NAKHLITE, CUMULATE EUCRITE, AND DIOGENITE MELT INCLUSION ANALYSES: INVESTIGATING PARENT MELT CHARACTERISTICS OF ACHONDRITES FROM MARS AND 4 VESTA. N. G. Limbaugh[1*], J. A. Cartwright[1], and L.J. Hallis[2]. [1]University of Alabama, Department of Geological Sciences, Tuscaloosa, AL. [2]University of Glasgow, School of Geographical and Earth Sciences, Glasgow, UK *(nglimbaugh@crimson.ua.edu)

Introduction: Achondrite meteorites are useful materials for studying the magmatic evolution of their parent bodies, including differentiated planets, moons, and asteroids. Howardite-eucrite-diogenites (HEDs) (believed to originate from 4 Vesta [1]) and Martian meteorites are achondrites and, in the absence of returned samples from Mars and 4 Vesta, are the best available recorders of magmatism within their respective differentiated planetary bodies. Martian nakhlites and Vestan cumulate eucrites and diogenites display cumulate igneous textures and features which contain valuable information about the magmatic processes of their parent bodies, especially in the form of melt inclusions (e.g. [2, 3, 4, 5]).

Melt inclusions are small (micrometer-scale) droplets of melt that have been trapped within crystallizing magmas, and are capable of retaining pristine geochemical signatures of parental melts (e.g. [6, 7]). There are two general categories of melt inclusions: 1) Primary melt inclusions, which are usually euhedral, core-restricted phases that petrographically and compositionally record "snapshots" of early magma conditions prior to the crystallization of their silicate host minerals, and are isolated from alteration due to their occurrence within host mineral cores [8]. 2) Secondary melt inclusions are unrestricted to host mineral cores, often form in clusters, and are indicative of later magmatic events such as melt rise and residual melt mixing within the parent body [9]. Importantly, elemental compositions of both types can highlight magmatic activity at different stages, from the earliest parent melt to later stages along the magmatic evolution sequence.

Terrestrial basalts, commonly known to contain melt inclusions, have been useful for developing melt inclusion studies to determine parent melt compositions for the Earth and are applicable for constraining compositional properties of achondrite parent melts [7]. Melt inclusions have been observed in several nakhlites [10, 11]. Cumulate eucrite melt inclusions have rarely been a focus in previous literature: though have been discussed in at least one sample (Dhofar 007) previously [12]. For diogenites, melt inclusions have been observed in Johnstown, Roda, Dhofar 700, Yamato 74097, Lewis Cliff 88679, and Tatahouine samples [2, 5, 12, 13]. The evolution of Martian and Vestan parent melts should be traceable in achondrite meteorite samples with melt inclusions given their similarities to terrestrial melt-inclusion-hosting basalts.

The Martian nakhlites consist of over 20 separate stones and are dominated by clinopyroxene with rare to uncommon olivine and plagioclase crystals [3, 11]. Nakhlites are believed to have been generated from partial melting of a garnet and calcium-rich pyroxene source [3, 11], which should be confirmed by primary melt inclusion compositions. Additionally, nakhlites show evidence for light rare Earth element (LREE) contamination of melts, which is likely due to open system partitioning during subsurface fluid injection [11, 14]. Nakhlites also show evidence for chlorine (Cl)-rich exogenous fluid alteration, likely promoting the formation of reddish, clay-like secondary phases found in some samples [11, 14, 15, 16, 17]. It is possible that secondary melt inclusions record LREE and Cl enrichment as a later mechanism. Investigating nakhlite melt inclusions can better define the compositional evolution of the nakhlite cumulate suite.

For HEDs, lower incompatible trace element abundances have been noted within cumulate eucrites [18], though modelling results suggest the HED parent body is enriched in rare earth elements (REEs) [19]. Cumulate eucrite melt inclusions should represent lower melt enrichment levels, reflecting early fractional crystallization in which REEs were preferentially retained in migrating melts, likely recording a more intermediate or depleted parent melt composition in primary melt inclusions compared to bulk parent body REE levels. Some diogenites are thought to originate from heavy rare earth element (HREE) enriched parent melts, potentially produced by cumulate remelting [20]. While there is some debate about whether diogenites formed with or after eucrites, petrographic similarities, chronological and compositional trends, and observed deep europium (Eu) anomalies (Eu/Eu* < 0.1) in some diogenites [5, 21] suggest that they intruded older eucritic crust. Such a process should be recorded by compositional features of diogenite melt inclusions. Investigating these materials thus may provide further insight into the indirectly cogenetic relationship between diogenites and cumulate eucrites and shed new light on the overall petrogenetic evolution of HEDs.

In this study, we will investigate melt inclusions from two nakhlites (NWA 11013 and NWA 13669), one cumulate eucrite (NWA 8564), and one diogenite

(NWA 7831) to determine the compositions of their progenitor melts and their evolution within each of their respective parent bodies. Primary nakhlite melt inclusion compositions should reflect a more depleted parent melt, while secondary melt inclusions should reflect enrichment. An olivine-rich layer at depth within the Vestan mantle is believed to reflect early stages of residual liquid melt migration grading upward, potentially sourcing eucrite and diogenite parent melts [19, 22], which may be confirmed by depleted to enriched composition progression of cumulate eucrite and diogenite primary melt inclusions respectively.

Methods: All samples are in-hand in the Cartwright Cosmochemistry Laboratory (CCL) and have been purchased commercially. We currently have thin sections of nakhlites NWA 11013 (x2) and NWA 13669 (x3), and diogenite NWA 7831 (x2), with cumulate eucrite NWA 8564 in progress. We will employ standard microscopy techniques in the CCL as well as scanning electron microscopy (SEM), and electron micro-probe analysis (EMPA) within the Alabama Analytical Research Center (AARC) at the University of Alabama (UA) to image the samples and locate melt inclusions for study.

We plan to conduct laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) to measure major, minor, and trace element compositions of melt inclusions. Examining elemental variations across melt inclusions and their host minerals (i.e. zonation) can elucidate key details regarding their origins and crystallization history. Future analyses will incorporate atom probe tomography (APT) to profile diffusion processes of target melt inclusions.

Preliminary Observations: Thus far in our study, we have identified melt inclusions in NWA 11013, NWA 13369, and NWA 7831 (Fig. 1). Rare polymineralic melt inclusions (PI) and three distinct monomineralic melt inclusion types are observable in thin sections: opaque inclusions (OI), crystalline inclusions (CI), and glassy inclusions (GI).

Overall, larger host minerals have more abundant and diverse types of melt inclusions. Opaque inclusions (likely iron oxides) are abundant and are present as either isolated, euhedral clasts (primary) or in "trailing" clusters transecting fractures and grain boundaries (secondary). Crystalline inclusions are likely early forming silicates (clinopyroxene) and are valuable for understanding parent melt compositions. Glassy inclusions range from subangular to rounded and could reflect either early or evolved parent melt compositions.

We will be selecting melt inclusions in these samples to target for LA-ICP-MS and APT and are working towards determining their composition.

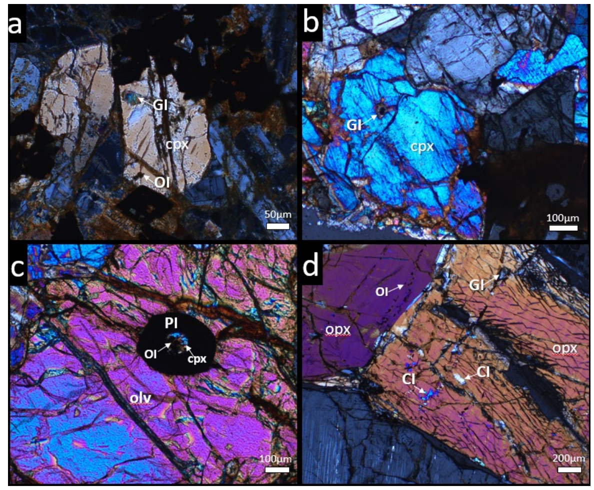

Fig. 1 - Cross polarized light photomicrographs of NWA 11013 (a), NWA 13669 (b) (c), and NWA 7831 (d) [olv = olivine, cpx = clinopyroxene, opx = orthopyroxene].

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