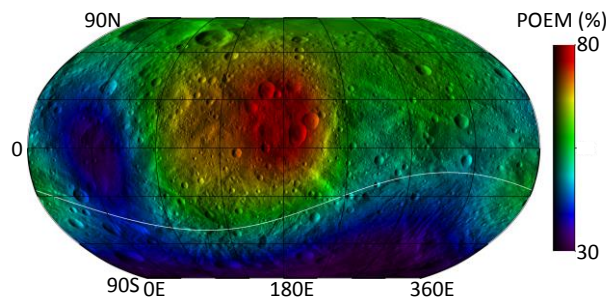


Fig. 1. The percentage of eucritic material (POEM) in Vesta's regolith determined by neutron spectroscopy [18] (color) is superimposed on shaded relief. Red regions are eucrite-rich; whereas, blue regions are rich in diogenite. The boundary of the Rheasilvia impact basin is shown (white line). Claudia longitudes [4] are shown.