COSMIC RAY EXPOSURE AGES, AR-AR AGES, AND THE ORIGIN AND HISTORY OF EUCRITES. Kelli Wakefield[1,2], Donald Bogard[1] & Daniel Garrison[1,3], [1]ARES, NASA Johnson Space Center, Houston, TX 77058; [2]Lunar & Planetary Institute, Houston, TX 77058, [3]Lockheed-Martin Corp., Houston, TX

Introduction: HED meteorites likely formed at different depths on the large asteroid 4-Vesta, but passed through Vesta-derived, km-sized intermediary bodies (Vestoids), before arriving at Earth (1,2). Most eucrites and diogenites (and all howardites) are brecciated (3), and impact heating disturbed or reset the K-Ar ages (and some Rb-Sr ages) of most eucrites in the time period of ~3.4-4.1 Gyr ago (4,5,6). Some basaltic eucrites and most cumulate eucrites, however, are not brecciated. We recently showed that the ^{39}Ar-^{40}Ar ages for several of these eucrites tightly cluster about a value of 4.48 ±0.02 Gyr, and we argue that this time likely represents a single large impact event on Vesta, which ejected these objects from depth and quenched their temperatures (6). A different parent body has been suggested for cumulate eucrites (7,8), although the Ar-Ar ages argue for a common parent. Similarities in the cosmic-ray (space) exposure ages for basaltic eucrites and diogenites also have been used to infer a common parent body for some HEDs (e.g.,9). Here we present CRE ages of several cumulate and unbrecciated basaltic (UB) eucrites and compare these with CRE ages of other HEDs. This comparison also has some interesting implications for the relative locations of various HED types on Vesta and/or the Vestoids.

Determination of CRE Ages: We used the isotopic data from Ar-Ar dating of six eucrites classed as cumulate and 11 eucrites classed as unbrecciated basalts. Total ^{36}Ar$_{cos}$, from which we calculate CRE (space) exposure ages, consists primarily of a cosmogenic component and small amounts of low-temperature terrestrial Ar. ^{38}Ar contains a component produced in the reactor from Cl, but ^{36}Ar does not In a typical eucrite, ~93% of cosmogenic ^{36}Ar is produced from Ca and most of the remainder is produced from Fe (10). We adopted the average eucrite ^{36}Ar production rate derived from ^{81}Kr ages by (11), and normalized this rate to the Ca concentration, determined from ^{37}Ar for each of our samples, assuming that average eucrites contain 8% Ca. Typically no shielding correction is applied to the Ar$_{cos}$ production rate, which for eucrite composition is predicted to vary by ~10-20% over a shielding range of 10-150 g/cm^2 (e.g.,10). We also analyzed four unirradiated samples of these eucrites. Their shielding, based on ^{22}Ne/^{21}Ne, is typical of eucrites, and their ^{36}Ar$_{cos}$ concentrations resemble those measured in irradiated samples.

CRE Age Comparisons: Fig. 1 is a histogram of our ^{36}Ar CRE ages for these cumulate and unbrecciated basaltic (UB) eucrites, as well as literature ^{81}Kr CRE ages for three additional cumulate eucrites. Uncertainties in CRE ages are typically proportional to the age, so each plotted age interval is 10% larger than the previous one; The value listed for every-other interval gives the low end of that age range, rounded to an integer (e.g., the 20 Myr interval covers 20-22 Myr). Uncertainties in our ages are probably ±10-20%. Among the nine cumulate ages, three are ~4 Myr, two ~16 Myr, and four ~20-26 Myr. Among 11 UB eucrites, four ages are ~13-16 Myr, four ages ~20-23 Myr, and two are higher. Figure 2 is a CRE age histogram of these 20 cumulate and UB eucrites (plotted together), 47 brecciated basaltic eucrites (^{81}Kr and Ne+Ar ages), and 26 diogenites (Ne+Ar ages). Ages for the latter two groups are taken from the literature (9, 11, 12, 13). Previous authors have suggested a strong CRE age cluster at ~20-22Myr for both brecciated eucrites and diogenites, a cluster at ~39 Myr for diogenites, and possible clusters at ~6-7 Myr and ~12-16 Myr for eucrites. CRE ages for several cumulate and UB eucrites also fall within or close to the ~21 Myr cluster, and other cumulate and UB eucrites show ages near the postulated 12-16 Myr eucrite cluster. Only one UB eucrite plots near the ~39 Myr diogenite cluster, and only one basaltic eucrite plots near the three cumulates with a young age. Thus, CRE ages of some cumulate and UB eucrites suggest that they were ejected in at least one (~21 Myr) impact event that also ejected brecciated eucrites and diogenites. This implies that cumulate and UB eucrites, as well as brecciated eucrites and diogenites, now reside in neighboring, near-surface locations, either on Vesta or on one or more Vestoids.

Implications for Origins: From a strong clustering of ^{39}Ar-^{40}Ar ages of several cumulate and unbrecciated basaltic (UB) eucrites at 4.48 ±0.02 Gyr, (6) concluded that cumulate eucrites derive from the same parent body as brecciated basaltic eucrites. Similarity in CRE ages seem consistent with this conclusion. Most cumulate and UB eucrites also escaped the impact brecciation that reset most eucrite Ar-Ar ages over the time period of ~3.4-4.1 Gyr, which is probably why they preserve older Ar-Ar ages. However, the Ar-Ar ages of two cumulate and two "UB" eucrites were reset ~3.4-3.6 Gyr ago (6), and the CRE ages of three of these are ~15-17 Myr. The apparent existence of cumulate and UB eucrites with CRE ages similar to CRE ages of brecciated eucrites and diogenites and the observation that a few cumulate and "UB" eucrites have Ar-Ar ages reset later than 4 Gyr ago, imply that these various subclasses of meteorites were located on the same immediate parent object over the last ~50 Myr. This argument is strongest for the ~21 Myr CRE impact, which apparently ejected all HED meteorite types into space and which was likely a relatively large event.

If the immediate HED parent object was Vesta, the age associations among various HED meteorite types can be readily explained by extensive and deep impact mixing throughout Vesta's history. However, dynamical arguments exist against direct ejection of HEDs from Vesta to Earth (14). If smaller (~10 km sized) Vestoids are the immediate parent of eucrites, as has been suggested to facilitate meteorite transport to Earth (1), then the lack of Ar-Ar age resetting over 4.1-3.4 Gyr for some cumulate and UB eucrites can be explained if these Vestoids were ejected from Vesta by the giant (~460 km) impact crater, for which (6) assigned an Ar-Ar age of 4.48 Gyr. In this case, the vestoid parent object(s) could not have experienced large impacts during the cataclysmic bombardment without being destroyed. However, how can we then explain similarities in CRE ages among HEDs, which imply that brecciated eucrites derive from the same immediate parent as UB and cumulate eucrites? Perhaps the most likely scenario is that at least some of the HED parent Vestoids were ejected ~3.5 Gyr ago, near the end of the cataclysmic bombardment period. In this case, the brecciation observed in most HEDs occurred on Vesta prior to this time, whereas unbrecciated HEDs giving older Ar-Ar ages would presumably represent impact survivors that represent small statistical probabilities. In any case, the parent vestoid(s) of HED meteorites likely contains all known HED meteorite types, and thus represents a deep sampling of the Vesta crust.

References: (1) Binzel & Xu, *Science 260*, 186, 1993; (2) Kelley et al, ??2003; (3) Mittlefehldt et al., *Revs. Mineral. Vol.36*, 1998; (4) Bogard, *Meteoritics 30*, 244, 1995; (5) Kunz et al., *Planet. Space Sci. 43*, 527, 1995; (6) Bogard & Garrison, *MAPS 38*, 669, 2003; (7) Tera et al., *EPSL 22*, 1, 1974 (8) Blichert-Toff et al; *EPSL 204*, 167, 2002; (9) Welton et al; *MAPS 32*, 891, 1997 (10) Hohenberg et al, *LPSC 9th*, 2311, 1978; (11) Eugster & Michel, *GCA 59*, 177, 1995; (12) Shukulkov & Begemann; *MAPS 31*, 60, 1996 (13) Miura et al; *GCA 62*, 2369, 1998 (14) Wetherill & Chapman, *Meteorites & Early Solar System*,1988