CHEMICAL MODELS FOR THE CRYSTALLIZATION OF A MAGMA OCEAN ON VESTA: MAKING HED LITHOLOGIES AND THE NARROW RANGE IN EUCRITE COMPOSITIONS. B. E. Mandler[1], L. T. Elkins-Tanton[2]. [1]Department of Earth, Atmospheric and Planetary Sciences, MIT, 77 Massachusetts Avenue, 54-1212, Cambridge, MA 02139, USA (bmandler@mit.edu), [2]Department of Terrestrial Magnetism, Carnegie Institution for Science, Washington, DC 20015, USA (ltelkins@dtm.ciw.edu).

Introduction: Much progress has been made in revealing the complex – if brief – magmatic history of the parent body of the howardite-eucrite-diogenite (HED) meteorite suite - long thought to be the asteroid Vesta [1,2]. Meteoritic studies reveal a detailed history of extensive melting, melt-rock reaction and surface processing [3-5]. The Dawn mission has shed new light on Vesta's interior and exterior structure and its surface and shallow subsurface composition [6]. However, two major – and related – problems remain unresolved: 1) how do we reconcile the narrow range in non-cumulate eucrite compositions [7] with the extensive melting that Vesta must have experienced? [3] 2) How are the eucrites related to the other HED lithologies, particularly diogenites, cumulate eucrites and olivine diogenites? These lithologies are found intimately mixed in howardites, and are thought to be genetically linked [e.g. 3,5,7]. However, no model has yet managed to answer both of these questions in a way that is consistent with chemical/petrological data and physical/spatial considerations of Vesta's history. We have tackled the problems of HED genesis and non-cumulate eucrite compositions in new modeling work on the crystallization of a Vestan magma ocean. We present a conceptual model that can explain the range of HED lithologies, their distribution in the shallow Vestan subsurface, and the narrow range in non-cumulate eucrite compositions.

Model Setup: We modeled the crystallization of a Vestan magma ocean using a variety of bulk compositions. Different crystallization scenarios involved various combinations of equilibrium and fractional crystallization, melt extraction and cumulate remelting. Models were run using MELTS [8,9]. The composition of the liquid was tracked for the duration of these model runs to determine how closely the liquids approached eucrite compositions. We measured this using the Aitchison distance (Fig. 1) [10], which is a measure of distance in composition space that is somewhat analogous to the normalized root-mean-square deviation in Euclidian space. This provides a fast and quantitative way to assess whether or not the models produce eucritic liquids: the most eucrite-like liquid in each model corresponds to the minimization of the Aitchison distance from a target eucrite. We chose Sioux County as our target eucrite because it is well-studied and relatively primitive (high Mg#, low Ti). The eucrites Juvinas and Sioux County are almost identical in composition, so the Aitchison distance between Juvinas and

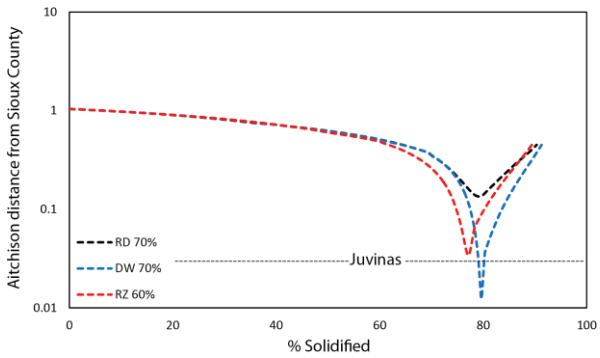

Figure 1. Evolution of magma ocean liquids in models where liquid is extracted to shallow magma chambers after 60-70% crystallization. Graph shows how close in composition space the liquids are to the composition of Sioux County (see text). Anything near or below the Juvinas line is near-identical in composition to primitive eucrites.

Sioux County was used to provide a less abstract indication of how closely our modeled melts approached these representative eucrite compositions (Fig. 1).

How to produce HEDs: Models dominated by fractional crystallization cannot produce HED lithologies because they lead to excessive Fe-enrichment and Si-depletion in the melt. Equally, cumulate remelting cannot produce HED lithologies because the melts are too Al+Ca-poor or Fe-rich. However, some fractional crystallization is required to produce orthopyroxene cumulates (diogenites). Models that successfully produce *all* HED lithologies are those that invoke 60-70% equilibrium crystallization of a magma ocean, followed by extraction of the residual melt and fractional crystallization of this melt in shallow magma chambers. This yields a harzburgite mantle and a crust that is crudely layered into a diogenitic lower crust and eucritic upper crust (Fig. 2).

How to produce non-cumulate eucrite compositions: Our most successful models produce all of the HED lithologies but do not explain the narrow range in non-cumulate eucrite compositions. However, this model becomes more appealing when we adapt it to consider the physical processes at work. After 60-70 % crystallization of the magma ocean, crystal-crystal interaction causes convective "lock-up", slowing convection and aiding mush compaction and extraction of the residual melt into shallow magma chambers (see "How to produce the HEDs", above). However, on a low-gravity body like Vesta, melt extraction would be slow, so shallow magma chambers would be continually

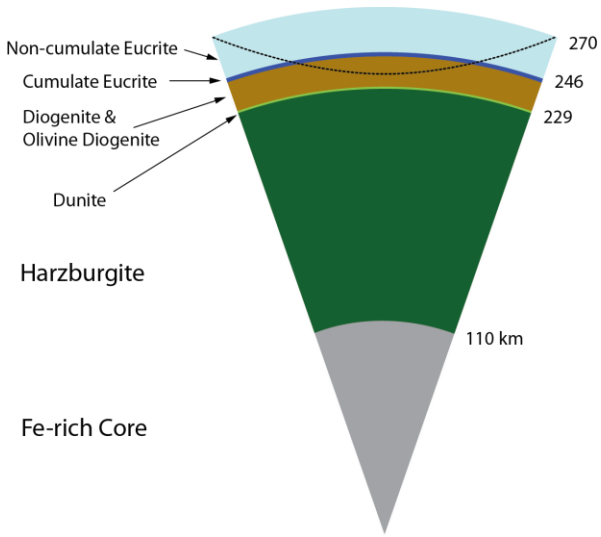

Figure 2. Predicted layer thicknesses from one of the successful models (RZ 60% in Fig. 1). Figure is drawn to show relative proportions of lithologies – actual layering is likely much more crude due to magma recharge (see text). Dotted line represents an impact excavation depth of 35 km.

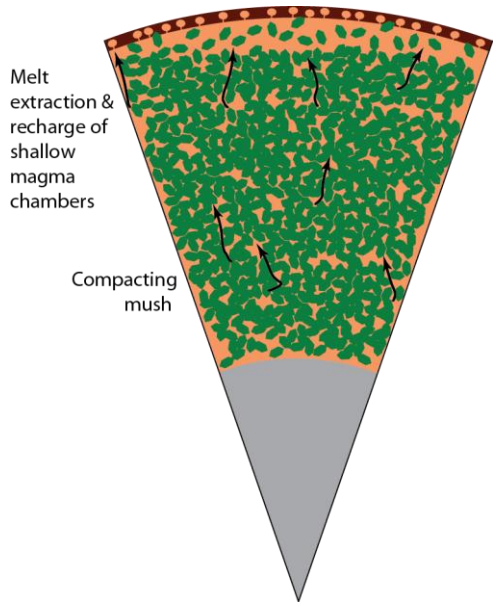

Figure 3. Mush compaction and continuous melt extraction into evolving shallow magma chambers

recharged by melt ascending from the underlying mush (Fig. 3). This continuous addition of olivine-normative melt to the shallow magma chambers would buffer the melt over a small range of compositions near the low-pressure olivine - low-Ca-pyroxene – plagioclase peritectic. These compositions correspond to those of the non-cumulate eucrites. Fractional crystallization combined with magmatic recharge would result in enrichment of the residual magma in trace elements while retaining a relatively constant major element composition. We may therefore also be able to explain the large range in trace and minor element concentrations in diogenites [11]. This is possible because magma recharge would occasionally lead to a periodic return to orthopyroxene crystallization (forming diogenites). For this reason, the Vestan crust is probably crudely layered rather than having a clear diogenite lower crust and eucrite upper crust.

Crustal thickness and the ejection of the HEDs from Vesta: Crustal thickness predictions from our models are 30-41 km. The impact that formed the Rheasilvia basin has long been thought to be the source of the HED meteorites [2]. Impact models suggest an excavation depth of 30-50 km at Rheasilvia [12,13]. Dawn observations show that there are no lithologies in this basin with >25% olivine [14]. Our crustal thickness prediction of 30-41 km is consistent with the excavation of all of the HED lithologies during the Rheasilvia-forming impact without exposing the olivine-rich mantle (Figure 2).

Conclusions: Fractional crystallization of a magma ocean on Vesta cannot produce all of the HED lithologies, nor their chemical compositions. However, all of the HED lithologies can be produced by 60-70% equilibrium crystallization of a magma ocean followed by extraction of the melt into shallow magma chambers that undergo fractional crystallization. Recharge of these magma chambers can explain the narrow range in non-cumulate eucrite compositions and perhaps also the large range in diogenite trace element concentrations. The Vestan crust is 30-41 km thick, which is consistent with ejection of the HED meteorites during the formation of the Rheasilvia basin. The absence of resolvable olivine in the Rheasilvia basin can be explained by the fact that the crust is sufficiently thick that the olivine-rich mantle was not exposed during the impact.

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