FORMATION OF A SHALLOW MAGMA OCEAN ON VESTA SUPPORTED BY MANTLE HARZBURGITE RESIDUA IN HOWARDITES . T.M. Hahn[1], N.G. Lunning[2], H.Y. McSween[1], R.J. Bodnar[3], and L.A. Taylor[1], [1]Planetary Geosciences Institute, Department of Earth and Planetary Sciences, University of Tennessee, Knoxville, TN 37996, USA (thahn1@vols.utk.edu), [2]Department of Mineral Sciences, Natural Museum of History, Smithsonian Institution, Washington, D.C., 20013, [3]Department of Geosciences, Virginia Tech, Blacksburg, VA 24061, USA.

Introduction: The accretion of planetesimals before significant decay of ^{26}Al, a potent heat source, presumably resulted in subsequent differentiation [1]. These differentiated bodies were likely the building blocks for the terrestrial planets; therefore, the survival of these protoplanetary bodies provides a unique opportunity to study their differentiation and interior structures.

Asteroid 4 Vesta − generally accepted as the parent body of the howardite-eucrite-diogenite (HED) meteorites [2] − has been extensively studied by the DAWN spacecraft mission, and hundreds of the associated HED meteorites have been characterized. Differentiation models of Vesta based on HEDs are commonly divided into two end-members: partial melting with serial magmatism e.g. [3], and global melting to form a magma ocean e.g [4]. Although ^{26}Al provides a significant heat source, the ascent rates of melts in asteroidal bodies might inhibit the formation of a magma ocean [5]. As an alternative to global melting, a shallow magma ocean model has recently been proposed by [6]. Such a model would likely sequester large amounts of olivine in the deep lower mantle, offering an explanation for the absence of significant amounts of olivine in the upper mantle-excavating Rheasilivia basin on Vesta [6]. Samples of the vestan mantle [7,8] could provide a means of distinguishing between these differentiation models.

During this study, we examined the major-, minor-, and trace-element characteristics of recently identified samples from the vestan mantle [8] in order to extract petrologic information. These data offer increasing support for a shallow magma ocean differentiation model [6]. Additionally, we provide evidence that suggests the formation of the vestan mantle occurred under highly reducing conditions (<<IW). Our conclusions have critical implications for the formation of the vestan mantle as residua from planetary differentiation.

Methods: Six thin-sections from the Dominion Range howardite pairing group (DOM 10100; DOM 10105; DOM 10120; DOM 10838; DOM 10837; DOM 10839) were examined, and contain lithic clasts interpreted to be from the vestan mantle [8]. Major- and minor-element chemistry were determined by electron microprobe, and trace-element concentrations were determined *in situ* with LA-ICP-MS.

Geochemical modeling using the MELTS program [12] allowed us to evaluate petrogenetic hypotheses, by modeling the geochemical characteristics of the vestan mantle. We used the widely accepted bulk composition proposed by [13] and model petrologic processes operating during the differentiation (i.e. restite formation and fractionation) of Vesta in order to predict the mantle characteristics for various differentiation models.

Results: Detailed petrography, along with major- and minor-element chemistry, were previously presented by [8], and suggested a Mg-rich harzburgite-dunite vestan mantle. Close examination of the major-element data for olivines and pyroxenes in diogenites and in the vestan mantle fragments reveal a potential compositional gap. Minor-element correlations in Mg-rich orthopyroxenes (Figure 1) suggest no clear genetic

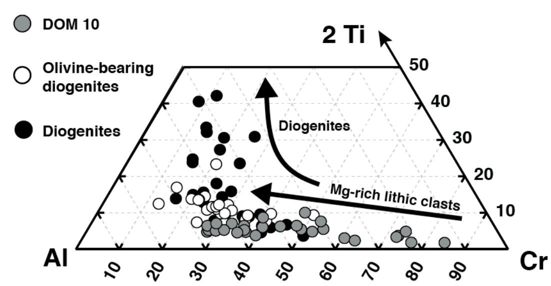

Figure 1. Ternary diagram of Al-Cr-2Ti in Mg-rich pyroxene in vestan mantle harzburgites. The diogenites, which have co-crystallized with minor amounts of plagioclase, show a continuous trend with a branch that extents towards the Ti apex. Conversely, the Mg-rich pyroxenes show decreasing Cr/Al with near constant Ti. This suggests that plagioclase did not play a significant role in the formation of the vestan mantle harzburgites. Diogenite data from [9,10]

relationship between diogenites and Mg-rich harzburgite-dunites from the vestan mantle. Rare earth element (REE) concentrations in Mg-rich olivine are below detection limits, and thus provide no constaints on their origin. However, Mg-rich orthopyroxenes show REE concentrations similar to diogenites; conversely, they exhibit pronounced LREE enrichments not typical of orthopyroxene in general, with La/Tm of 0.2 to 1.2 (Figure 2). Moreover, pyroxenes also contain variable Eu and Sr anomalies. Grains of FeNi metal occasionally occur in the mantle clasts and contain up to 2 wt.% Cr. Furthermore, orthopyroxene-

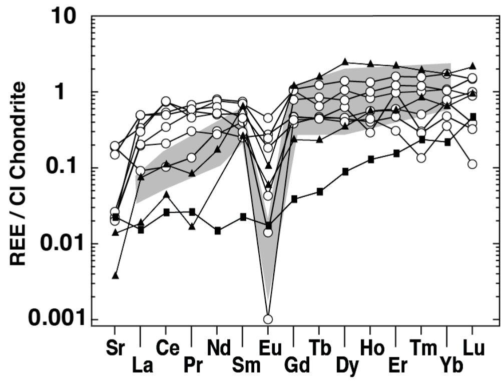

Figure 2. REE patterns of Mg-rich pyroxenes (open circles) compared to diogenites (gray area; [10]), GRO 95 mantle fragments (triangles; [7]), and QUE 93148 (squares; [11]).

chromite symplectites that occur only within these clasts, as described by [8], also contain blebs of FeNi metal with similar abundances of Cr.

Discussion and Conclusions: Similarities between the vestan mantle clasts in the DOM 10 howardite pairing group and both Mg-rich mineral fragments in the GRO 95 howardites [7] and ungrouped achondrite QUE 93148 [11] have been noted by [8]; these similarities have been used to further argue for their formation in the mantle of Vesta. Similarities include the primitive major- (Mg# >85) and minor-element compositions, which are consistent with a mantle origin. However, the more evolved REE concentrations in Mg-rich pyroxenes are not necessarily consistent with a mantle origin, and may suggest a cognate origin with diogenites. If QUE 93148 originated in its parent body's mantle (Vesta? [11]), it is expected that the harzburgite clasts might show similar patterns; this is clearly not the case (Figure 2). We, however, argue that the REE abundances and LREE enrichments can be attributed to secondary processes (metosomatic event?) that produced the symplectites; an interstitial trapped melt composition is preserved, which seems to supports this hypothesis. This mechanism has also been hypothesized for similar symplectites in the lunar Mg-suite [14].

The Fe/Mn and Fe/Mg systematics of Mg-rich olivines and orthopyroxenes are consistent with the formation of the Mg-rich harzburgites as solid residues from planetary differentiation (Figure 3; [15]). An origin as a mantle residue places strict limitations on plausible models for the differentiation of Vesta. Specifically, a Mg-rich (Mg# >85) residue is possible if melting is greater than 50% but incomplete enough to allow for preservation and excavation of this lithology. Such conditions could occur during the formation and solidification of a shallow magma ocean.

Numerical Modeling: Our MELTS models of solid residue formation on a vestan bulk composition proposed by [13] fail to match the major-element composition of the mantle harzburgite clasts. For example, the olivines in the residua are not Mg-rich enough until excessive amounts of melting have occurred (>80%), at which point orthopyroxene has been exhausted. These conditions would not favor the preservation of harzburgite mantle residua. In order to produce compositions similar to the vestan mantle clasts, conditions would have to be highly reducing; this conclusion is supported by the presence of large amounts of Cr (~2 wt.%) in FeNi metal in the mantle clasts, which can only be achieved under reducing conditions (<<IW; [16]). This observation is futher consistent with an origin in the mantle of Vesta during core formation [17].

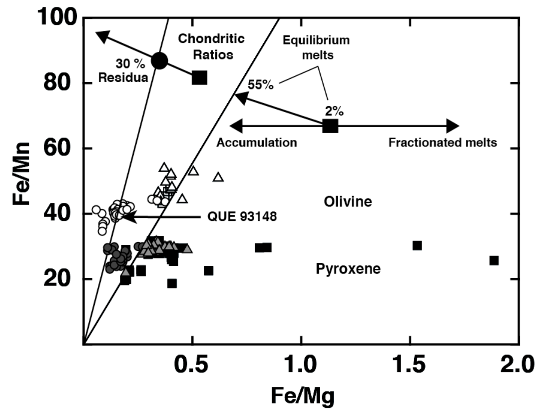

Figure 3. Fe/Mn and Fe/Mg systematics in olivine and pyroxene from DOM 10 (circles). These trends support an origin as a mantle residue [15]. Data for diogenites from [9,10] (squares and triangles, respectively). Olivine and pyroxene distinguished by open and closed symbols, respectively.

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