Unique, Antique Vesta



Asteroid Vesta, 510 km in diameter. PHOTO CREDIT: NASA

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Most asteroids are collisional rubble from eons past, and few of them have survived intact. Vesta, the second most massive asteroid, is the only differentiated, rocky body in this category. This asteroid provides a unique view of the kinds of planetesimals that accreted to form the terrestrial planets. We know more about this asteroid than any other, thanks to its recently completed exploration by the orbiting Dawn spacecraft and studies of the ~1000 meteorites derived from it. The synergy provided by in situ analyses and samples has allowed an unparalleled understanding of Vesta's mineralogy, petrology, geochemistry, and geochronology.

KEYWORDS: Vesta, asteroid, HED meteorites, differentiation, impact

VESTA—OUTSIDE AND IN

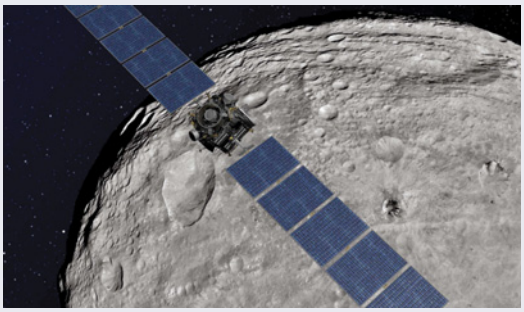
Asteroid Vesta, once called the smallest terrestrial planet (Keil 2002), is a leftover planetary building block. It was recently imaged, analyzed, and mapped from orbit by the Dawn spacecraft mission (described in Box 1).

Vesta has an average diameter of 510 km and a mean density of 3456 kg/m^3 (Russell et al. 2012). Although the body is massive enough to have assumed a spherical shape, it is conspicuously out of round, a consequence of a huge impact basin (FIG. 1) near its south pole (Schenk et al. 2012). This basin, called Rheasilvia[4], has a diameter almost equal to that of Vesta. Rheasilvia is superimposed on an older crater, Veneneia. The combined impacts excavated deeply enough to expose the Vestan mantle (Jutzi et al. 2013; McSween et al. 2013). The Rheasilvia event launched a host of multikilometer-sized bodies that are still orbitally linked to Vesta—the Vesta family, or "Vestoids" (Binzel and Xu 1993). Dislodged samples of the Vestoids have migrated into nearby resonances—"escape hatches" from which they were perturbed into Earth-crossing orbits to eventually become meteorites.

Vesta is covered with a regolith of impact-comminuted igneous rocks and pocked with hundreds of craters. However, no lava flows or other volcanic constructs are recognizable (Jaumann et al. 2012). Steep slopes are everywhere on Vesta, complicating our understanding of its geomorphology.

Modeling of Vesta's gravity and shape reveals its dense heart—an iron metal core 220 km across (Russell et al. 2012). The catastrophic Rheasilvia impact should likely have destroyed Vesta, but its metallic skeleton may have aided the asteroid's survival. The effects of Rheasilvia, though, are hard to miss. A girdle of ridges and troughs that encircles the equator (Buczkowski et al. 2012) is thought to be a result of seismic reverberations from the core, and a thick blanket of ejecta extends outward from the basin to cover the southern half of the asteroid (Schenk et al. 2012).

Box 1 THE DAWN MISSION



Artist's depiction of the Dawn spacecraft in orbit around Vesta. REPRODUCED COURTESY OF NASA

The Dawn spacecraft (Russell and Raymond 2011) was launched in September 2007 and traveled for nearly four years to reach its first objective, 4 Vesta. The spacecraft is powered by solar panels with an ~20 m wingspan, and thrust is provided by a novel ion propulsion system that expels xenon ions. After a slow but steady acceleration, Dawn now holds the records for the greatest velocity increase and the longest powered flight. Once in Vestan orbit, the spacecraft spent more than a year mapping the asteroid from altitudes of 2735, 685, and 210 km.

Dawn carries three kinds of instruments: dual Framing Cameras for geologic imagery and navigation, provided by the German Max Planck Institute for Solar System Studies; a Visible and Infrared Spectrometer (VIR) for mineral identification and mapping, provided by the Italian National Institute for Astrophysics; and a Gamma Ray and Neutron Detector (GRaND) for geochemical analysis and mapping, operated by the U.S. Planetary Science Institute. In addition, a gravity experiment, carried out using radio tracking of the spacecraft's orbit with detailed topographic mapping, provided constraints on Vesta's interior structure and on its mean density.

Upon completion of its exploration of Vesta in October 2012, Dawn departed Vesta's gravitational grasp and set sail on a three-year journey to 1 Ceres, the largest asteroid.

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4 The names of Vestan features follow a Roman naming convention; Rheasilvia is named after the mother of Rome's founders, Romulus and Remus.

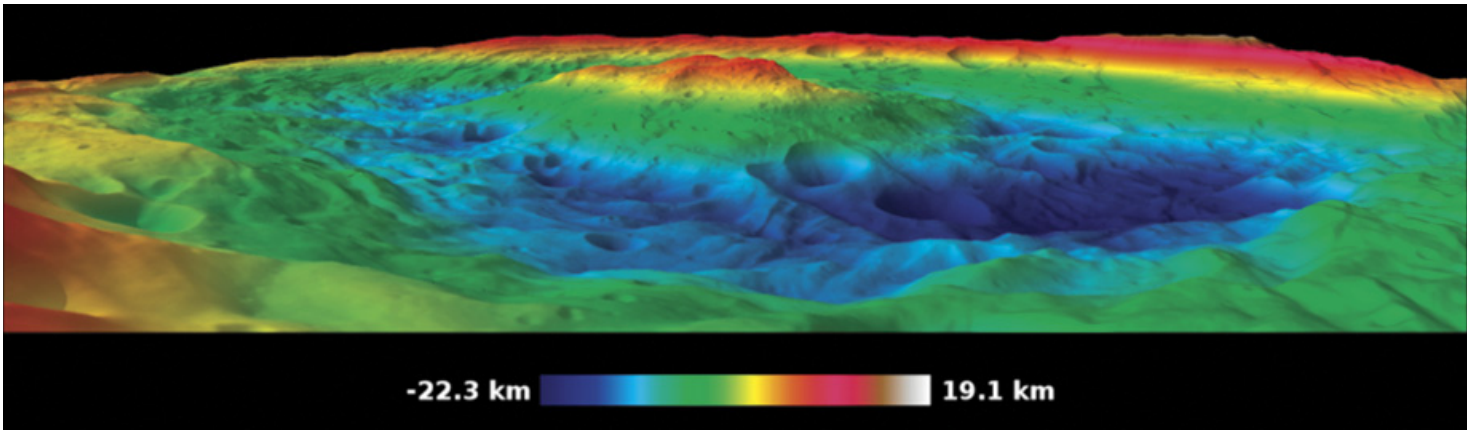


Figure 1 Perspective view of the topography of Vesta's south pole region, showing the huge Rheasilvia impact basin. Elevations, relative to the average Vesta surface, are indicated by coloration and demonstrate that this basin significantly affects the asteroid's overall shape. This view was compiled by the Dawn Science Team from Framing Camera images.

VESTA SAMPLES—HED METEORITES

Four decades ago, McCord et al. (1970) identified Vesta as the likely parent body for the igneous howardite-eucrite-diogenite ("HED") meteorites, based on their spectral similarities. Eucrites are comprised of plagioclase plus pyroxene and are commonly subdivided into fine-grained volcanic (basaltic eucrite) and coarse-grained plutonic (cumulate gabbroic eucrite) varieties (Fig. 2). Diogenites are ultramafic rocks formed through accumulation of crystals of orthopyroxene (pyroxenite) or orthopyroxene plus olivine (harzburgite) (Fig. 2). One mostly olivine cumulate (dunite) obviously linked to diogenites has also been described. Most eucrites and diogenites are breccias and represent regolith materials. These breccias can be monomict (containing clasts of a single lithology) or polymict (containing clasts of both basaltic and cumulate eucrite, or of multiple diogenite units). If both eucrite and diogenite clasts are present, the meteorite is a howardite. There is a continuum between polymict eucrites, howardites, and polymict diogenites, making the distinction somewhat arbitrary. The co-occurrence of these different rock types within breccias supports the idea that they formed on a common parent body. The oxygen isotope compositions of most HEDs also lie on the same ^{16}O–^{17}O–^{18}O mass-fractionation line (Greenwood et al. 2005), taken as a geochemical fingerprint of their parent asteroid. Descriptions of the petrology and geochemistry of these meteorites abound, and are most recently reviewed by McSween et al. (2011).

The crystallization ages of basaltic eucrites, determined from radiogenic isotopes (^{87}Rb–^{87}Sr, ^{147}Sm–^{143}Nd, ^{207}Pb–^{206}Pb), are ~4.5 billion years (numerous references in McSween et al. 2011). The measured ages of plutonic diogenites and cumulate eucrites tend to be slightly younger, likely reflecting slower cooling through the isotope blocking temperatures. The decay products of short-lived radionuclides (^{26}Al, ^{53}Mn, ^{182}Hf) are also found in HED meteorites, further confirming their ancient ages and the rapid differentiation of their parent body.

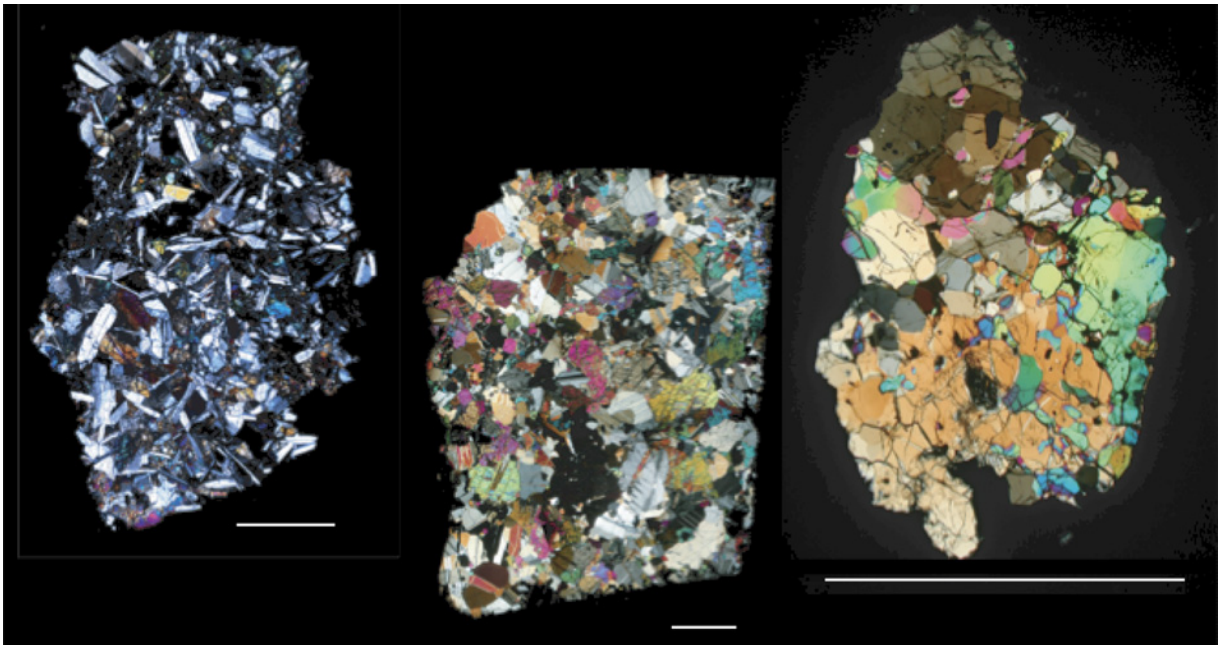


Figure 2 Photomicrographs (crossed polars) of (**left**) basaltic eucrite, composed of ferroan pyroxenes and plagioclase; (**center**) cumulate eucrite, composed of magnesian pyroxenes and plagioclase; and (**right**) diogenite, composed of orthopyroxene and, locally, olivine. Scale bars are 2.5 mm.

Despite the association of eucrites and diogenites in breccias, the petrogenetic relationships between them are not well understood. An early model explaining eucrites as partial melts and diogenites as solid residues (Stolper 1977) has mostly been supplanted by magma-ocean models that explain diogenites as cumulates and eucrites as residual liquids (e.g. Righter and Drake 1997; Greenwood et al. 2005; Mandler and Elkins-Tanton 2013). Asteroid-wide melting is suggested by rapid heating through decay of ^{26}Al. However, models indicate highly efficient melt removal from asteroid mantles, so that only a few percent of magma might be present at any particular time, possibly preventing formation of a magma ocean (Wilson and Keil 2012). For a body the size of Vesta, eruptions directly to the surface via dikes would be mechanically difficult; instead, large magma chambers would likely form in the subsurface, and flows could erupt episodically from these chambers (Wilson and Keil 2012; Mandler and Elkins-Tanton 2013). The varied trace element patterns in diogenites are consistent with their derivation from separate magma chambers (Shearer et al. 1997; Mittlefehldt et al. 2012), and geochemical trends in basaltic eucrites may require multiple magmas and complex processes within the crust (Barrat et al. 2007).

VESTA'S COMPOSITION AS MEASURED BY DAWN

Comparing the reflectance spectra of Vesta, as measured by a visible–infrared spectrometer (VIR) (De Sanctis et al. 2012a), with the spectra of HEDs provides a means of identifying surface lithologies. Figure 3 shows a plot of the center positions of the 1 µm and 2 µm absorption bands (henceforth called BI and BII) in well-characterized HED meteorites measured in the laboratory; these bands vary with pyroxene composition and abundance. The boxes in Figure 3 serve as a spectral classification, and a contoured, global cloud of Vestan spectral pixels measured by Dawn's VIR spectrometer is also shown. The greatest concentration of Vestan pixels corresponds to howardite or cumulate eucrite. Howardite, representing the regolith, is the more likely interpretation. The eucrite and diogenite boxes in Figure 3 are not completely populated by Vesta data. This presumably reflects the large spatial resolution of VIR data (~700 m/pixel at the altitude where global mapping occurred). Mixing of eucrite with diogenite, or vice versa, is apparently common at this scale on Vesta, pulling spectra towards the center of the plot.

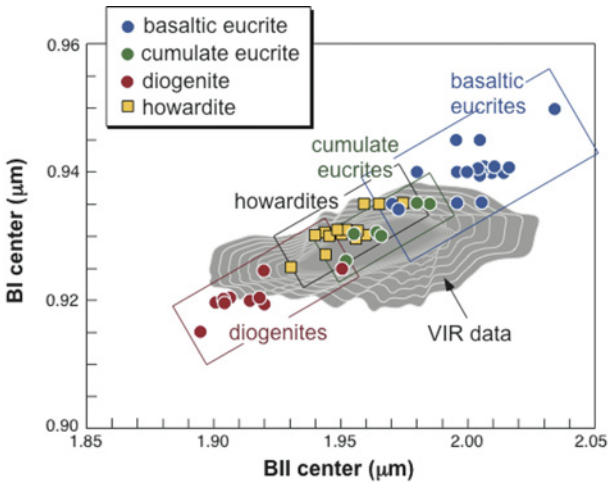


Figure 3 BI versus BII band center positions for spectra of HED meteorites, and a cloud of Vesta data measured by visible-light–infrared (VIR) spectroscopy. The boxes are defined by well-characterized HEDs, each having at least 30 spectral measurements.

Vesta's global weight ratio of Fe/Si and Fe/O, determined by GRaND (Prettyman et al. 2012), also identifies HED-like compositions (Fig. 4). In this diagram, howardite and diogenite provide the best match for Vesta data. Other meteorite types mostly plot outside the Vesta data ovals.

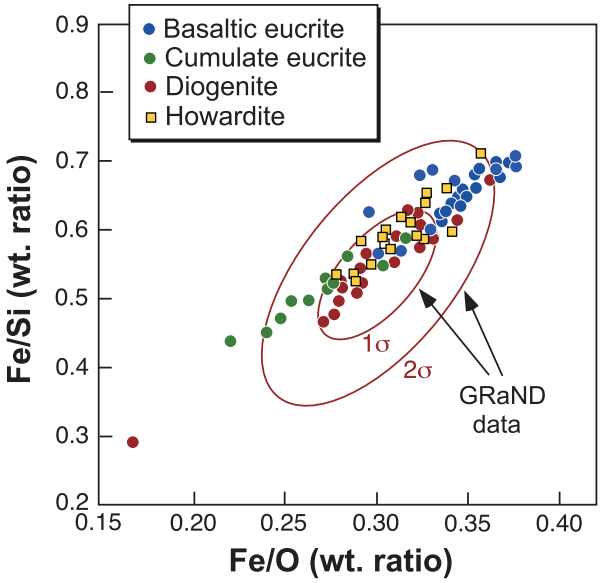


Figure 4 GRaND element ratios for Vesta compared to the compositions of HED meteorites. The 1σ and 2σ ovals indicate standard deviations of the mean for GRaND's Vesta data. Data from Prettyman et al. (2012)

A VIR global map (De Sanctis et al. 2012a), using the classification in Figure 3, distinguishes areas dominated by howardite, eucrite, and diogenite (Fig. 5). Eucrite mostly occurs in heavily cratered, ancient crust near the equator, and diogenite is concentrated in the southern hemisphere. A global map of GRaND-measured variations in neutron absorption (Prettyman et al. 2012), which relate to the different element abundances in eucrites and diogenites, is illustrated in Figure 6. Although the spatial footprint of GRaND is large (~300 km), these data confirm the distributions of HED lithologies determined by VIR spectra.

VIR and GRaND maps of Vesta's south pole region demonstrate that diogenite is exposed on the floor of the Rheasilvia basin and is a major component of its ejecta blanket (McSween et al. 2013). The estimated depth of excavation of Rheasilvia is at least twice the crustal thickness, so diogenite is interpreted as mantle rock. Although the occurrence of diogenite is at about the right depth (~20 km) for some magma-ocean models, its lateral extent is not known, so excavated plutons are possible.

The measured depletions of siderophile (metal-loving) trace elements (Righter and Drake 1997) and paleomagnetic indications of a former magnetic dynamo (Fu et al. 2012) in eucrites are evidence for a metal core in the HED parent asteroid. Compositional models of the interior of the HED parent body, constructed from the meteorite compositions, predict a metallic core with a mass fraction of 15–20% (Righter and Drake 1997). This compares favorably with the ~18% mass fraction of Vesta's core determined by Dawn (Russell et al. 2012).

VESTA'S CHRONOLOGY AND IMPACT HISTORY

The ages of Vesta's surface units, derived from the density of craters, are 3 to 4 billion years (Marchi et al. 2012). These are minimum ages, because the surface has become effectively saturated with craters, so that new craters destroy older ones. The ~4.5-billion-year crystallization ages of eucrites, and especially the former presence of short-lived radionuclides, reveal that Vesta melted and differentiated earlier, within the first several million years of Solar System history. However, somewhat younger ages for diogenites and cumulate eucrites indicate a protracted cooling history lasting perhaps 50 million years.

Like other bodies in the Solar System, Vesta was struck by careening, massive bolides in the period from 4.1 to 3.5 billion years ago. This period of high impactor flux, sometimes called the "late heavy bombardment," is thought to have resulted from gravitational stirring of the asteroid belt when the giant planets migrated inward or outward to their present orbital positions. This bombardment is revealed by a number of peaks among the ^{40}Ar–^{39}Ar ages of eucrite breccias, and these peaks represent a series of age-resetting events.

Rheasilvia, the most prominent feature on Vesta, is ~1.0 billion years old as determined from crater counting and therefore is considerably younger than the rest of the asteroid's surface (Marchi et al. 2012). This age is consistent with the ages of the Vestoids, the orbits of which would have been scrambled if they had been launched from Vesta much earlier.

VESTA'S SURPRISING SOIL

Although howardite covers most of Vesta's surface, it is not the most abundant type of HED meteorite. The Rheasilvia impact excavated much more material from the deep crust and mantle than from the veneer of regolith on the surface. A prediction that the regolith might have a globally homogenized composition (Warren et al. 2009) was not borne out, as Figures 5 and 6 show that the proportions of eucrite and diogenite in howardite terranes vary considerably. Although a few exotic components have been found in howardites, such as potassium-rich glasses suggested to represent a highly fractionated component analogous to lunar KREEP (Barrat et al. 2009), none has been detected at Dawn mapping scales.

Another surprise was GRaND's discovery of hydrogen in the regolith (Prettyman et al. 2012). Broad regions of the surface contain >400 µg/g H (Fig. 7), an abundance that cannot be explained by solar wind implantation, as on the Moon. The hydrogen-rich regions have low albedo and exhibit a 2.8 µm absorption in VIR spectra, which is attributable to OH in phyllosilicate minerals (De Sanctis et al. 2012b). In hindsight, this discovery should not have been a surprise. Howardites commonly contain foreign clasts of carbonaceous chondrite meteorites (Fig. 7), which are largely composed of OH-bearing serpentine and clays. Laboratory spectra of eucrites mixed with a few percent carbonaceous chondrite (which would give bulk hydrogen contents like those measured by GRaND) provide an excellent match with the spectra of these dark regions (Reddy et al. 2012).

Solar irradiation and micrometeorite bombardment have altered the spectrum of lunar soil—a process called space weathering. The spectral changes result from the production of nanoscale iron metal particles, which subdue absorption bands and modify the continuum slope. On Vesta, space weathering takes a different form. Although the albedo of the Vestan surface exposed by recent impacts changes over time, its spectrum does not show the characteristics of nanophase iron (Pieters et al. 2012), and this mineral is virtually absent from howardites. Vesta's location so far from the Sun, where impact velocities are lower, and possible shielding of cosmic rays by its remnant magnetic field (Fu et al. 2012) may account for this difference in soil mineralogy.

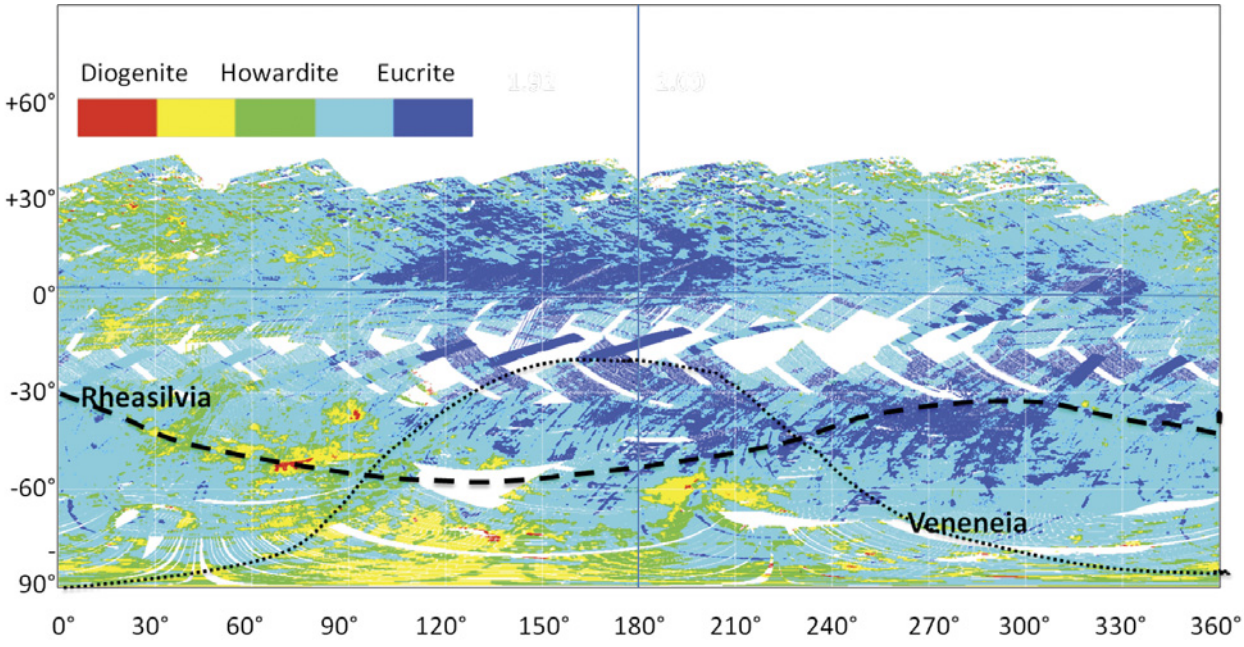


Figure 5 Global map of the distribution of terrains dominated by eucrite, diogenite, and howardite on Vesta, based on VIR spectra from De Sanctis et al. (2012a). The dashed and dotted lines represent the limits of the Rheasilvia and Veneneia impact basins, respectively.

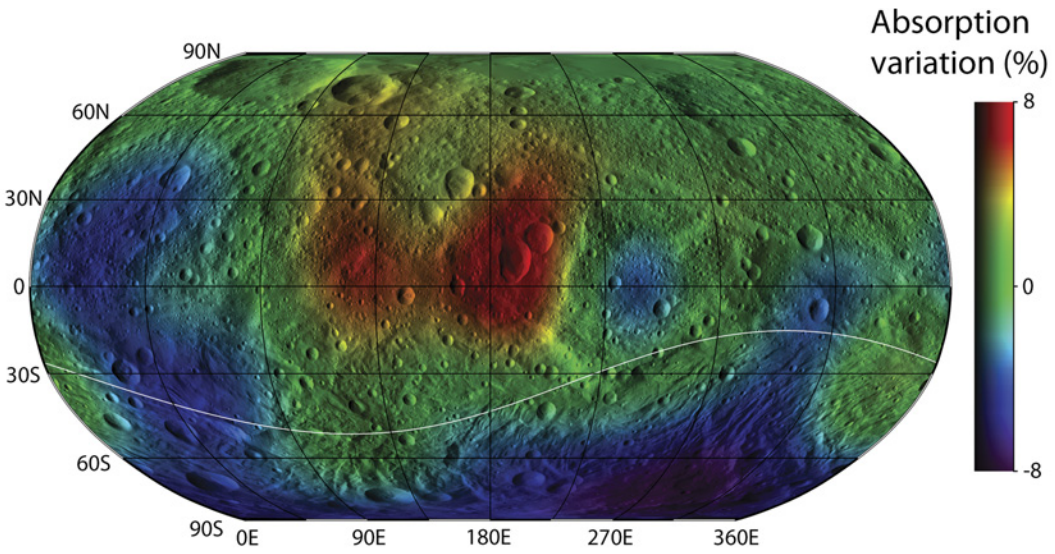


Figure 6 Global map of the relative variations of thermal neutron absorption measured by GRaND, confirming the identification and distribution of lithologies based on VIR spectra. Regions with low (blue) or high (red) absorption contain more diogenite or basaltic eucrite, respectively. The Rheasilvia boundary is shown by the white line. GRaND data are superimposed on a shaded relief map provided by R. Gaskell.

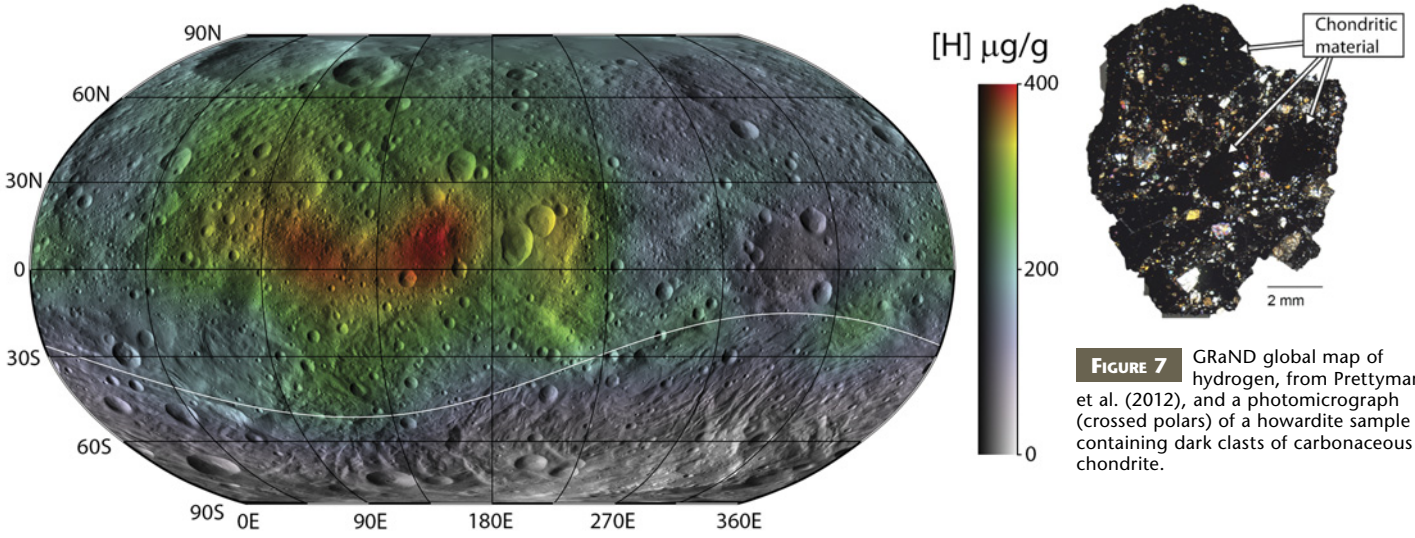


Figure 7 GRaND global map of hydrogen, from Prettyman et al. (2012), and a photomicrograph (crossed polars) of a howardite sample containing dark clasts of carbonaceous chondrite.

SUMMARY

Coupling the petrologic, geochemical, and geochronologic information afforded by laboratory studies of HED meteorites with the geologic context provided by Dawn's orbital exploration of Vesta allows an understanding of this unique, antique asteroid—the kind of objects that accreted to form our own planet. Its early differentiation and magmatic evolution, violent collisional history, and interaction with the space environment are all imprinted on its surface and written in its rocks. Asteroid Vesta now joins the Moon and Mars as astronomical objects that have been transformed into geologic worlds.

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REFERENCES

Barrat JA, Yamaguchi A, Greenwood RC, Bohn M, Cotton J, Benoit M, Franchi IA (2007) The Stannern trend eucrites: Contamination of main group eucritic magmas by crustal partial melts. Geochimica et Cosmochimica Acta 71: 4108-4124

Barrat JA, Bohn M, Gillet P, Yamaguchi A (2009) Evidence for K-rich terranes on Vesta from impact spherules. Meteoritics & Planetary Science 44: 359-374

Binzel RP, Xu S (1993) Chips off asteroid 4 Vesta: Evidence for the parent body of basaltic achondrite meteorites. Science 260: 186-191

Buczkowski DL and 19 coauthors (2012) Large-scale troughs on Vesta: A signature of planetary tectonics. Geophysical Research Letters 39: L18205

De Sanctis MC and 22 coauthors (2012a) Spectroscopic characterization of mineralogy and its diversity across Vesta. Science 336: 697-700

De Sanctis MC and 20 coauthors (2012b) Detection of widespread hydrated materials on Vesta by the VIR imaging spectrometer on board the Dawn mission. Astrophysical Journal Letters 758: L36

Fu RR and 8 coauthors (2012) An ancient core dynamo in asteroid Vesta. Science 338: 238-241

Greenwood RC, Franchi IA, Jambon A, Buchanan PC (2005) Widespread magma oceans on asteroidal bodies in the early Solar System. Nature 435: 916-918

Jaumann R and 42 coauthors (2012) Vesta's shape and morphology. Science 336: 687-690

Jutzi M, Asphaug E, Gillet P, Barrat J-A, Benz W (2013) The structure of the asteroid 4 Vesta as revealed by models of planet-scale collisions. Nature 494: 207-210

Keil K (2002) Geological history of asteroid 4 Vesta: The "smallest terrestrial planet". In: Bottke W, Cellino A, Paolicchi P, Binzel RP (eds) Asteroids III. University of Arizona Press, Tucson, pp 573-584

Mandler BE, Elkins-Tanton LT (2013) The origin of eucrites, diogenites, and olivine diogenites: Magma ocean crystallization and shallow magma chamber processes on Vesta. Meteoritics & Planetary Science 48: 2333-2349

Marchi S and 11 coauthors (2012) The violent collisional history of asteroid 4 Vesta. Science 336: 690-694

McCord TB, Adams JB, Johnson TV (1970) Asteroid Vesta: Spectral reflectivity and compositional implications. Science 168: 1445-1447

McSween HY Jr, Mittlefehldt DW, Beck AW, Mayne RG, McCoy TJ (2011) HED meteorites and their relationship to the geology of Vesta and the Dawn mission. Space Science Reviews 163: 141-174

McSween HY and 21 coauthors (2013) Composition of the Rheasilvia basin, a window into Vesta's interior. Journal of Geophysical Research: Planets 118: 335-346

Mittlefehldt DW, Beck AW, Lee C-TA, McSween HY Jr, Buchanan PC (2012) Compositional constraints on the genesis of diogenites. Meteoritics & Planetary Science 47: 72-98

Pieters CM and 16 coauthors (2012) Distinctive space weathering on Vesta from regolith mixing processes. Nature 491: 79-82

Prettyman TH and 19 coauthors (2012) Elemental mapping by Dawn reveals exogenic H in Vesta's regolith. Science 338: 242-246

Reddy V and 24 coauthors (2012) Delivery of dark material to Vesta via carbonaceous chondritic impacts. Icarus 221: 544-559

Righter K, Drake MJ (1997) A magma ocean on Vesta: Core formation and petrogenesis of eucrites and diogenites. Meteoritics & Planetary Science 32: 929-944

Russell CT, Raymond CA (2011) The Dawn mission to Vesta and Ceres. Space Science Reviews 163: 3-23

Russell CT and 27 coauthors (2012) Dawn at Vesta: Testing the protoplanetary paradigm. Science 336: 684-686

Schenk P and 13 coauthors (2012) The geologically recent giant impact basins at Vesta's south pole. Science 336: 694-697

Shearer CK, Fowler GW, Papike JJ (1997) Petrogenetic models for magmatism on the eucrite parent body: Evidence from othopyroxene in diogenites. Meteoritics & Planetary Science 32: 877-889

Stolper EM (1977) Experimental petrology of eucritic meteorites. Geochimica et Cosmochimica Acta 41: 587-681

Warren PH, Kallemeyn GW, Huber H, Ulf-Møller F, Choe W (2009) Siderophile and other geochemical constraints on mixing relationships among HED-meteoritic breccias. Geochimica et Cosmochimica Acta 73: 5918-5943

Wilson L and Keil K (2012) Volcanic activity on differentiated asteroids: A review and analysis. Chemie der Erde 72: 289-321

