A METEORITE ANALOG FOR OLIVINE-RICH TERRAIN IN UNEXPECTED LOCATIONS ON VESTA.

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Introduction: Asteroid 4 Vesta, the likely parent body of the howardite, eucrite, diogenite (HED) meteorites [1], is one of the largest protoplanetary bodies in our solar system. It differentiated into a core, lower mantle, ultramafic upper mantle/lower crust (diogenite) capped by a basaltic veneer (eucrite). The diogenites consist mainly of low-Ca pyroxene, with some samples containing ~25 vol.% olivine [2]. Eucrites are mixtures of low- and high-Ca pyroxene, and plagioclase [3]. The vast majority of the surface of Vesta is howarditic [4], a mixture of eucrite and diogenite created by impact gardening. The Dawn Spacecraft recently completed its mission to Vesta [5] leaving behind some unresolved questions about the vestan surface, which can be addressed by further examination of the HEDs.

Background: Prior to Dawn's arrival at Vesta, meteorite studies [6] and Hubble Space Telescope observations [7] suggested that olivine would be associated with diogenite-rich terrain and would likely be observed in impact craters that penetrate deep into the lower crust. The instrument onboard Dawn best suited to identify olivine is the visible and near-infrared spectrometer, VIR [8]. HEDs display strong ~0.9 μm (BI) and ~1.9 μm (BII) absorption features, and the more Fe-rich eucrites have BI and BII features at longer wavelengths relative to diogenites.

Olivine-enrichment in pyroxene dominated rocks, like the HEDs, can be identified at VIR spectral resolutions by: #1) the presence of a broad ~1.2 μm shoulder, which also causes #2) BI center shift to longer wavelengths, and #3) reduction of BII depth. Another indicator of olivine in an HED-like mixture is #4) lack of significant BII center shift when BI shift *is* observed [9]. In the HED system, BI and BII centers shift in tandem as a result of increased Fe in pyroxene, with a greater shift occurring in BII center (ΔBI center from diogenite to eucrite = 0.04 μm, ΔBII center = 0.1 μm [10,11]). The addition of olivine, however, only affects BI center, leaving BII center relatively unchanged [9].

Unexpectedly, VIR did not detect olivine-rich terrains in the ~500 km diameter deep impact crater, the diogenite-rich Rheasilvia Basin [12], or any other diogenite-rich area on Vesta [13]. It is likely that the olivine abundance in the "olivine-rich" diogenites, is too low to effectively alter pyroxene BI and BI absorption features, making them unresolvable (if present) in Rheasilvia or other diogenite-rich areas [2]. However, VIR did detect olivine-rich (50-80 vol.%) regions along portions of the walls of two smaller (~40 km and ~11 km, diameter) craters in the howarditic, northern latitudes of Vesta [13]. The a) high abundance of olivine, b) howarditic compositions, and c) near-surface locations of this unit are not consistent with the "olivine-rich" diogenites, and thus the identity of these olivine-rich terrains remain unresolved.

Objectives: Here we test the hypothesis that the olivine-rich unit in the northern hemisphere of Vesta is analogous to olivine-rich impact melts that have recently been identified in howardites [14,15]. First we compare the petrology of the olivine-rich impact melts to what has been inferred for the olivine-rich units on Vesta, then we compare spectra from the olivine-rich impact melts to the units identified on the surface. Petrologic data were gathered using electron microscopy at the Univ. of Tennessee and the Smithsonian. Spectra were collected at the Brown Univ. RELAB and The Johns Hopkins Univ. Applied Physics Lab on an ASD field spectrometer.

Discussion: *Petrology:* The Pecora Escarpment Icefield 2002 (PCA 02) howardite group contains impact melt clasts with mm-sized olivine phenocrysts set in a melt matrix that has a mode of ~50 vol.% olivine, ~30 vol.% pyroxene, ~20 vol.% plagioclase. We estimate the mode of entire melt clasts (phenocrysts + melt matrix) to be ~75 vol.% olivine, 15 vol.% pyroxene, 10 vol.% plagioclase. The olivine abundance of an entire impact melt clast, rather than the abundance in the melt matrix or the entire howardite, is representative of olivine abundances expected if these melts were present on the surface of Vesta. Some olivine-rich impact melts in the PCA 02 howardite group contain less olivine (~15 vol.%), but are less common [14]. The Grosvenor Mountains (GRO) 95574 howardite contains olivine-rich impact melt that has ~50 vol.% olivine and ~50 vol.% glass. Abundance of olivine in these howardite impact melt clasts closely matches the 50-80 vol.% range predicted for the olivine-rich area in the northern hemisphere of Vesta identified by [13].

Spectra: Splits of four howardites previously identified as containing ~0-30 vol.% impact melt (which, as described above, contain ~50-75 vol.% olivine) were used for spectral analysis. It is important to note that the vol.% of impact melt in the splits is likely not identical to that measured in thin section [14]; further, the howardite splits are composites of impact melt clasts and howardite (pyroxene), not pure impact melt.

For comparison, representative VIR spectra from the olivine-rich area on Vesta and an average vestan spectra from [13] are also examined (Fig. 1a). The olivine-rich area on Vesta is distinguished by: #1) a broad 1.2 μm absorption shoulder, likely causing #2) BI center shift to longer wavelengths, #3) a lack of significant BII center shift, and #4) a reduction in BII depth without reduction in BI depth. Similarly, increased abundance of olivine-rich impact melt in howardites results in #2), #3) and #4) (Fig 1b.). The lack of development of a 1.2 μm shoulder in the impact melt-bearing howardites can be ascribed to the fact that the melt does not comprise the entire split used for spectral analysis; a 1.2 μm shoulder would be expected if a pure olivine-rich impact melt was measured. Efforts to conduct VIS/NIR spot analyses of olivine-rich impact melt are ongoing.

If BII vs. BI centers are examined, the olivine-rich terrain on Vesta becomes more distinct (Fig. 2a). VIS/NIR spectra of HED meteorites and the average vestan surface (howardite) are confined to the same shallow-sloped linear trend from diogenite to eucrite BII vs. BI centers. Olivine-enrichment of HEDs results in steep, positive divergence

from this trend. Laboratory mixtures from this study and [9] show that $Fo_{89\text{-}90}$ olivine, when mixed with diogenite pyroxene in abundances from 0-90%, result in BI vs. BII center positions unlike those observed in the northern olivine-rich terrains on Vesta (Fig 2a). While olivine in diogenites is more Fe-rich (~$Fo_{61\text{-}80}$), this would not have an effect on BII center position (horizontal position on HED BI vs. BII trend), which is governed by pyroxene Fe concentration (Fig. 2a). However, PCA 02015, the howardite with the highest concentration of olivine-rich impact melt, matches the BI vs. BII center position of the olivine-rich terrain on Vesta quite well (Fig. 2b). The positive divergence from the typical HED BI vs. BII center trend in the impact melt spectra is presumably due to an abundance of olivine, displaying a comparable trend to the olivine-rich area on Vesta. The overlap in location in BII center between the melts and the vestan olivine rich-terrain suggests that they have similar pyroxene Fe content, strengthening their connection. Pyroxene in the impact melts are howarditic in composition (~En_{65},[14]), explaining their offset to the right of diogenite + olivine mixtures, which contain more Mg-rich pyroxene (~En_{75}[6]) and therefore have lower BII center values. As mentioned previously, the splits used in this study were mixtures of olivine-rich impact melt and howardite. As such, we would expect pure olivine-rich impact melt to have higher BI centers with little change in BII center, matching the data for the olivine-rich area on the surface of Vesta at the upper portion of this plot (Fig. 2b). The spectral data presented here support the hypothesis that the olivine-rich impact melts in howardites are analogous to olivine-rich terrains on Vesta.

Conclusions: To date, olivine-rich impact melts in howardites are the best petrologic and spectral analog in HEDs for the olivine-rich terrain in the northern hemisphere of Vesta; they have similar olivine abundances, they have similar pyroxene compositions, combining to produce similar BI and BII features, and they both formed in near-surface environments. The precursor materials for these impact melts, however, remains unresolved. How are impact melts with 50-80 vol.% olivine and ~En_{65} pyroxene created from HED starting materials? Olivine-rich diogenites contain less olivine and/or more Mg-rich pyroxene than what is observed in the melts, and thus other precursor components or crystallization processes relating to the origin of the melts should be considered. Perhaps a CM chondrite component, or quench melting, would aid in achieving the ultramafic, yet relatively Fe-rich petrology observed. Future work is planned to investigate target rock petrology, melt petrogenesis, and to measure spectra of olivine-rich melt clasts using spot analysis.

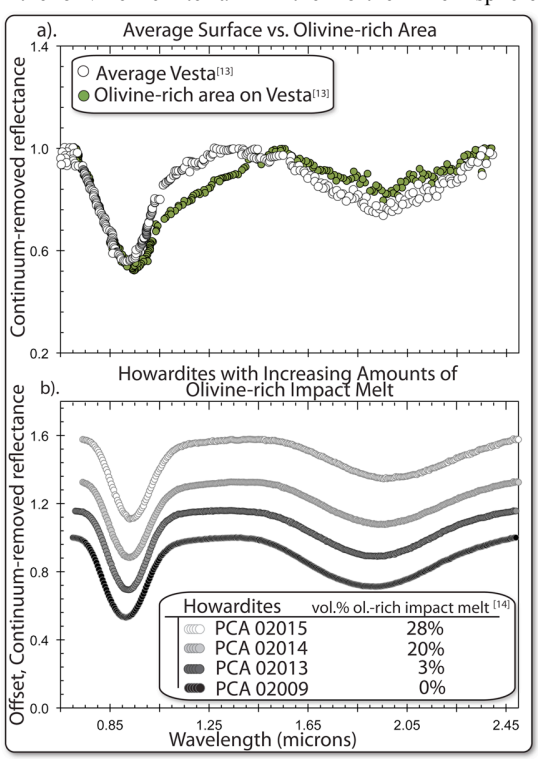

Fig. 1 a) Average Vesta spectra vs. ol.-rich region, taken from [13], **b)** spectra of howardites with increasing ol.-rich impact melt, showing similar features (#2, #3, #4, described in text) as the ol.-rich region on Vesta.

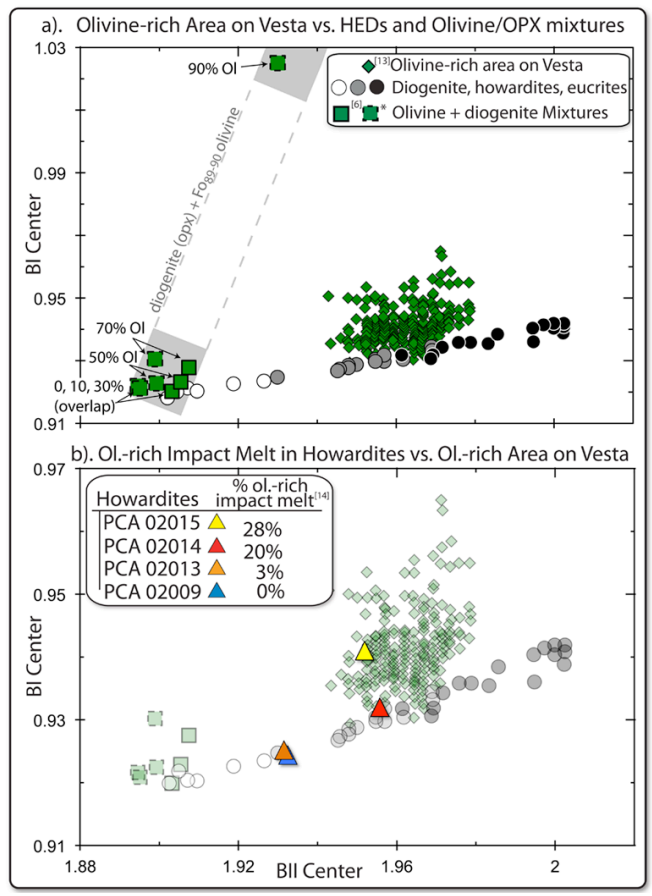

Fig. 2 a) Linear trending HED BI vs. BII centers correlate to BI and BII centers for the average surface of Vesta. Addition of olivine causes positive divergence from the trend, as seen by diogenite + ol. mixtures, and the ol.-rich area on Vesta [13], **b)** ol.-rich impact melt in PCA 02015 matches the divergence of the ol.-rich area on Vesta and BII center position, supporting their interpretation as analogs

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