TRACE ELEMENTS REVEAL COMPLEX HISTORIES IN DIOGENITES. J. B. Balta,[1] A.W. Beck[2], and H.Y. McSween Jr.[1], [1]Planetary Geoscience Institute and Department of Earth & Planetary Sciences, University of Tennessee, Knoxville, TN 37996-1410, [2]Smithsonian institution, Washington, DC, 37012, corresponding author: jbalta@utk.edu.

Introduction: Early results of the Dawn mission to 4 Vesta have revealed that the asteroid acts in many ways as a terrestrial planet; it differentiated early in the solar system's history, cooled, formed planetary scale structures in large impacts, and evolved in response to gravity. Vesta's differentiation process took place early in the solar system's history, likely forming a magma ocean while the short-lived radioisotope ^{26}Al was still extant [1]. Previous authors have proposed a variety of crystallization paths for a Vestan magma ocean, some of which can lead to the the HED meteorite types believed to derive from Vesta [2]. However, there are still complexities unexplained by the magma ocean model; in particular, pyroxenes in diogenites exhibit a wide range in trace element compositions, seemingly necessitating derivation from multiple parental magmas [3].

Given the dominance of impact processes in Vestas history, it is likely that the HED meteorites would have experienced a wide variety of magmatic and cooling histories, depending on their location within the body relative to major impact events. These processes would variably cool and reheat the impacted rocks, possibly eliminating evidence of the impact.

In general, pyroxenes in diogenite meteorites are homogeneous in Fe-Mg compositions within a single grain, suggesting long periods of high-temperature equilibration. However, compositional variability is preserved between samples and even within some samples, as some meteorites contain more than 1 lithology [4]. These results imply a complex relationship between cooling and crystallization, which homogenized some samples but not others. Based on these results, [5] analyzed trace element zoning in a group of Diogenite orthopyroxene (OPX) and found remnant patterns suggesting preservation of magmatic features. We have expanded upon these results by analyzing trace element zoning in larger number of diogenite OPX. We report a wide variety of textures preserved by trace elements within seemingly homogeneous grains, including remnants of impact brecciation, magmatic processing, and possible liquid or melt flow along fractures.

Analytical Procedure: Using the Cameca SX-100 EMP at the University of Tennessee, we produced high-current composition maps of a growing series of OPX (and olivine) grains from diogenites. Pyroxenes were analyzed for Ti, Cr, Al, and Mg in ~1000 x 1000 μm sections, with current set to 200 nA and counting times of 900 ms. Due to the time it took to collect each map (~60 hours), only a few maps could be collected on any given sample. Backscatter electron images (BSE) were also collected for each sample. Image contrasts were re-scaled manually to illustrate variation in trace elements. EMP spot transects were collected across features once they had been mapped. Count times were increased to 60 seconds per spot for pyroxene trace elements (Cr, Al, Ti) and currents of 30 nA were used to increase precision.

Results:

GRA 98018: This sample was classified by [4] as a harzburgitic diogenite, containing >10% olivine along with OPX. [6] measured trace elements in the OPX and suggest that this sample underwent post-magmatic alteration, with trace elements migrating from the pyroxenes into grains such as apatite. While OPX in this sample appears to be manifested as single, large (~400 μm) grains, trace element mapping in areas containing both olivine and OPX shows clear remnant magmatic patterns, including well-developed triple junctions between smaller original grains (Fig. 1). Trace element abundances in pyroxenes decrease at remnant grain boundaries, implying depletion of trace elements, possibly due to removal of small degree melts from these boundaries. Removal of small degree melts is consistent with the mechanism for trace element depletion suggested by [6]. We also note that these magmatic features are not seen in OPX from areas devoid of oli vine within this sample.

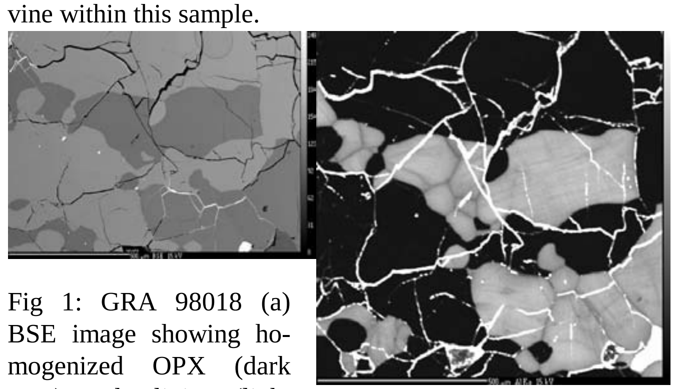


Fig 1: GRA 98018 (a) BSE image showing homogenized OPX (dark gray) and olivine (light grey) grains and (b) trace element (Al) map showing magmatic textures and preserved, low Al boundaries.

Lew 88008: This sample was classified by [7] as a dimict breccia, containing both harzburgitic and orthopyroxenitic diogenite lithologies.

The harzburgitic lithology is brecciated but contains large grains that appear homogeneous in their trace elements (Fig. 2). The orthopyroxenitic lithology is coarse grained, but trace elements show some evidence of remanent grains, possibly from a previous brecciation event, including the remnants of a twinned grain and trails of inclusions which may have marked grain boundaries (Fig. 2).

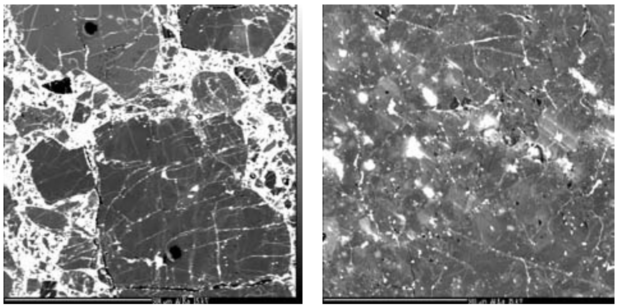
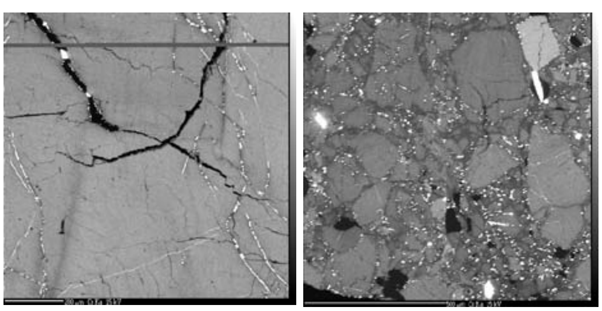


Fig. 2: Lew 88008 (a) harzburgite and (b) orthopyroxenite Cr maps

MET 01084: This sample was also classified as a dimict breccia by [7]. The harzburgitic lithology contains very coarse grains with little remanent trace element zoning (Fig. 3.) The orthopyroxenite lithology consists of very coarse OPX grains, but trace elements preserve spectacular evidence of brecciation and near complete recrystallization. The grain was clearly brecciated by an impact and then recrystallized during a second heating event. Ti contents are uncorrelated with the other mapped trace elements (Fig. 3c). Ti contents remain below the detection limit of EMP spot analyses and could not be determined accurately.



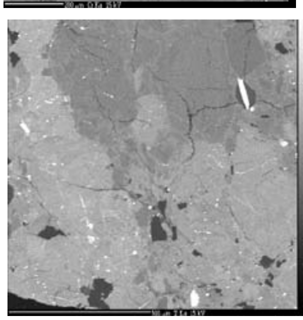


Fig 3. MET 01084 (a) Hzbg. Cr map, showing weak/no zoning, (b) opx-nite Cr map, showing brecciation (c) Ti map in same area.

Lew 88769: This sample was also classified by [7] as a brecciated dimict diogenite and was suggested by [6] to be anomalously depleted in several incompatible trace elements. This meteorite preserves evidence of annealed fractures in major elements, suggesting limited time for reequlibration. We mapped across these zones and found that Cr decreases across annealed fractures but Mg, Al, and Ti increase. This pattern was not observed in any other sample. The decrease in some trace elements could be related to the low incompatible trace element composition, but would imply a unique process for their removal, such as the involvement of fluids or of a unique melt composition. The harzburgitic OPX contains additional signs of brecciation and recrystallization, the only sample where that is suggested in the harzburgite lithology.

These images suggest a wide range of cooling histories are represented by the diogenites in our collection, from samples preserving pristine magmatic textures to samples that have been heavily recrystallized following brecciation, presumably caused by impacts. We conclude that diogenite lithologies on Vesta have been exposed to multiple reheating events and many not have as a uniform, single thermal history as has been proposed [1,2]. [8] proposed a similar history for Eucrites, but thermal histories could not be obtained for diogenites due to low K abundances. The Dawn mission at Vesta is capable of identifying zones rich in pyroxene that may represent exposed diogenitic material. These images suggest that exposed diogenites are likely still highly processed and have gone through several metamorphic events prior to emplacement and exposure, and thus interpretations of Vesta's geologic history must take these steps into account.

[1] Schiller, M. et al., . (2011) *Astrophys. J. Letters 740*, L22. [2] Righter, K, and Drake, M.J. (1997) *Meteoritics & Planet. Sci., 32,* 929. [3] Mittlefehldt (1994), *Geochim. Cosmochim. Acta.* **58**, 5. [4] Beck et al., (2011), *Meteoritics & Planet. Sci.,* **45**, 850. [5] Balta. J.B., et al., *LPS XXVII*, Abstract #1608. [6] Mittlefehldt et al., (2011), *Meteoritics & Planet. Sci., in press.* [7] Beck et al. (2012), *Meteoritics and Planet. Sci. in review* [8] Bogard and Garrison (2003), *Meteoritics and Planet. Sci.38, 669.*

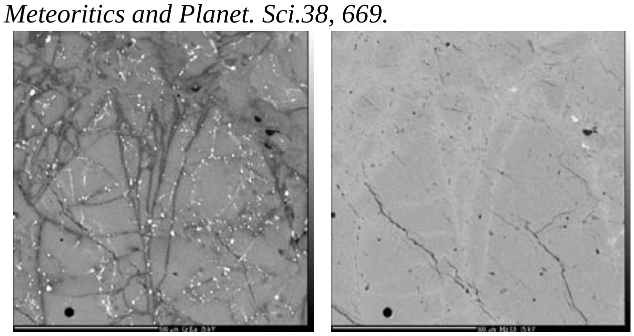


Fig. 4: LEW 88679 (a) Mg map and (b) Cr map showing remanent fractures in orthopyroxenite. Low-Cr fractures correspond to high-Mg zones.