DATING HOWARDITE MELT CLASTS: EVIDENCE FOR AN EXTENDED VESTAN BOMBARDMENT?
J. A. Cartwright[1,2] K.V. Hodges[2], M. Wadhwa[1,2] and D.W. Mittlefehldt[3] [1] Center for Meteorite Studies, [2]School of Earth & Space Exploration, Arizona State University, Tempe, AZ 85287, [3]NASA/Johnson Space Center, Houston, TX 77058. (julia.cartwright@asu.edu).

Introduction: Howardites are polymict breccias that, together with eucrites and diogenites (HED), likely originate from the vestan surface (regolith/ megaregolith), and display a heterogeneous distribution of eucritic and diogenitic material [1]. Melt clasts are also present alongside other regolithic features within howardites, and are noteworthy for their compositional variability and appearance (e.g. [2,3]). Melt clasts formed by impact events provide a snapshot of the timings and conditions of surface gardening and bombardment on the vestan surface. By dating such clasts, we aim to better constrain the timings of impact events on Vesta, and to establish whether the impact flux in the asteroid belt was similar to that on the Moon. As the Moon is used as the basis for characterising impact models of the inner solar system, it is necessary to verify that apparent wide-scale events are seen in other planetary bodies. In particular, the observed clustering of Apollo melt clast ages between 3.8-4.0 Ga (e.g. [4]) has led to two hypotheses: 1) The Moon was subjected to a sudden event - 'Lunar Cataclysm' or period of 'Late Heavy Bombardment' (LHB), e.g. [5]; 2) The age cluster represents the end of an epoch of declining bombardment or 'Heavy Bombardment', e.g. [6]. No consensus has emerged regarding one or other hypothesis. We are testing these hypotheses by seeking evidence for such events in materials other than those derived from the Moon.

Previous chronological studies, mainly on eucrites, revealed a ranged of ages of 2-4.5 Ga with a clustering at 3.4-4.1Ga, interpreted as evidence for comparable bombardment of the HED parent asteroid with the Moon (e.g., [7]). A recent review of HED ages [8], however, suggests two periods of significant impacts at 4.5 Ga and between 3.5-3.8 Ga, which the authors suggest may relate to the Veneneia and Rheasilvia basins respectively, e.g. [9]. Early studies that have targeted melt clasts have shown a range of ages of 3.7-4.2 Ga (12 clasts, 5 howardites) [10-13]. A recent study [14] used a micro-corer to target specific clasts for extraction and Ar analysis, yielding ages of 3.2-3.7 Ga (8 clasts, 3 howardites). The author concluded that higher velocity rather than higher frequency impacts was likely the cause of this age range, and that the data coincided with LHB on the Moon starting at ~4.0 Ga [14].

We present the first chronology data for howardites Northwest Africa (NWA) 1929 and Dhofar (Dho) 485 as part of our investigation into the petrology, composition and chronology of howardite melt clasts using the $^{40}Ar/^{39}Ar$ and Pb-Pb chronometers [15]. Our Ar data is presented here, with Pb data to follow. We applied *in-situ*, high spatial-resolution analytical techniques to acquire $^{40}Ar/^{39}Ar$ dates using an ultra-violet laser ablation microprobe (UVLAMP). This technique allows for specific targeting of crystals or clasts of interest with no significant heating of surrounding areas. Additionally, the technique allows for rapid acquisition of a large number of data from small, rare samples such as meteorites. This technique has been applied with exciting results to lunar materials [16], and is first applied to vestan materials here.

Samples & Methodology: Dho 485 contains eucritic and diogenitic clasts (< 2cm) set in a well-consolidated matrix that also contains abundant melt clasts (mainly < 1mm, some 2-3 mm) with both impact (relict grains present) and recrystallised textures. NWA 1929 is coarse grained, with large eucritic and diogenitic fragments set in a fine grained, possibly annealed matrix. The sample has an unusually high abundance of melt clasts (~ 6%) with impact and recrystallised textures.

Polished thick-sections (~ 9 x 9 mm across, ~150 µm thick) and facing thin-sections of the meteorites were made from samples obtained from the Center for Meteorite Studies collection. Backscattered electron image (JEOL JXA-8530F, ASU), plane polarized light and reflected light mosaics were created of the thick-sections prior to analysis in the Group 18 laboratories at ASU. Clasts within the sections were targeted for ablation by an excimer laser (193nm wavelength), using the mosaics. Pit sizes, designed to yield sufficient argon for analysis with suitably high precision, were <200 µm, with estimated depths <80 µm. Following ablation and gas purification, gases were analyzed using a Nu Instruments *Noblesse* multicollector mass spectrometer. Data correction protocols included the removal of detector baselines, blank correction, and mass discrimination. Irradiation corrections were required to correct for the production of interference isotopes and the decay of ^{37}Ar and ^{39}Ar. We used a cosmogenic $^{38}Ar/^{36}Ar$ ratio of 1.535 (e.g. [17]) and the cosmochron technique (e.g. [18]) to derive contributions of cosmogenic and trapped ^{38}Ar and ^{36}Ar, and used a normal isochron to correct for trapped ^{40}Ar ($^{40}Ar/^{36}Ar_t$ ~ 190 for NWA 1929, ~1 for Dho 485).

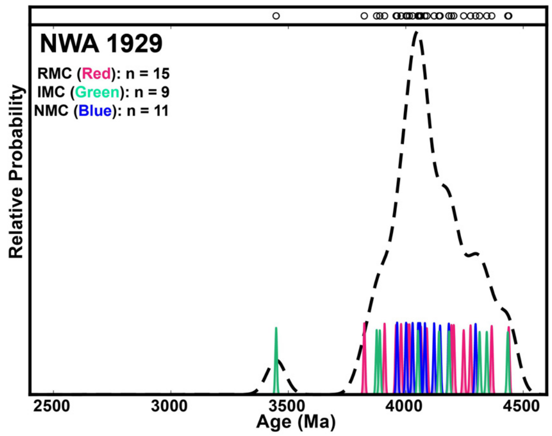

Fig.1: A KDE plot for our NWA 1929 data (bandwidth = 40 applied, dashed black line) with red, green and blue gaussian curves for RMC, IMCs and NMCs respectively. Black circles at the top of the plot represent the individual dates.

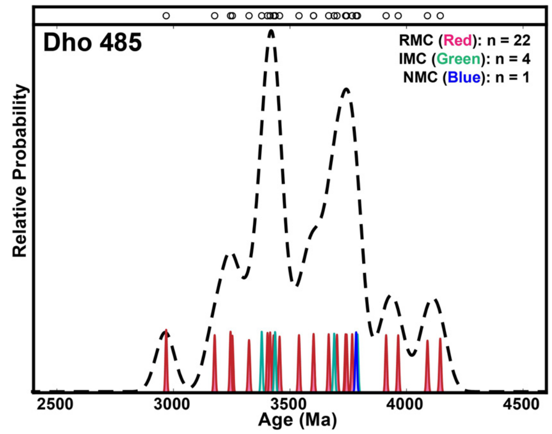

Fig.2: A KDE plot for our Dho 485 data (bandwidth = 40 applied, dashed black line) with red, green and blue gaussian curves for RMCs, IMCs and a single NMC respectively. Black curves represent individual dates.

These corrections had minor effects on the age, but contributed to the uncertainty. We note that uncertainties are reduced by a factor of ~10 by not correcting for trapped and cosmogenic contributions – as adopted previously by [11, 14]. Ages have been calculated relative to age monitor PP20 (1078.9 ± 4.6 Ma, [16]) and the ^{40}K decay constants from [19].

Results and Discussion: Thirty-five clasts within NWA 1929 were dated, yielding dates varying from 3823 ± 24 Ma to 4438 ± 103 Ma. (All uncertainties cited in the text of this abstract are at the 2σ level and include fully propagated systematic and non-systematic errors.) Twenty-seven clasts from Dho 485 yielded a mostly younger range of apparent ages: 3176 ± 42 Ma to 4144 ± 22 Ma. Based on petrography and chemistry, we defined three categories of clasts: recrystallized melt (RMC), impact melt (IMC), and non-melt clasts (NMC). For both samples, clasts from each of these categories yielded a range of ^{40}Ar/^{39}Ar dates with dispersions that cannot be explained by analytical error, implying that they represent distinctive populations. Of particular significance are the melt clasts, which yield dates ranging from the oldest to the youngest encountered in the two datsets. We interpret this extended range as direct evidence that the Ar isotopic systematics of vestan samples record a long bombardment history. Within the range of dates, however, there is some evidence of clustering which could be interpreted in terms of increased meteorite flux to the parent body. These clusters are best illuminated by kernel density estimation plots (KDE's) shown in Figures 1 and 2 (bandwith = 40 Ma). For Dho 485, major clusters occur at ~3.4 Ga and ~3.7 Ga. For NWA 1929, the highest concentration of dates is at ~ 4.0 Ga. As NWA 1929 does not show strong evidence for ages younger than 3.8 Ga, our dataset for this sample might be interpreted as suggesting a similar vestan bombardment history to that of the Moon. However, the clustering observed in Dho 485 points to significant impact melt formation after ~3.9 Ga, indicating a complex and extended bombardment history for Vesta.

With further Ar analyses on these samples planned, as well as Pb-Pb dating of similar clasts, we hope to add to our data set and better define the clustering observed. Importantly, the use of *in-situ* Ar analyses has highlighted the importance of obtaining a large, statistically significant population of dates for HED samples – regardless of method or isotopic system – in order to make robust interpretations regarding the early bombardment history of Vesta.

References: [1] Mittlefehldt, D.W. (2015) *Chem. Erde Geochem.* 75: 155-183. [2] Barrat, J.A. et al. (2012) LPSC XLIII (abs. #1438). [3] Barrat, J.A. et al. (2009) *GCA* 73:5944-5958. [4] Norman, M.D. & Nemchin, A.A., (2014) *EPSL* 388:387-398. [5] Tera, F. et al. (1974) *EPSL* 22:1-21. [6] Hartmann, W.K. and Neukum, G. (2001) *SSR* 96:165-194. [7] Bogard, D.D. (2011) *Chem. Erde Geochem.* 71:207-226. [8] Kennedy, T. et al. (2013) *GCA* 115:162-182. [9] Schenk, P. et al. (2012) *Science* 336:694-697. [10] Bogard, D.D. and Garrison, D.H. (1992) XXIII, 131-132.[11] Bogard D.D. and Garrison D.H. (2003) *MAPS* 38:669-710. [12] Kirsten, T. and Horn, P. (1977) *Sov.-Am. Conf. Cosmo. Moon & Planets 525-540.* [13] Rajan R.S. et al. *EPSL* 27:181-190. [14] Cohen, B.A. (2013) *MAPS* 48:771-785. [15] Cartwright, J.A. et al. (2015) *XLVI LPSC*, abs# 1452. [16] Mercer, C.M. et al. (2015) *Science Advances* 1. [17] Wieler, R. (2002) *Min. Soc. Am.* 47:71-100. [18] Levine, J. et al. (2007) *GCA* 71:1624-1635. [19] Steiger R. H. and Jäger E. (1977) *EPSL* 36:359-362.