OLIVINE FROM THE MANTLE OF 4 VESTA IDENTIFIED IN HOWARDITES.

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Introduction: Some meteorites sample separate portions of differentiated asteroids: iron meteorites are likely core samples and basaltic achondrites are crustal samples. Even though these meteorites originate from as many as 150 geochemically distinct parent bodies [1], samples that represent the mantles of these differentiated asteroids are notably missing. The only exceptions are the pallasites, which may be mantle-core boundary samples [2].

Meteoritic mantle samples and their accompanying geochemical information could be used to advance our understanding of differentiated asteroids:

1. Bulk compositions, which are important for constraining differentiation models and connecting their precursor material to different chemical reservoirs from the early solar system.
2. Core formation and subsequent magmatic evolution of achondrite parent bodies.

Vesta. We have samples of the basaltic crust of the asteroid 4 Vesta in the form of howardite, eucrite, and diogenite (HED) meteorites [e.g., 4]. The geochemistry of the eucrites (basalts) and diogenite (plutonic orthopyroxenites and harzburgites) have been used to anchor models of Vesta's magmatic evolution.

One of the key distinctions between models is the set of conditions they use for the vestan mantle (all used some form of a dry magma ocean): variants of fractional crystallization [5] and of equilibrium crystallization [6, 7]. In each of these studies the vestan mantle contained olivine with different mineral chemistries (Fo-content) and/or different proportions of olivine and pyroxene.

The ideal way to test these models is to study unbrecciated samples of the vestan mantle. Unfortunately, as mentioned previously, no such meteorite samples have been described. In this study, we examine fragmental olivine grains found in regolithic howardite breccias that are of potential mantle origin because they are more Mg-rich ($Fo_{80\text{-}92}$) than olivine found in the most ultramafic HEDs [e.g., 8]. We investigate whether these Mg-rich olivine grains are indigenous to Vesta, and explore how their chemistry may forward our understanding of Vesta's differentiation and magmatic evolution.

Methods: Thin sections analyzed include four paired howardites found in the Grosvenor Mountains (GRO) in Antarctica (GRO 95534,4; GRO 95535,16; GRO 95574,17; GRO 95581,7) and two diogenites (Graves Nunataks (GRA) 98108,16 and Lewis Cliff (LEW) 88008,14) also found in Antarctica.

Electron microprobe (EMP) analyses were performed with a Cameca SX-100 EMP at the University of Tennessee. Mineral spot analyses were conducted with a 1-µm beam at 15 kV 30 nA or 20 kV 100 nA.

In situ SIMS oxygen three-isotope analyses of olivines were conducted using the IMS 1280 at the University of Wisconsin. Analytical conditions and data reduction are similar to those in [9,10]. The primary Cs^+ beam was focused to a 15 µm diameter spot with an intensity of 3 nA. Reproducibilities in oxygen isotope ratios of a terrestrial olivine standard (Fo_{89}) were ~0.3‰ (2SD).

Results: The Mg-rich (potential mantle) olivine grains are monomineralic clasts that do not preserve any igneous textures or mineral associations. The Mg-rich grains are compositionally homogeneous within individual grains; they have $Fo_{80\text{-}92}$ and molar Fe/Mn=37-44. The molar Fe/Mn ratios of diogenite olivine ($Fo_{61\text{-}78}$) measured in this study have Fe/Mn=42-55. Ni-concentrations for both the Mg-rich and diogenite olivine analyzed in this study are close to and/or below the detection limits of ~40 ppm for this study's EMP conditions.

We obtained 50 oxygen isotope analyses from 18 Mg-rich olivine grains and 30 analyses from 12 diogenite olivine grains in GRO 95 howardites. Olivine grains from each group have variations in their oxygen isotope ratios that are smaller than the reproducibilities of SIMS analyses. Group averages are shown in Fig. 1 with $\Delta^{17}O$ values of –0.30±0.08 ‰ and –0.24±0.09 ‰ for Mg-rich olivine and diogenite olivine, respectively.

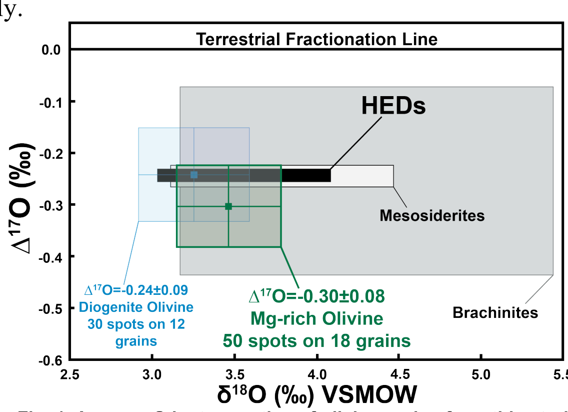

Fig. 1. Average O isotope ratios of olivine grains from this study, compared to data reported in [11].

Discussion: The O isotopic signatures and mineral chemistry provide evidence for a vestan provenance of these Mg-rich olivine grains, allowing us to begin to examine their petrogenesis.

Vestan-HED parent body affinity. The O isotopic signatures of Mg-rich olivine constrain their origin to HED, mesosiderite or brachinite parent bodies [11] (Fig. 1). The Fe/Mn ratio of olivine in bachinites are much higher (Fe/Mn >65) [e.g., 12] than these and known HED olivines (Fe/Mn=40-60) [13]. A mesosiderite origin is not supported by Ni-content of Mg-rich olivine (~10s of ppm Ni), which is lower than in mesosiderite olivine (~100s of ppm Ni) [14].

The O isotopic signature and elemental chemistry provide compelling evidence that this Mg-rich olivine is from Vesta. The major element chemistry of these olivine (Fo_{80-92}) are too Mg-rich to be associated with the diogenites and overlap the olivine compositions modeled for the Vestan mantle [5,7].

Vestan mantle olivine and models. The major element chemistry of Mg-rich olivine in howardite breccia (Fo_{80-92}) coincides with projections from the vestan magma ocean fractional crystallization model from [5] (Fo_{80-93}), regardless of the chondritic bulk composition they used. In contrast, [7] projected Fo_{83} olivine in a harzburgite mantle formed by equilibrium crystallization (with plutonism).

Within the population of Mg-rich olivines the upper end (Fo_{87-92}) of this range is well represented. And although the model from [5] projects a similar range, it also predicts that the most Mg-rich olivine (and orthopyroxene) would have settled out first and would be the deepest portion of the vestan mantle. But it is difficult to explain how the deepest portion of a magma ocean fractional crystallization sequence could end up in the regolith of an intact differentiated asteroid.

Equilibrium crystallization in the vestan magma ocean would produce a single olivine composition or small range. However, the range we have found in the Mg-rich olivine is fairly large. These Mg-rich mantle olivines reveal that processes in the vestan mantle are not governed solely by fractional crystallization or equilibrium crystallization. Processes in the vestan mantle are likely more complex than previously imagined. For instance, convection and/or mantle plumes may have entrained Mg-rich olivine that settled out. Alternatively, Mg-rich olivine may have been segregated from the rest of the mantle without settling out.

Samples of the vestan mantle may help constrain the proportion of metal that separated out to form Vesta's core. The Ni-content of the Mg-rich olivine is the same order of magnitude calculated (10s of ppm Ni) by the Righter and Drake [6], who estimated a core that comprised 5-25% of Vesta's mass, consistent with Dawn's recent estimate of 18% [15]. Future analyses of siderophile element abundances in these Mg-rich mantle olivines will enable us to more directly examine metal-silicate partitioning during Vesta's differentiation than previously possible.

The petrology of the vestan mantle is presently unclear: most model results imply it is dunite and/or harzburgite. The recent models that constrained the vestan core size using data collected by the Dawn Spacecraft (while in orbit) have projected a harzburgite [7] and/or pyroxene-rich [16] mantle. However, the most Mg-rich pyroxene we have currently found in these howardites has En_{84} which falls within the range for diogenites [11] and would not crystallize in equilibrium with the most Mg-rich olivine (Fo_{85-92}) [e.g., 17].

Establishing vestan mantle petrology will better constrain the bulk composition of Vesta. Currently, Vesta's bulk composition can be best described as a alkali-depleted mixture of H- and CM-chondrites [16]. How Vesta became depleted in alkalies and other volatiles remains an open question. Whether or not these depletions were inherited from its prolith or from devolatilization during or after differentiation could be tested by comparing the trace elements concentrations of Vesta's mantle to its crust.

Implications of mantle olivine in howardites. It is also important to consider how mantle samples came to be fragmental grains in regolith breccias (howardites). In seems unlikely, albeit not impossible, that these grains were mantle xenoliths that reached the crust by igneous processes, since this olivine has only been found in howardites and not in diogenites or eucrites. It is more likely that Mg-rich grains were in the upper mantle and incorporated into the regolith by large impacts: the Rheasilvia impact basin could have excavated material from the mantle [7].

Conclusion: We have recognized the first samples of a differentiated asteroid's mantle that can be connected to a group of basaltic meteorites. These samples indicate that processes in the mantle of Vesta were more complex than previously considered. With further analyses, we will be able to examine asteroid differentiation more directly than has ever been possible.

References: [1] Burbine T.H. et al. (2002) In *Asteroids III* ed. Bottke W.F. et al. U of Arizona Press [2] Mittlefehldt D.W. et al. (1998) In *Planetary Materials* ed. Papike J.J. et al. Min Soc of America [3] McCoy T.J. et al. (2006) *EPSL* 246, 102 [4] McSween H.Y. et al. (2012) *Space Sci Rev* 163, 141 [5] Ruzicka A. et al. (1997) *MAPS* 32, 825 [6] Righter K. & Drake M.J. (1997) *MAPS* 32, 929 [7] Mandler B.E. & Elkins-Tanton L.T. (2013) *MAPS* 48, 2333 [8] Beck A.W. et al. (2012) *MAPS* 47, 947 [9] Kita N.T. et al. (2010) GCA 74, 6610 [10] Tenner T.J. et al. (2013) GCA 102, 226 [11] Greenwood R.C. et al. (2012) *GCA* 94, 146 [12] Gradner-Vandy K.G. et al. (2013) *GCA* 122, 36 [13] Beck A.W. et al. (2011) *MAPS* 46, 1133 [14] Kong P. et al. (2008) *MAPS* 45, 451 [15] Russell C.T. et al. (2012) *Science* 336, 684 [16] Toplis M.J. et al. (2013) *MAPS* 48, 2300 [17] Beck A.W. & McSween H.Y. (2010) *MAPS* 45, 850