Spectroscopic Characterization of Mineralogy and Its Diversity Across Vesta
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The mineralogy of Vesta, based on data obtained by the Dawn spacecraft's visible and infrared spectrometer, is consistent with howardite-eucrite-diogenite meteorites. There are considerable regional and local variations across the asteroid: Spectrally distinct regions include the south-polar Rheasilvia basin, which displays a higher diogenitic component, and equatorial regions, which show a higher eucritic component. The lithographic distribution indicates a deeper diogenitic crust, exposed after excavation by the impact that formed Rheasilvia, and an upper eucritic crust. Evidence for mineralogical stratigraphic layering is observed on crater walls and in ejecta. This is broadly consistent with magma-ocean models, but spectral variability highlights local variations, which suggests that the crust can be a complex assemblage of eucritic basalts and pyroxene that has been modified by numerous impact events. Overall, Vesta mineralogy indicates a complex magmatic evolution that led to a differentiated crust and mantle.

geological context relevant to the question of its formation history.

The visible and infrared spectrometer (VIR) on Dawn is a high-resolution imaging spectrometer with a spectral range of 0.25 to 5.01 μm and a spatial sampling of 250 μrad. It combines two data channels in one compact instrument: the visible-infrared (0.25 to 1.07 μm) and the infrared (0.95 to 5.1 μm) channels, with a spectral sampling of ΔλVIS = 1.8 nm per band and ΔλIR = 9.8 nm per band, respectively.

VIR obtained spatially resolved hyperspectral images of Vesta (fig. S1) with a nominal spatial sampling up to ~0.7 km. The orientation of Vesta’s spin axis and Dawn’s orbital characteristics have allowed >65% of the surface to be imaged, ranging from the south pole up to about 45°N (the northern polar region was in shadow). VIR has acquired about four million spectra of Vesta’s surface under different illumination conditions, with phase angles from 67.8° to 7.9°.

The first data, at a resolution twice that of the Hubble Space Telescope, were obtained from a distance of ~99,200 km. The spectra show clear evidence of pyroxene absorption bands at 0.9 and 1.9 μm (hereafter BI and BII). Different regions of Vesta are characterized by distinctly different band depths, widths, shapes, and centers. Beyond ~3.5 μm, thermal emission of the surface becomes increasingly important, and the spectral variations also reflect diurnal changes with the corresponding surface temperature changes.

The color composite image of Vesta (Fig. 1) demonstrates that there are large-scale variations in the spectral properties of the surface material and that these variations are greater in magnitude than those described on other asteroids (17, 18). In this image, the reddish color of the northern hemisphere indicates greater reflectivity at 0.92 μm, and hence shallower pyroxene bands compared with the southern hemisphere. The representative spectrum from region A shows stronger absorption at 0.92 μm relative to the continuum at 0.7 μm than does region B.
Although the surface of Vesta exhibits spectral variations at both large and small scales, the materials on the surface are always dominated by rocks formed by mafic magmatism, as indicated by the ubiquitous BI and BII pyroxene signatures.

These bands are caused by absorption of photons, primarily by Fe\textsuperscript{3+}, and their exact position and shape are driven by the relative proportion of Fe to Mg in the M1 and M2 sites of pyroxene crystal structures (19, 20).

VIR spatial resolution allows for the definition of localized mineralogical units: The results indicate a complex geological and collisional history (21–23) and reveal a crust that was differentiated before impact bombardment. The spectral variations indicate that Vesta’s crust is compositionally variable at vertical scales from a few hundred meters to 20 km, the depth of excavation of the southern impact basins (16).

A global-scale spectral difference is observed between the equatorial and southern Rheasilvia regions, as shown on maps of BI and BII depths and centers (Fig. 2). In the south pole region, pyroxene bands are, on average, deeper and wider than in the equatorial region (fig. S3). In general, BI depths in the equatorial region are ~0.35 to 0.4, whereas those in the Rheasilvia basin are commonly 0.45 to 0.55. Similarly, BII depths in the equatorial region are typically ~0.15 to 0.2, whereas in the southern region they are ~0.25 to 0.3. The depth of an absorption band is mainly determined by the abundance of the absorbing minerals, the grain size distribution, and the abundance of opaque phases. The process known as space weathering also modifies reflectance spectra and can make lithological interpretation difficult. Regolithic howardites show some characteristics of exposure to the space environment, such as high noble gas and siderophile element contents, and impact-produced glass, but these characteristics are not as well developed as in mature lunar regolith breccias (24, 25). Vesta retains a reflectance spectrum dominated by pyroxene absorption bands (fig. S5), indicating that the effects of space weathering are much less pronounced on Vesta compared with the Moon or Mercury.

Thus, the VIR data suggest that the region of the Rheasilvia basin is richer in pyroxene than the equatorial regions or that the regolith in this region has a larger average grain size distribution and/or contains fewer opaque minerals. A larger grain size would be consistent with less impact comminution in the southern region because of the younger age of the Rheasilvia basin (23). The lower crust is also expected to have had a coarser initial grain size because pyroxene grain sizes vary from diogenites, which are much larger than cumulate eucrites, to basaltic eucrites (12).

The global asymmetry evident in the distributions of pyroxene band depths is also demonstrated by variations in band center wavelengths (Fig. 2, C and D). Laboratory studies indicate that band centers for BI and BII pyroxene absorptions are systematically different for diogenites and eucrites (26). To directly compare Vesta band centers with HEDs, we computed the band centers of HEDs by applying the same method to both data sets (Fig. 3). BI and BII centers are at slightly shorter wavelengths for diogenites than for eucrites (Fig. 3), a consequence of more Mg-rich pyroxenes with lower Ca concentrations in the former (26). Howardites, because of their intermediate nature, lie between, but partially overlap the fields of diogenites and eucrites.

The BI and BII centers in the VIR spectra form a trend from diogenites to eucrites, and most plots in the howardites region. Band center values are not uniformly distributed on Vesta, but they differ systematically between the equatorial and southern regions, and band center values often correlate inversely with band depths (Fig. 2). Equatorial regions are prevalently characterized by band centers at longer wavelengths (average BI = 0.930 μm and BII = 1.96 μm) and typically have intermediate to shallow band depths. In contrast, band centers in the Rheasilvia basin are at shorter wavelengths (average BI = 0.926 μm and BII = 1.94 μm), and these often correspond to the deepest pyroxene absorption bands (Fig. 2).

Overall, the correlations between band depths and band centers can be interpreted in terms of diogenite/eucrite content of the different terrains. Diogenites contain ~90 to 95 volume % (vol %) pyroxene (27), whereas basaltic eucrites contain ~50 vol % pyroxene (28), implying that, for a given grain size, the diogenite spectra have stronger bands with respect to eucrites, as confirmed by HED spectra (table S1). The correspondence of stronger pyroxene absorptions with shorter BII and BI centers in the Rheasilvia basin is consistent with a greater proportion of diogenite on the surface in this deeply excavated region.

Spectra from the equatorial regions have band centers shifted to longer wavelengths, indicating more Fe-rich pyroxenes, and intermediate or shallow band depths, indicating lower pyroxene abundance, both consistent with a greater eucrite component. However, the equatorial region is not spectrally uniform. An extensive area at about 40°E has measurably deeper absorption bands and shorter wavelengths, suggesting a lower proportion of eucritic material in this region, possibly related to the influence of Rheasilvia ejecta (23–25). Overall, the mineralogical north-south diversity indicates that the lower crust exposed in Rheasilvia is dominated by pyroxene-rich, diogenitic material.

Although the difference between the south polar and equatorial regions is the dominant first-order feature (Fig. 2), VIR data also demonstrate that Vesta’s surface and subsurface show variations at local scales, that is, bright and dark localized areas (fig. S4). Study of geological structures at scales of tens of kilometers, in particular impact craters with copious ejecta and
Color and Albedo Heterogeneity of Vesta from Dawn

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Multispectral images (0.44 to 0.98 μm) of asteroid (4) Vesta obtained by the Dawn Framing Cameras reveal global color variations that uncover and help understand the north-south hemispherical dichotomy. The signature of deep lithologies excavated during the formation of the Rheasilvia basin on the south pole has been preserved on the surface. Color variations (band depth, spectral slope, and eucrite-diogenite abundance) clearly correlate with distinct compositional units. Vesta displays the greatest variation of geometric albedo (0.10 to 0.67) of any asteroid yet observed. Four distinct color units are recognized that include chronosequences—including impact excavation, mass wasting, and space weathering—that shaped the asteroid’s surface. Vesta’s color and photometric diversity are indicative of its status as a preserved, differentiated protoplanet.

The Dawn spacecraft rendezvoused with the asteroid Vesta on 16 July 2011, and the Framing Cameras (FCs) (7) acquired images in seven colors (0.44 to 0.98 μm) and one broadband clear filter, mapping the entire sunlit surface at a detail of ~9 to ~0.016 km/pixel. We used

References and Notes
7. N. A. Moscovita et al., Icarus 208, 773 (2010).

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Supplementary Materials
www.sciencemag.org/cgi/content/full/336/6082/697/DC1 Supplementary Text
Figs. S1 to S5
Table S1
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