PLANETARY SCIENCE RESEARCH PSRD Discoveries



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# The Complicated Geologic History of Asteroid 4 Vesta

--- Meteorites from asteroid 4 Vesta show that it contains patches of granite-like rock.

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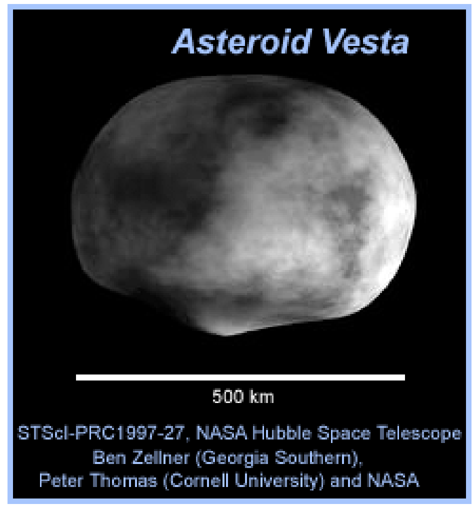



Planetary scientists are pretty sure that almost all of the HED meteorites come from the fourth-largest asteroid, 4 Vesta. HED stands for the three types of rocks that make up the group. As cosmochemists have studied the meteorites over the years, their view of the geologic history of the asteroid has become progressively more complicated. Jean-Alix Barrat and Marcel Bohn (CNRS and University of Brest, France), Philippe Gillet (CNRS and Ecole Normale Supérieure de Lyon, France), and Akira Yamaguchi (National Institute of Polar Research, Tokyo, Japan) have found that Vesta is even more complicated--and interesting--than we thought.

Barrat and his colleagues analyzed impact-produced glass spherules and fragments in several howardites (mixtures of the two other main types, eucrites and diogenites). Not surprisingly, most of the glasses have compositions similar to eucrites, which are basalts, or mixtures of them with diogenites, but a few are surprisingly rich in silicon and potassium (expressed as the percentages of $SiO_2$ and $K_2O$, respectively). In fact, the concentrations of these oxides are similar to granites, compositionally far from basalt. Their manufacture requires extensive crystallization of magma. Combined with a more subtle variation among the basalts, the emerging picture is one that includes formation of a basaltic crust, partial melting of parts of the crust, mixing of those melts with some (not all) magmas as they migrated through the crust, and extensive crystallization of magma bodies to produce residual magma resembling granites. On top of that, Vestan rocks were thermally metamorphosed and battered and mixed by impacts. A pretty complicated little planetary body!

**Reference:**

- Barrat, J. A., Bohn, M., Gillet, Ph., and Yamaguchi, A. (2009) Evidence for K-rich Terranes on Vesta from Impact Spherules, *Meteoritics and Planetary Science*, v. 44, p. 359-374.

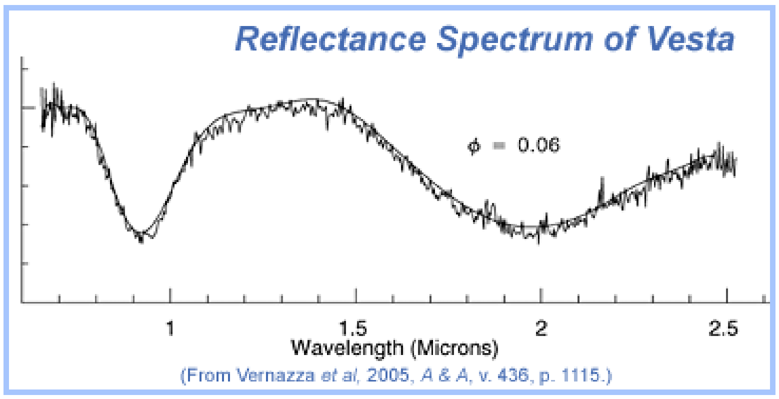
**PSRDpresents:** The Complicated Geologic History of Asteroid 4 Vesta--Short Slide Summary (with accompanying notes).

## Howardites, Eucrites, Diogenites: Chunks of Vesta

One group of meteorites from Vesta is called eucrites, the E in HED. They are mostly basalts. In the microscope, they resemble terrestrial lava flows, and for a long time cosmochemists figured that eucrites formed the same way terrestrial basalts form, by partial melting of the interior. However, assorted geochemical arguments, especially the concentrations of siderophile elements (they concentrate in metallic iron), suggest that Vesta was totally melted (or nearly so) when it formed. As it crystallized, the last 10-20% of magma would have a composition like the eucrites. Of course, somehow that magma has to be squirted onto the surface to make lava flows. The kinks have not been ironed out of the idea. Nevertheless, it is clear that eucrites formed as lava flows. Their ages indicate that it happened 4.5 billion years ago.

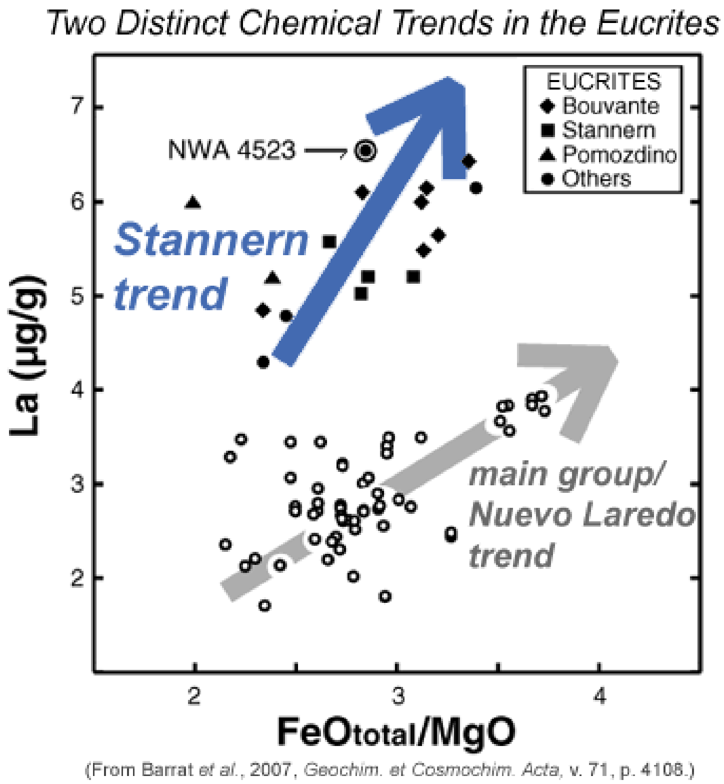
The other main igneous rock type from Vesta is diogenite. These are composed almost entirely of orthopyroxene, so must represent accumulations of this mineral from a slowly-cooling magma. This might have been the magma ocean, but that is not certain. The howardites are impact-produced mixtures of the other two rock types, completing the Howardite, Eucrite, Diogenite suite, the HED meteorites.

I keep saying that the HEDs come from asteroid 4 Vesta. How do we know that? The answer comes from astronomical measurements of the spectral characteristic of light reflected from the asteroid's surface, which looks very much like measurements of HED meteorites in the lab. See **PSRD** article: Getting to Know Vesta for more detail.




This is a spectral plot of Vesta obtained at the NASA Infrared Telescope Facility on Maunakea, Hawai'i by scientists in France using remote control networks from l'Observatoire de Paris-Meudon. In particular, it is the presence of the 0.9 and 1.9 micrometer absorption bands for pyroxene in the spectra of Vesta that match spectra of the HED meteorites.

Over the years, cosmochemists have studied the HED meteorites in detail, making subdivisions (as cosmochemists are want to do!). One of the most interesting subdivisions is the identification of two distinct chemical trends among the eucrites, illustrated in the diagram below. One is called the main group trend, which is also called the Nuevo Laredo trend after a prominent member of it. It is characterized by lower concentrations of rare earth elements (such as lanthanum) than the Stannen trend (named after the eucrite Stannern).




A plot of lanthanum (La) versus the ratio the oxides of iron to magnesium (FeO/MgO). Note the two distinct trends among the eucrites, indicating two different suites of igneous rocks from Vesta.

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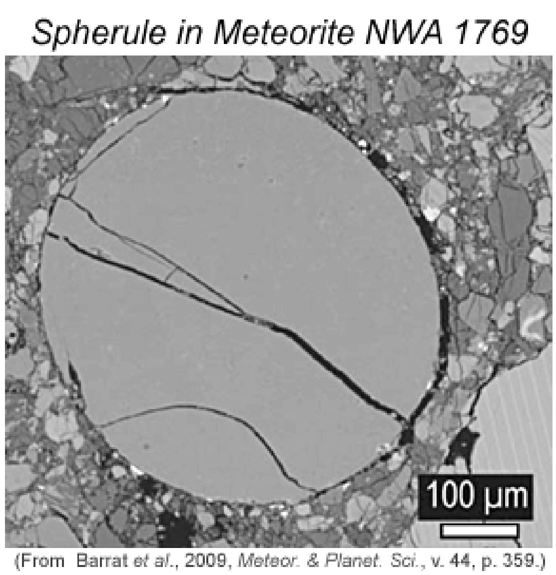
## Glassy Spherules

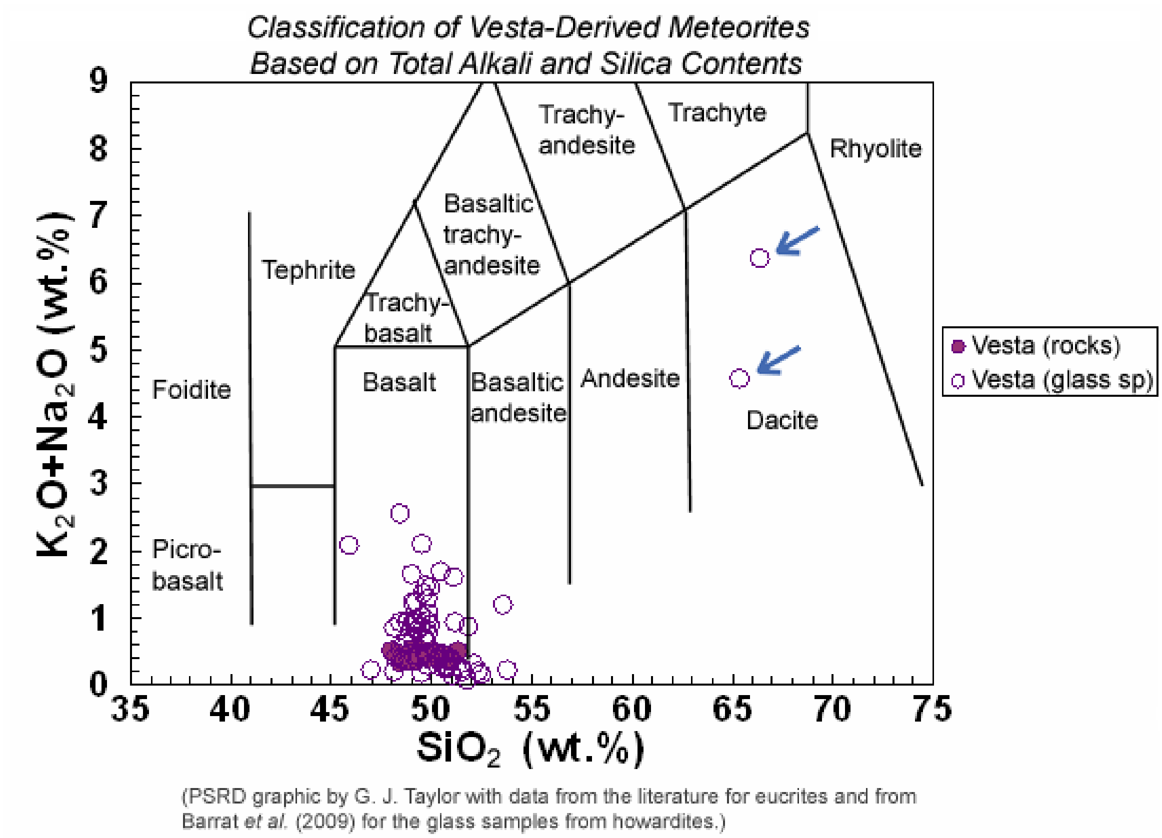
The howardites are impact breccias. They are mixtures of almost all the rocky components making up the crust of Vesta. Some of them contain glassy spherules and glass fragments formed by impact. Jean-Alix Barrat and his colleagues searched for them in eight howardites and found numerous objects. Some are partly crystallized, but they found 61 fragments and spherules that were almost entirely glass and they report the chemical compositions of them in their paper.




Glass spherule in the howardite NWA 1769. It is surrounded by mineral fragments. The image is of the intensity of backscattered electrons, taken with an electron microprobe.

Most of the glassy objects have compositions like those of eucrites or mixtures of them with diogenites, as shown in the diagram below. (Cosmochemists and geochemists are fond of this diagram, which plots weight percentages of total alkalis and silica ($Na_2O$+$K_2O$ vs $SiO_2$). It is called a TAS diagram and is used widely to classify igneous rocks.)

However, note that quite a few glass samples have elevated alkalis compared to typical eucrite rocks (solid symbols in the diagram). More importantly, note that two of them plot in the dacite field, substantially enriched in alkalis and silica compared to the basalts. In fact, they correspond roughly to terrestrial granites, but formed in a different way.




This TAS diagram shows total alkalis (oxides of potassium and sodium) versus silicon dioxide concentration (all in weight percent) for eucrites and impact glasses from howardites. The fields show where different types of terrestrial rocks plot. Note that many of the glass samples (open circle symbols) plot close to and on top of the eucrite basalt samples (solid symbols), but some have elevated alkalis, and two are drastically different with high $SiO_2$ and alkalis. These two (indicated by blue arrows) plot in the dacite field, which along with rhyolites correspond to the compositions of granite and similar rocks on Earth. Data are from the literature for eucrites and from Barrat *et al.* (2009) for the glass samples.

Barrat and his colleagues show that the glass compositions represent impact melts, not unusual condensates from impact-produced vapor, and that they have not lost any elements while they were hot droplets of magma. They also show through calculations called chemical mixing models that some of the glasses enriched in potassium but not silica could be mixtures of typical eucrites and diogenites with granite, but many are not. It appears that there is yet another chemical component lurking in the crust of Vesta.

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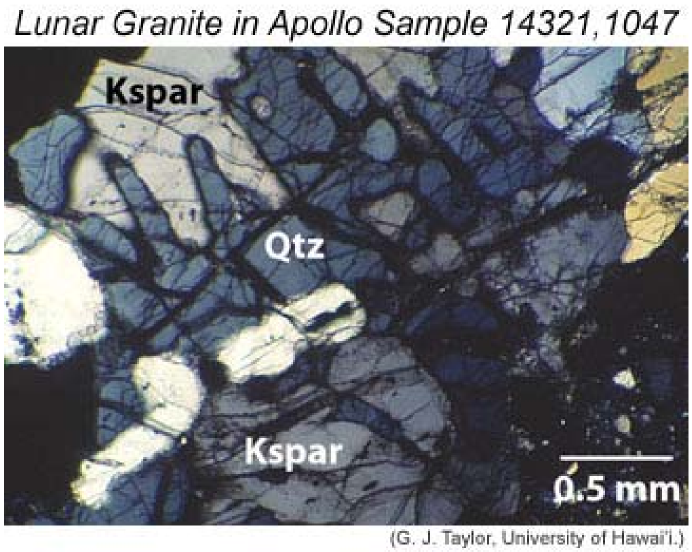
## Making Granite the Hard Way

Earth is home to almost all the granite in the solar system. Almost all of it forms by remelting of pre-existing crust, either sediments or by crystallization of somewhat silica-enriched magmas formed when an oceanic plate subducts beneath a continental plate or another oceanic plate. It makes vast bodies of rock making up major mountain ranges such as the Sierra Nevada in the western United States.

The Vestan granites are not at all like terrestrial granites. They are not abundant on Vesta and do not contain water-bearing minerals such as mica that characterize terrestrial granite. The Vestan ones are more like lunar granites. Like the Vestan samples, the lunar ones are also rare and water-free. They are also small--the largest sample weighs only 1.8 grams! It is quite possible, however, that regions of the Moon tens of kilometers across are made of granite-like rock. We need better remote sensing data to know for sure.




This photomicrograph shows graphic intergrowth of quartz (Qtz) and potassium feldspar (Kspar) in a lunar granite, sample 14321,1047.

A lot of us have done a lot of work on lunar granites (also called "felsites" to distinguish them from mountains of terrestrial granites). Ideas for their origin fall into two main categories: Extensive crystallization of basaltic magma and partial melting of the lunar crust by intrusions of basalt causing partial melting. When magmas crystallize, minerals are often removed by sinking or other processes and so do not react with the magma any further. Removal of crystals changes the composition of the magmatic system, a process called fractional crystallization. Continued fractional crystallization leads to progressively smaller amounts of magma that is progressively different in composition from the original magma. Depending on the chemical composition of the parent magma, the evolved magma might resemble the granites. In other cases, the magma enters an unusual compositional field that promotes separation of two magmas, one iron rich, the other rich in silica and alkalis. In either case, extensive crystallization can lead to formation of granite-like magma. Barrat and his colleagues conclude that this is a feasible way to make the patches of granite in the crust of Vesta.

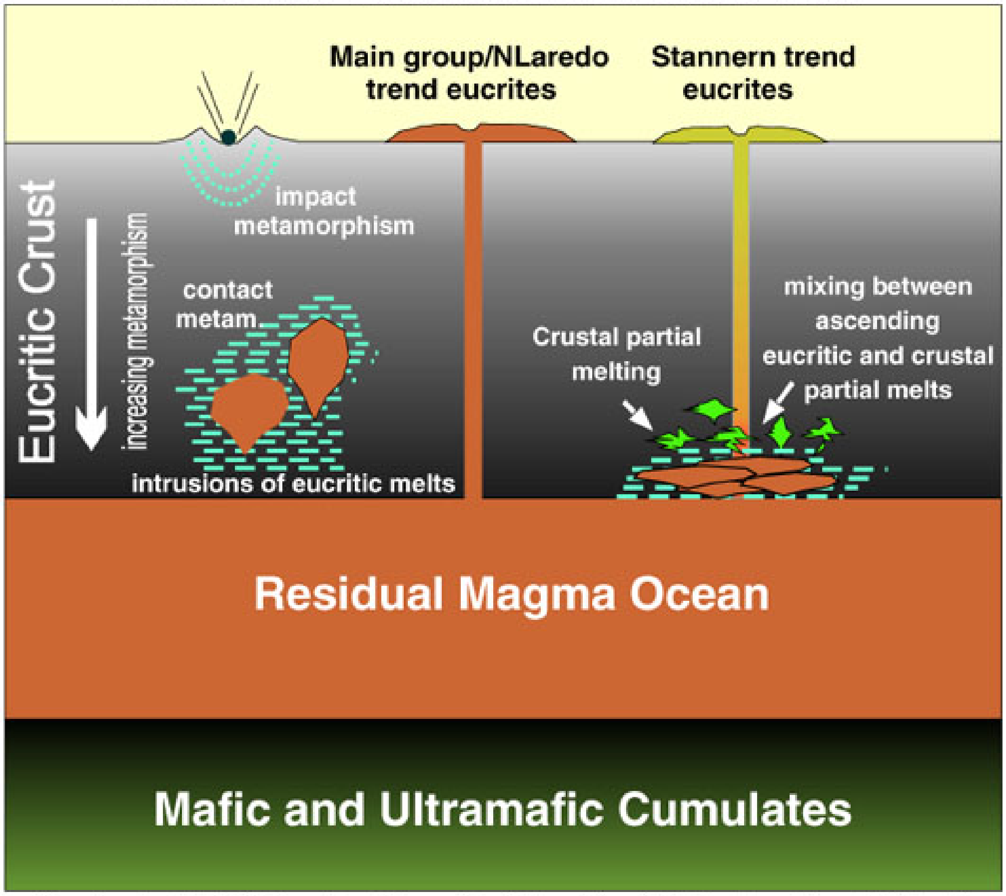
Looking at it in the opposite way, if a rock is heated enough it will partially melt. A pre-existing basalt could partially melt to form a granite-like magma, although the composition of the rock has to be in the right range. Heat for melting can come from the injection of large amounts of hot magma, which heats a region of the crust, forming patches of granites. There is clear evidence that partial melting of pre-existing rocks occurred on Vesta. For example, Akira Yamaguchi and colleagues (including me) showed in 2001 that eucrite EET 90020 had clear evidence that it partially melted. So, the conditions for the partial melting mechanism certainly existed, but Barrat and colleagues do not think this is feasible for producing the granites. They point out that when an eucrite is partially melted, the initial magma is not like the granitic impact glasses. It is not rich enough in potassium.

So, we are not sure about how Vestan granite-like rocks formed, how abundant they are, or the size of the outcrops. To answer those questions cosmochemists need to make additional detailed studies of howardites and eucrites.

## Vesta's Rich Geological History

In their paper about the Stannern trend eucrites, Barrat and coworkers present an interesting picture of the processes that affected Vesta's crust. Tying together observations and interpretations by other investigators and themselves, they propose that the crust formed by eruption of basalt, the leftovers of magma ocean crystallization. The specifics of this process are not clear cut yet, but Akira Yamaguchi and colleagues showed earlier that it is likely that the crust was formed rapidly and that the first basalts to erupt were buried by subsequent flows. This led to creation of an insulating layer above the early flows, causing the early flows to increase in temperature because of heat flowing from the hot interior. This resulted in most eucrites being metamorphosed. Intrusions of basalt magma into the crust caused additional metamorphism, possibly even partial melting, of the rocks surrounding the pools of magma. In addition, the pools fractionally crystallized, forming what cosmochemists call cumulate eucrites and perhaps in some extreme cases forming granites.

A Model of the Construction of the Crust of Vesta



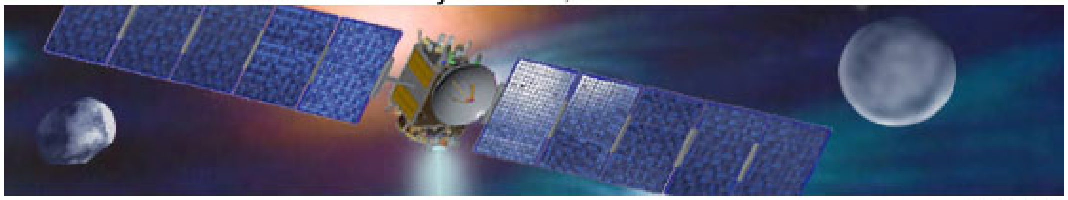

(From Barrat *et al.*, 2007, *Geochim. et Cosmochim. Acta*, v. 71, p. 4118. Courtesy of Jean-Alix Barrat.)

This diagram by Jean-Alix Barrat and colleagues shows a reasonable snapshot of processes operating during the construction of the crust of Vesta. Thermal metamorphism, driven by heat flowing from the hot interior, is more severe as depth increases. Intrusions of basalt magma cause addition metamorphism of the rock surrounding them, and allow for fractional crystallization. Some areas, especially near the base of the crust, become hot enough to partially melt, producing magma richer in trace elements than typical eucrites. When normal eucrites interact with these partially melted zones, they produce hybrid magmas (the Stannern trend eucrites). In most cases, the basalt magma passes through the crust without interacting with it, leading to eruption of normal, or Nuevo Laredo trend eucrites.

In their 2007 paper, Barrat and coworkers suggest that the Stannern trend eucrites (the ones richer in rare earth elements and geochemically similar elements) form when normal eucrite magmas pass through regions that were heated enough to partially melt. Such partial melts would contain higher levels of elements that are not incorporated readily into major minerals, so have higher concentrations in melted regions. Mixing of normal eucrite basalt with relatively modest amounts of partial melt could have produced the Stannern trend eucrites. Barrat and colleagues back up this model with quantitative trace element modeling. If a magma did not pass through a partially melting zone, a normal eucrite erupted.

This is a surprisingly complicated history for tiny planet about 530 km across. It melted, formed a basaltic crust, and made an array of rocks by accumulation in magma bodies. The crust remelted, and some of those magmas mixed with normal eucrite basaltic magma to make the Stannern trend lavas. The crust was metamorphosed by burial, and heated and mixed by impacts while it was still hot. It will be fascinating to see what the Dawn spacecraft finds when it spends half a year in orbit around Vesta. Maybe its reflectance spectrometer will see little areas of HED granite.

Dawn: NASA's ninth Discovery Mission, Enroute to Orbit Vesta and Ceres



NASA / JPL

NASA's Dawn spacecraft launched in 2007. The science payload onboard Dawn consists of two cameras, a visible and infrared mapping spectrometer to map surface minerals, and a gamma-ray and neutron spectrometer to measure elemental compositions of the surface of asteroid 4 Vesta (beginning in 2011) and dwarf planet Ceres (in 2015). This is an artist's rendition of the Dawn spacecraft, Vesta, and Ceres.

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## Additional Resources

**LINKS OPEN IN A NEW WINDOW.**

- **PSRDpresents:** The Complicated Geologic History of Asteroid 4 Vesta--Short Slide Summary (with accompanying notes).

- Barrat, J. A., Bohn, M., Gillet, Ph., and Yamaguchi, A. (2009) Evidence for K-rich Terranes on Vesta from Impact Spherules. *Meteoritics and Planetary Science*, v. 44, p. 359-374.
- Barrat, M. A., Yamaguchi, A., Greenwood, R. C., Bohn, M., Cotton, J., Benoit, M., and Franchi, I. A. (2007) The Stannern Trend Eucrites: Contamination of Main Group Eucritic Magmas by Crustal Partial Melts. *Geochimica et Cosmochimica Acta*, v. 71, p. 4108-4124.
- Dawn Mission homepage
- Martel, L. M. V. (2007) Getting to Know Vesta. *Planetary Science Research Discoveries.* http://www.psrd.hawaii.edu/Nov07/HEDs-Vesta.html
- Yamaguchi, A., Taylor, G. J., Keil, K., Floss, C., Crozaz, G., Nyquist, L. E., Bogard, D. D., Garrison, D. H., Reese, Y. D., Wiesmann, H., and Shih, C-Y. (2001) Post-crystallization Reheating and Partial Melting of Eucrite EET90020 by Impact into the Hot Crust of Asteroid 4 Vesta 4.5 Ga ago. *Geochimica et Cosmochimica Acta*, v. 65, p. 3577-3599.

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