DISTINGUISHING INTRUSIVE AND EXTRUSIVE MAGMATISM ON VESTA. H. Y. McSween[1], E. M. Stolper[2], M. B. Baker[2], N. G. Lunning[3], and C. A. Raymond[4]. [1]Earth and Planetary Sciences, University of Tennessee, Knoxville, TN 37996, mcsween@utk.edu, [2]Geological and Planetary Sciences, Caltech, Pasadena, CA 91109, [3]Earrth and Planetary Sciences, Rutgers University, New Brunswick, NJ 08901 [4]Jet Propulsion Laboratory, Pasadena, CA 91105.

Introduction: Magmatism is a common thread running through the geologic evolution of planets large and small. Intrusive (I) rocks are more abundant than extrusive (E) rocks on Earth; for igneous provinces with sufficient data, [1] calculated a median I:E volumetric ratio of ~5:1 (with many provinces in the range of 2-3:1). [2] proposed an I:E ratio of ~5-12:1 for Mars, and [3] also advocated a higher I:E ratio for Tharsis and Syrtis Major than for Earth. No I:E ratio estimates have been made for asteroids. Low gravity in small bodies may facilitate magma ascent and allow more extensive extrusion than on Earth. Indeed, calculations by [4] indicate that magmas in asteroid-size bodies would be efficiently removed from the mantle, although dikes that transport magmas to the surface would be unstable, possibly leading to accumulation in magma chambers. Average lower and upper crustal thicknesses from a recent magma ocean-based petrogenetic model for Vesta [5] yield an I:E volume ratio of ~0.7:1 (assigning diogenites and cumulate eucrites in the lower crust as intrusive and the eucrite upper crust as extrusive).

Vesta offers a unique opportunity to examine the efficiency of magma ascent and eruption in asteroids. A DAWN crustal density map of Vesta obtained by minimizing residual gravity [6] suggests the existence of denser subsurface plutons (Fig. 1).

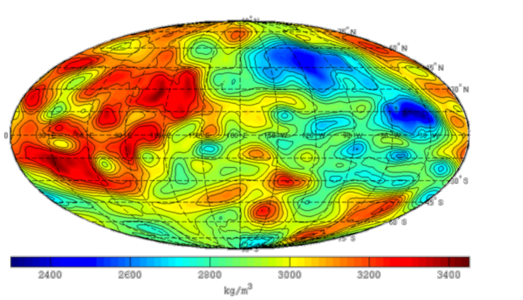

Fig. 1. Crustal density map of Vesta [6], showing quasi-circular, higher-density areas (red) interpreted to be plutons in the crust.

Vestan samples (HED meteorites) are both volcanic (basaltic and polymict eucrites) and plutonic (diogenites and cumulate eucrites) materials. Howardites, comprising the bulk of Vesta's surface [7,8], are brecciated mixtures of both plutonic and volcanic rocks. The superposition of the Rheasilvia and Veneneia basins at Vesta's south pole excavated huge amounts of rock [9], scattering ejecta that now covers much of Vesta's surface and launching large blocks (Vestoids), which are likely direct sources of the HEDs. Thus, the petrology of HEDs (especially howardites) and petrologic mapping of Vesta by DAWN's instruments may provide insights into the relative portions of intrusive and extrusive rocks and, indirectly, into the eruptability of vestan magmas. The relative proportions by mass of eucritic (V-type) and diogenitic (J-type) bodies among the Vestoids [10] might provide another useful comparison, but quantitative data are not available.

HED Meteorites: Relative numbers of plutonic (cumulate eucrites + diogenites [includes olivine diogenites]) to volcanic (basaltic + polymict eucrites) meteorites in the Meteoritical Bulletin Database [11] are 0.45:1, showing an apparent predominance of extrusive rocks; the compilation by mass (0.07:1) is even more skewed toward volcanic rocks. This ratio may reflect the relative abundances in launched ejecta, which are plausibly dominated by near-surface (extrusive) materials.

Howardites may provide a more meaningful average sampling of Vesta's crust. Careful petrographic mapping of the volume proportions of basaltic eucrite, cumulate eucrite, and diogenite (based on clasts and individual mineral grains) in 13 well-sampled howardites (especially large meteorites studied in multiple sections, or paired meteorites) is available [12, 13, 14, 15, 16, 17]. The calculated I:E volume proportions vary greatly, ranging from 0.9:1 to 99:1. Most of that variation is due to 2 howardites that contain virtually no basaltic eucrite. The other 11 howardites give an average ratio of 2.3:1, with a standard deviation of 1.5.

Howardite bulk chemistry has also been used to estimate the weight percentage of eucritic material (called "POEM" [18]). POEM is calculated from Al and Ca contents, assuming that howardites are mixtures of basaltic eucrite and diogenite. Unfortunately, POEM does not distinguish basaltic and cumulate eucrite, although cumulate eucrites are commonly cited as only a minor component of howardites. If we calculate the proportions of basaltic eucrite versus cumulate eucrite by adjusting published POEM values for 15 howardites [18] using the average measured ratio of basaltic eucrite to total eucrite from petrographic analyses of howardites (0.49) and assuming that basaltic and cumulate eucrites have similar densities, we derive an I:E (weight) ratio of 2.1:1. This ratio is very similar to the average I:E (volume) ratio from petrologic mapping of howardites (2.3:1).

Vesta Mapping by DAWN: VISNIR spectra cannot distinguish cumulate eucrite from howardite (Fig. 2), so the amount of intrusive material mapped on Vesta's surface is underestimated by both VIR and Framing Camera (FC) data.

Basaltic and cumulate eucrites can be distinguished from each other and from howardites using GRaND data. Fig. 3 illustrates the use of Fe abundance and fast neutron counts in classifying HED meteorites [20]. However, using these parameters, GRaND did not recognize cumulate eucrite on Vesta [21]. The absence of cumulate eucrite in GRaND spectra and the small amounts inferred from howardite bulk chemistry are at variance with howardite petrographic mapping and have no ready explanation.

Global maps showing the amounts and distributions of eucritic material, roughly POEM, measured by DAWN's instruments (VIR, FC, and GRaND), have been generated and were compared by [6]. The I:E proportions are hard to quantify from these maps, because of the high abundances of rocks classified as howardite. However, if the proportions of components petrographically measured in howardites apply, plutonic rocks dominate Vesta's surface.

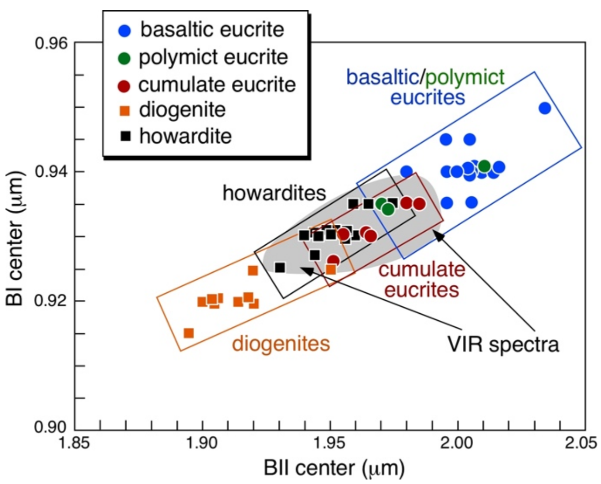

Fig. 2. Comparison of laboratory spectra of HEDs, from [19], and VIR spectra of Vesta from DAWN (gray data cloud, from [7]. VISNIR data do not distinguish howarditesa and cumulate eucrites.

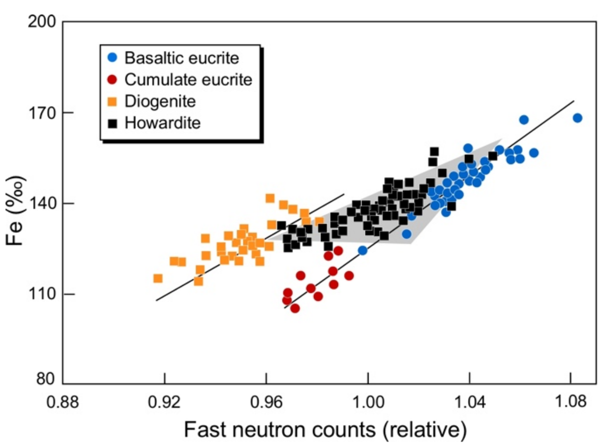

Fig. 3. Fe abundance versus counts of fast neutrons for HED meteorites [21]. GRaND thus has the ability to distinguish cumulate eucrites from basaltic eucrites and from howardites. Gray triangle shows that howardites are mixtures of diogenites and varying amounts of basaltic and cumulate eucrite.

Conclusions: The ratio of intrusive (diogenite + cumulate eucrite) to extrusive (basaltic eucrite) rocks in howardites (~2-3:1 or higher) is a plausible proxy for the I:E ratio in Vesta's crust. This result, based on howardite petrographic mapping, differs from the well-known diogenite to total eucrite ratio of 1:2, inferred from howardite bulk chemistry [17, 22), because the latter does not distinguish cumulate and basaltic eucrites. The lower I:E ratios (whether by volume or mass) from the HED collection likely reflects a higher proportion of near-surface material in launched ejecta. The results of howardite petrography suggest that the relative volumetric proportions of plutonic and volcanic rocks in Vesta's crust may be roughly similar to many magmatic provinces on Earth [1].

The I:E ratio is important because it determines the structure and flexural state of the crust and the efficiency and speciation of outgassing [3]. It may also serve as a test for petrologic and thermal models based on a magma ocean or serial magmatism – in this case implying a significant role for pluton emplacement in the formation of Vesta's crust.

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