

Figure 2.– PGE contents in an enstatite achondrite (Mt. Egerton in black) are similar to those of enstatite achondrites (EL in grey).

This study was published in *Geochimica et Cosmochimica Acta*:

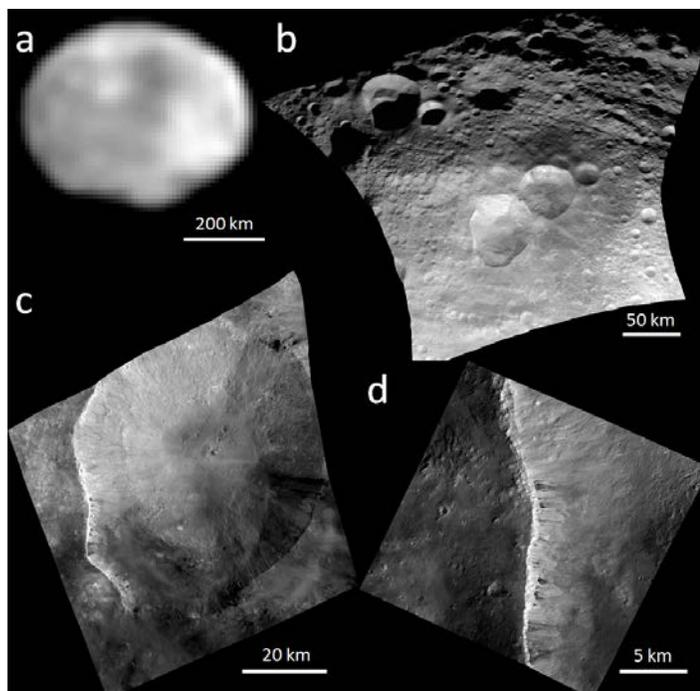
Van Acken D., Humayun M., Brandon A.D., Peslier A.H. (2012); Siderophile Trace Elements in Metals and Sulfides in Enstatite Achondrites Record Planetary Differentiation in an Enstatite Chondritic Parent Body. *Geochim. Cosmochim. Acta* 83, pp. 272-291.

## ***Probing Asteroid (4) Vesta, Part 1: Dawn Mission Science***

*David W. Mittlefehldt*

A long, long time ago in a state far, far away, a young geochemistry graduate student began his research career studying a clan of igneous meteorites that were thought to have come from the asteroid (4) Vesta. Little did he know that NASA would launch a spacecraft mission to that asteroid in his “greybeard” years, or that he would be a member of the mission science team. The Dawn spacecraft was launched in September 2007 and, using the turtle’s “slow and steady wins the race” methodology, arrived at Vesta in July 2011. The spacecraft spent 14 months in a series of orbits of different altitudes, studying the surface with its framing camera (FC), visible and infrared mapping spectrometer (VIR), and gamma ray and neutron detector (GRaND), and probing the interior through gravity measurements. Vesta is located in the asteroid belt between Mars and Jupiter and is the second largest asteroid, with a mean radius of 263 km.

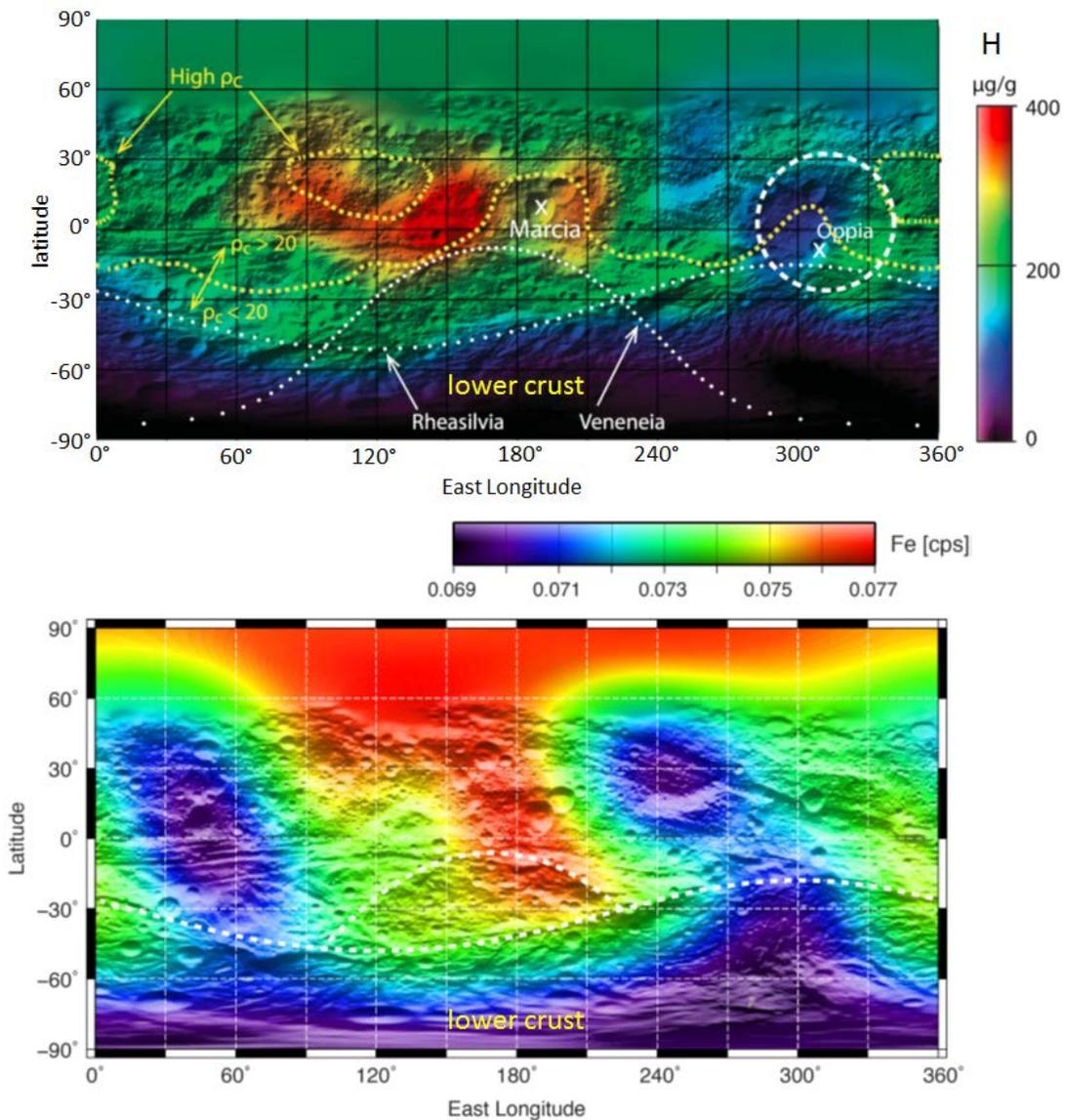
The Dawn mission has confirmed that the mineralogy, composition, and interior structure of Vesta are fully consistent with its being the source of the howardite, eucrite, and diogenite (HED) clan of meteorites. More importantly, the wealth of data returned by the spacecraft has provided an unprecedentedly detailed look at the geology of any asteroid. Prior to Dawn’s arrival, Vesta was known to have broad terrains of differing albedo and spectra, as shown by Hubble Space Telescope images (figure 1a). As Dawn orbited ever closer to the surface, geologic detail came into focus in FC images. The triplet of craters informally known as “the snowman” was discovered within a broad region of low albedo (figure 1b). The southern-most of the three, Marcia crater, is fresh and young and contains layered deposits of bright and dark materials high on the crater walls (figures 1c and d). Young craters such as Marcia have exposed rock units with differing albedos and spectral characteristics that allow the Dawn science team to investigate the detailed geologic history of Vesta.



*Figure 1.– (a) NASA/ESA Hubble Space Telescope image of the asteroid Vesta taken in May 1996. Image credit: Ben Zellner (Georgia Southern University), Peter Thomas (Cornell University), NASA/ESA. (b-d) Framing camera clear filter images of the Vesta “snowman” region at increasing resolution, revealing details of the geologic structure of Vesta. Images courtesy of NASA/JPL-Caltech/ UCLA/MPS/DLR/IDA.*

The composition of the Vestan surface was measured by the GRaND instrument. As is the case for all airless bodies in the solar system, the surface of Vesta is covered by fragmental debris produced by a continuous bombardment of asteroids and meteoroids. The GRaND instrument collects data on this debris down to a depth of about 1 m, but at relatively coarse spatial scale. GRaND has shown that the composition of the regolith is consistent with that of meteorites of the HED clan. Laboratory studies of HED meteorites indicate that Vesta is very poor in volatile elements, such as hydrogen. Nevertheless, GRaND has detected hydrogen on the surface (figure 2) and has shown that its abundance correlates with the age of the surface estimated from the density of craters and that the maximum abundance matches predictions based on the content of carbonaceous chondrite debris found in howardite meteorites. Together with other Dawn observations, the GRaND data show that the H was delivered to the surface of Vesta by carbonaceous chondrite impactors. The distribution of iron across the Vestan surface shows that the southern hemisphere is poor in Fe compared to the northern hemisphere (figure 2). The large Rheasilvia and Veneneia basins lie in this region, and their diameters show that they excavated the lower crust. Models derived from HED meteorite

studies posit that the lower crust should be iron-poor compared to the upper crust – exactly what the GRaND instrument has determined.



*Figure 2.— Compositional maps of Vesta derived from the GRaND instrument. Upper panel: Hydrogen distribution in relation to geological feature; the rims of the large Rheasilvia and Veneneia basins and regions of high crater density ( $\rho_c$ ), which indicate terrains with greater age. Map modified from Prettyman et al. (2012). Lower panel: Iron distribution in relation to the Rheasilvia and Veneneia basin rims. Map modified from Yamashita et al. (2013).*

Dawn is now speeding toward its final destination, asteroid (1) Ceres. The Dawn science team continues working through the wealth of data returned from Vesta, and additional revelations on Vesta’s geologic history will undoubtedly result.

Early results of the Dawn mission were published as collected papers in issues of *Science* and *Nature*, as listed below:

*Science* vol. **336**, no. 6082, 11 May 2012; six papers on the geology, lithologic diversity, mineralogy and cratering history of Vesta.

*Science* vol. **338**, no. 6104, 12 October 2012; two papers on the composition of the Vestan surface and the geology of an unusual terrain.

*Nature* vol. **491**, no. 7422, 01 November 2012; two papers on an unusual lithology on Vesta and on alteration of the surface characteristics by space weathering.

The GRaND element maps shown in figure 2 are from

Prettyman, T.H., Mittlefehldt, D.W., Yamashita, N., Lawrence, D.J., Beck, A.W., Feldman, W.C., McCoy, T.J., McSween, H.Y., Toplis, M.J., Titus, T.N., Tricarico, P., Reedy, R.C., Hendricks, J.S., Forni, O., Le Corre, L., Li, J.-Y., Mizzon, H., Reddy, V., Raymond, C.A., Russell, C.T., 2012. Elemental Mapping by Dawn Reveals Exogenic H in Vesta's Regolith. *Science* **338**, 242-246.

Yamashita, N., Prettyman, T.H., Mittlefehldt, D.W., Toplis, M.J., McCoy, T.J., Beck, A.W., Reedy, R.C., Feldman, W.C., Lawrence, D.J., Peplowski, P.N., Forni, O., Mizzon, H., Raymond, C.A., Russell, C.T., 2013. Distribution of Iron on Vesta. *Meteoritics & Planetary Science*, in press.

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## *Probing Asteroid (4) Vesta, Part 2: Meteorites From Vesta*

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*David W. Mittlefehldt*

In the early 1970s, asteroid (4) Vesta was shown to have a unique reflectance spectra in the visible to infrared wavelength range and to be similar to the laboratory spectra of a clan of igneous meteorites composed of the groups howardites, eucrites, and diogenites (HEDs). With continued astronomical study, the hypothesis that Vesta is the parent asteroid of the HED clan gained widespread support in the scientific community. At the same time, laboratory studies of the HED meteorites resulted in increasingly detailed models for the geologic evolution of their parent asteroid. In anticipation of the arrival of the Dawn spacecraft at Vesta, I began synergistic studies of two types of HED meteorites, diogenites and howardites.

The consensus view is that Vesta differentiated as a global magma ocean that crystallized upon cooling. This model is derived primarily through matching the compositions of basaltic eucrites with chemical models. Diogenites are igneous rocks that were formed by accumulation of minerals from an intrusive magma body. The major minerals of diogenites are magnesium-rich orthopyroxene and olivine. In the consensus view of Vestan geologic evolution, the diogenites formed prior to basaltic eucrites, and thus diogenite compositions should indicate an earlier stage of magma-ocean crystallization. Curiously, the mineralogies (figure 1) and compositions of diogenites do not easily fit into the consensus model. Diogenites show a wide range of trace element