PETROLOGY OF IGNEOUS CLASTS IN REGOLITHIC HOWARDITE EET 87503.

Z. V. Hodges[1] and D. W. Mittlefehldt[2], [1]Department of Earth Sciences, Durham University, Durham, UK (zvhodges@hotmail.com) [2]Astromaterials Research Office, NASA Johnson Space Center, Houston, TX, USA.

Introduction: The howardite, eucrite and diogenite (HED) clan of meteorites is widely considered to originate from asteroid 4 Vesta [1], as a result of a global magma ocean style of differentiation [2]. A global magmatic stage would allow silicate material to be well mixed, destroying any initial heterogeneity that may have been present resulting in the uniformity of eucrite and diogenite $\Delta^{17}O$ [3], for example.

The Fe/Mn ratio of mafic phases in planetary basalts can be diagnostic of different source bodies as this ratio is little-affected by igneous processes, so long as the oxygen and sulphur fugacities are buffered [4]. Here, pyroxene Fe/Mn ratios in mafic clasts in howardite EET 87503 have been determined to further evaluate whether the HED parent asteroid is uniform. Uniformity would suggest that the parent asteroid was subject to homogenization prior to the formation of HED lithologies, likely through an extensive melting phase. Whereas, distinct differences may point towards preservation of heterogeneity of the parent body through the differentiation process.

Samples and Methods: Pyroxene and plagioclase compositions from 17 mafic clasts in EET 87503 were determined by electron microprobe analysis at NASA Johnson Space Center. These are compared to a reference unbrecciated basaltic eucrite, EET 87520, and to basaltic clasts in Sioux County [5]. Importantly, analytical conditions for pyroxenes were set to achieve increased precision on Fe/Mn ratios [e.g., 6].

Pyroxene compositions are compared using Fe/Mn. Divalent Fe and Mn partition differently in pigeonite and augite because of the order of filling of the M1 and M2 sites with Mg, Ca, Mn and Fe [7]. Thus only low-Ca pyroxenes are used for comparisons. Normality tests were conducted to establish the distribution of the data for each clast. Statistical techniques, such as the Student's t-test, were used to compare Fe/Mn ratio means for low-Ca pyroxenes from individual clasts in EET 87503 to those in basaltic eucrite, EET 87520.

Petrology and Mineral Compositions: EET 87503 is a regolithic howardite [8] with an overall fragmental brecciated texture containing abundant lithic clasts within a clastic matrix composed of single crystal fragments (Fig. 1). The matrix comprises varying grain sizes of pigeonite, augite, plagioclase, orthopyroxene, olivine, ilmenite, chromite, silica, metal and troilite. Lithic clasts show a variety of textures from igneous subophitic basaltic clasts with unequilibrated, zoned pyroxenes, to metamorphosed clasts with hornfelsic to granoblastic textures and equilibrated pyroxenes. Impact melt clasts and chondritic clasts are also evident.

Pyroxenes in EET 87503 show great variability (Fig. 2). For example, highly metamorphosed clast 5 shows a clear distinction between pigeonite and augite compositions, as a result of equilibration. In contrast, clast 6 contains pyroxenes that are unequilibrated and display extreme igneous zoning.

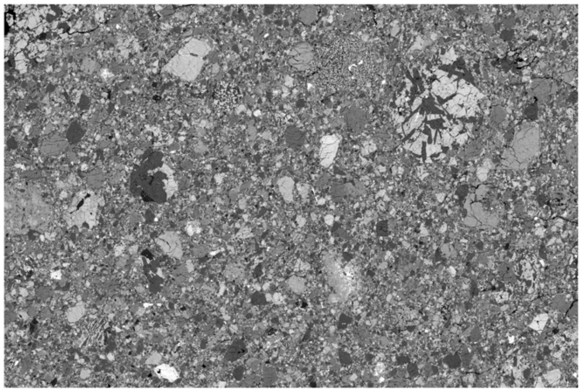

Figure 1: BSE image of EET 87503. Lithic and mineral clasts are visible within the fragmental matrix. Image is 12 mm across.

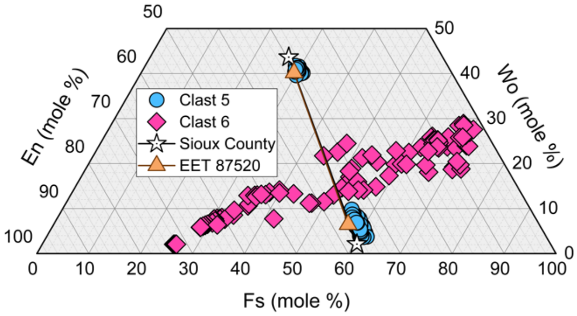

Figure 2: Pyroxene quadrilateral for representative clasts in EET 87503 compared to eucrites Sioux County [5] and EET 87520.

Clast average plagioclase compositions range from An_{86-92}. Clast plagioclase compositions show a variety of ranges with some being very narrow, e.g. clast 5 $An_{88.5-89.0}$, and some much wider, e.g. clast 10 $An_{81.0-92.4}$.

EET 87520 is a coarse-grained unbrecciated eucrite [9] composed of pigeonite ($Wo_{6.5}En_{36.8}Fs_{56.7}$), augite ($Wo_{40.2}En_{30.3}Fs_{29.5}$) as exsolution lamellae and discrete grains, plagioclase, silica, ilmenite and ulvöspinel.

Discussion: The majority of basaltic eucrites have so far demonstrated homogeneous oxygen isotopes, and this has been taken as evidence for homogenization of the parent body during igneous differentiation [3]. Nevertheless, some mafic achondrites have small, but distinctive isotopic and petrologic differences from most eucrites which has been taken as evidence for an origin on different parent bodies [5, 6, 10].

The simplest interpretation for the origin of EET 87503 is that it is a regolith breccia dominated by debris from the parent asteroid, with a small component of admixed chondritic impactor debris [8], and thus, the mafic clasts we have studied are fragments of the HED parent asteroid crust. Therefore, mafic clasts in EET 87503 ought to have pyroxene Fe/Mn indistinguishable from those of most eucrites.

Statistical tests on the mafic clasts, compared to the reference eucrite EET 87520, reveal robust differences in Fe/Mn ratios at the 99% confidence level for some of them (Fig. 3). However, the differences are much smaller than those found for anomalous eucrites such as QUE 94484, EET 87542 and Ibitira [5, 6]. The variations we have documented demonstrate some compositional heterogeneity on the HED parent body.

One possible interpretation of our results is that the HED parent body did not completely homogenize through extensive differentiation via a magma ocean stage [3]. However, the scale of Fe/Mn variation among clasts in EET 87503 we observe is much less than the difference between Ibitira and normal basaltic eucrites (Fig. 3). In the case of Ibitira, the larger difference in O isotopic composition [10, 11], coupled with petrologic and bulk-rock trace element differences, led to the conclusion that Ibitira was formed on a different parent asteroid [6]. For the EET 87503 clasts, we do not have companion isotopic or trace element data to aid in interpreting the petrological differences. The small differences in Fe/Mn ratios of mafic clasts plausibly indicate small intrinsic variations within the parent body crust. These variations could arise within pyroxenes formed from magmas on a single parent body, even one that underwent a global magma ocean stage.

A simple model of the effect on Fe/Mn and Fe/Mg ratios with varying molar Fe is plotted in Figure 3. The variation in clast Fe/Mn is consistent with either the addition or removal of a small amount of Fe through redox processes. Redox processes could, for example, involve late stage reduction of FeO, perhaps as a result of increasing f_{S_2} and sulphur saturation with cooling and crystallization [12]. Subsolidus reduction of FeO should form Fe metal, silica and more Mg-rich pyroxene with low Fe/Mn. If the reducing agent was S, the mesostasis would likely be rich in troilite [9,12]. Evidence of pockets of mesostasis of silica and troilite is sparse in clasts of EET 87503, but this may be a result of the small scale of clasts analysed here (a few hundred microns).

Igneous fractionation would result in early crystallized pyroxenes having lower Fe/Mg and Fe/Mn than the melt [13]. The apparent trend of basaltic clasts in Figure 3 is generally consistent with this hypothesis and may therefore simply reflect normal igneous fractionation of HED basalts.

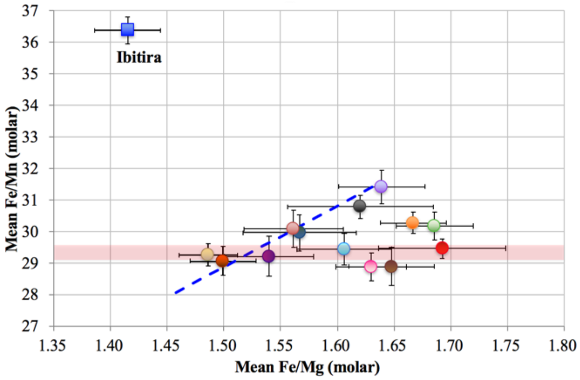

Figure 3: Mean Fe/Mn vs. mean Fe/Mg for select EET 87503 clasts compared to Ibitira [6]. Each symbol represents a different clast. Red band: Fe/Mn of reference eucrite EET 87520. Blue line: effect of varying molar Fe only.

Summary: Our results show statistically sound variations in low-Ca pyroxene Fe/Mn of individual clasts in howardite EET 87503. While this variation could be a result of a heterogeneous parent body that did not undergo extensive differentiation, we think it more likely that such small variations in Fe/Mn ratios arise as a result of normal igneous fractionation and/or late-stage redox processes. These small statistical differences then have geological significance regarding the detailed history of individual magma pulses. Our results provide important constraints on using pyroxene Fe/Mn in interpreting the petrology of basaltic eucrites.

Acknowledgements: We thank D. K. Ross, E. L. Berger, L. Le and A. H. Peslier for their assistance. This project was funded through the NASA Emerging Worlds Program.

References: [1] McSween Jr. H. Y. et al. (2013) *Meteoritics & Planet. Sci., 48,* 2090. [2] Mandler B. E. and Elkins-Tanton L. T. (2013) *Meteoritics & Planet. Sci., 48,* 2333. [3] Greenwood R. C. et al. (2005) *Nature, 435,* 916. [4] Papike J. J. et al. (2003) *Am. Min., 8,* 469. [5] Mittlefehldt D. W. et al. (2016) *LPS XLVII,* Abstract #1240. [6] Mittlefehldt D. W. (2005) *Meteoritics & Planet. Sci., 40,* 665. [7] Cameron M. and Papike J. J. (1981) *Am. Min. 66,* 1. [8] Mittlefehldt D. W. et al. (2013) *Meteoritics & Planet. Sci., 48,* 2105. [9] Mayne R. G. et al. (2009) *Geochim. Cosmochim. Acta, 73,* 794. [10] Scott E. R. D. et al. (2009) *Geochim. Cosmochim. Acta, 73,* 5835. [11] Wiechert U. H. et al. (2004) *Earth Planet. Sci. Lett., 211,* 373. [12] Mittlefehldt D. W. & Peng Z. X. (2015) 78th Ann. Meeting Meteoritical Society, Abstract #5342. [13] Stolper E. (1977) *Geochim. Cosmochim. Acta, 41,* 587.