VESTA'S PRIMORDIAL DIFFERENTIATION AS REVEALED BY ^{26}Al-^{26}Mg ISOTOPE SYSTEMATICS OF BULK EUCRITES AND DIOGENITES.

Josh Wimpenny[1], Qing-Zhu Yin[1] and Yuri Amelin[2], [1]Department of Geology, University of California, One Shields Avenue, Davis, CA 95616, USA (jbwimpenny@ucdavis.edu, qyin@ucdavis.edu). [2]Research School of Earth Sciences, Mills Rd., The Australian National University, Canberra ACT 0200 Australia (yuri.amelin@anu.edu.au)

Introduction: The very short half-life of the extinct ^{26}Al-^{26}Mg system ($t_{0.5}$ = 0.73Myr) allows us to constrain the chronology of events in our early solar system to very high precision. Accordingly, the Al-Mg system has been applied to a range of meteorites and meteoritic components in recent times, including investigations into the relative formation ages of chondrules and CAI's (e.g. [1, 2]), as well as achondritic meteorites such as eucrites [3].

Eucrites and diogenites are part of the HED meteorite group that share similar oxygen isotope compositions [4], and based on similarities in spectral analyses [5] are thought to have originated on a single parent body, the asteroid 4 Vesta (e.g. [5]). Eucrites are composed of mostly pyroxene and plagioclase, and split into two groups; the medium to fine grained basaltic eucrites, and the coarser, gabbroic cumulate eucrites [6]. Diogenites are also cumulates, but comprised almost entirely of orthopyroxene (~90%) [6].

With some rare exception (e.g. Piplia Kalan [3]), few eucrites show the former presence of ^{26}Al in their internal mineral isochrons. This posed a serious question to the assumption that ^{26}Al was the major heat source of Vesta's primordial differentiation. On the other hand, recent high precision Mg isotope measurements by MC-ICP-MS [7, 8] demonstrated measurable excesses in ^{26}Mg* suggesting that the HED's must have formed early in our solar systems history; within ~3-4 Ma of the formation of CAI's, which would be consistent with ^{182}Hf-^{182}W and ^{53}Mn-^{53}Cr chronology for Vesta [9, 10] We aim to further our understanding of the chronology of early planetary differentiation by studying the Al-Mg system in a suite of eucrites and diogenites. Unlike previous studies, our approach to address the problem is to examine Al-Mg isotope systematics of large-scale chemical reservoirs on Vesta, by choosing three distinct groups of meteoritic lithologies representing these reservoirs: namely diogenite (very low Al/Mg), cumulate eucrites (intermediate Al/Mg) and basaltic eucrites (high Al/Mg), and pose the question if we could constrain the timing of global scale silicate mantle differentiation of chemical reservoirs in Vesta to the first order (Fig. 1 below), in combination of literature data. In addition, we also present preliminary Mg isotope data for Asuka 881394; a unique achondrite that was once thought to be associated with the HED's but has since been shown to have distinct oxygen isotope [11] and Mn-Cr systematics [12], suggesting it originates from a different parent body to Vesta. While Asuka 881394 is a crucial "milestone" in solar system chronology [12, 13], current Al-Mg data is inconsistent [14]; our second aim is thus to add crucial Al-Mg data to improve the current data set [12, 13] in order to better constrain the timing of differentiation of Asuka parent body.

Methods: 0.5 mg fragments of one basaltic eucrite (Juvinas), three cumulate eucrites (Moama, Binda, Agoult), three diogenites (Garland, Johnstown, Shalka) and one non-HED achondrite (Asuka 881394) were dissolved using the standard HF:HNO_3 dissolution technique. After dissolution, ~1% of this material was saved for Al/Mg analyses. The remainder was processed using cation exchange resin; separating Mg from any interferences in order to accurately measure the Mg isotope ratio. Both Mg isotopes and Al/Mg ratios were measured on a Thermo *Neptune Plus* MC-ICP-MS in the Geology Department at UC Davis.

Al/Mg ratios were normalized by calibrating to five reference materials in which the Al and Mg contents are well known (BCR-2, BHVO-2, AGV-2, Peace River Chondrite, San Carlos Olivine). Magnesium isotope ratios were bracketed against the DSM-3 standard, with each sample measured a minimum of nine times. Typical reproducibility of δ^{26}Mg* for each unknown is better than 0.015‰ (2 s.e.). Accuracy was assessed by repeat measurements of BCR-2, giving a δ^{26}Mg* value of 0.002 +/- 0.013 (n = 6)

Results: *Eucrites* - The diogenites contain sub-chondritic Al/Mg ratios of 0.013 to 0.087, and δ^{26}Mg* values of -0.003 to -0.005‰. The cumulate eucrites and basaltic eucrites contain supra-chondritic Al/Mg ratios of 0.34 to 2.37, and an excess in ^{26}Mg, with δ^{26}Mg* values of up to 0.035‰. Individual model ages for the basaltic and cumulate eucrites have been generated assuming an initial chondritic composition (Al/Mg = 0.101 [15], δ^{26}Mg* = 0‰). Currently the $t_{0.5}$ for ^{26}Al in the literature range from 0.70 to 0.73; we use 0.73Myr in all calculations, consistent with recent studies [e.g. 1, 7], but 0.72 [12] and 0.705Myr [16] are also in use. Clearly a consensus must be reached in the future to truly benefit from self-consistent, high resolution dates that Al-Mg system could offer..

When anchored to the Allende CAI AJEF (Pb-Pb age 4567.6±0.38 Ma, $^{26}Al/^{27}Al_0 = 4.96\pm0.25 \times 10^{-5}$ [1]) the model ages range from 2.39 to 3.56 Ma after CAI formation (ΔT_{CAI}).

Asuka 881394 – Two splits of Asuka were dissolved and analysed; one being richer in plagioclase than the other, and hence contains a higher Al/Mg ratio (Al/Mg = 29). The plagioclase rich sample has a significant excess in ^{26}Mg (δ^{26}Mg* = 0.325‰).

Discussion: The resolvable excess in ^{26}Mg for the basaltic and cumulate eucrites is consistent with melting and differentiation on the eucrite parent body early in our solar systems history, while ^{26}Al was still present. Our data compare well with previous analyses of HED meteorites [7, 8]. The Al-Mg whole rock isochron in Fig. 1 is a compilation of recently published eucrite data together with our own study. Regressing these data gives a ^{26}Al/^{27}Al$_0$ value of 2.29 ± 0.56 × 10^{-6} which corresponds to an age of 4564.4 ± 0.65Ma or a ΔT_{CAI} of 3.20 ± 0.65Ma relative to AJEF, and is similar to previous eucrite ΔT_{CAI} model ages which range between 2.6 and 4Ma [7, 8]. We argue this event represents a global silicate mantle differentiation on Vesta from its primordial magma ocean stage [17].

This age is supported by the diogenite data; on average these contain sub-chondritic Al/Mg ratios yet only a slight depletion in ^{26}Mg (~-0.003‰). If we assume that the magmatic reservoir on Vesta was chondritic (with a solar initial δ^{26}Mg* of -0.038‰, an ^{27}Al/^{24}Mg of 0.101 [18], and a canonical ^{26}Al/^{27}Al$_0$ [14]) then differentiation must have begun ~3 Ma after CAIs to explain the excess ^{26}Mg in the diogenites, representing the intercept of Al-Mg isotope systematics of Vesta's three major lithologies. Thus two different approaches of estimating Vesta's primordial differentiation (isochron slope and initial intercept model ages) give self-consistent results.

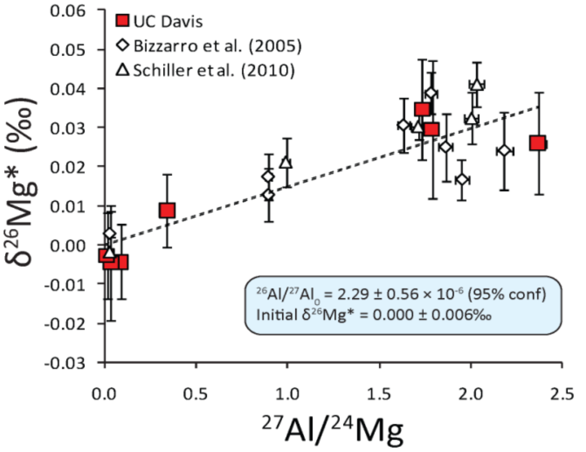

Fig. 1 – Compiled Al-Mg isochron for HED eucrites and diogenites measured at UC Davis (red) and literature values (open symbols, [7, 8]). Error bars on δ^{26}Mg* are 2σ (standard error), errors on Al/Mg ratios are 2%.

So far, previous analyses of Asuka 881394 have concentrated on mineral separates, i.e. plagioclase and pyroxene ([12, 13] see Fig. 2). However, it is clear from the spread in the plagioclase data that this system has been disturbed and this spread adds significant uncertainty to what is essentially a two point isochron. We present preliminary data that helps to constrain an initial ^{26}Al/^{27}Al$_0$ of 1.27 ± 0.09 × 10^{-6}, which equates to a ΔT_{CAI} of 3.81 ± 0.4Ma. This age is within error of a previous attempt to date Asuka using the Al-Mg system [13]. In addition, our pyroxene rich sample (Al/Mg of 0.06) contains a resolvable excess of ^{26}Mg, with a δ^{26}Mg* of 0.065 ± 0.008. As the Al/Mg ratio of this sample is subchondritic, such an excess in radiogenic Mg cannot be explained by straightforward evolution of a chondritic reservoir. Instead, it suggests that Asuka must have crystallized from a supra-chondritic reservoir that had differentiated while ^{26}Al was still active. More analyses will be needed to confirm whether this sample is an isolated example, or is truly representative of pyroxene crystals from Asuka.

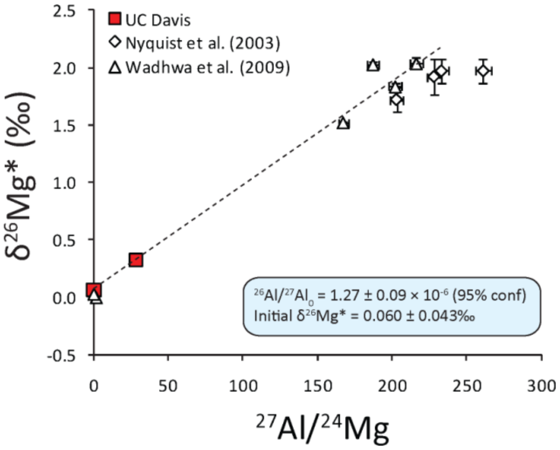

Fig. 2 - Compiled Al-Mg isochron for the achondrite Asuka 881394. Samples measured at UC Davis are in red, while literature values are open symbols [12, 13]. Error bars on δ^{26}Mg* are 2σ (standard error), errors on Al/Mg ratios are 2%.

References: [1] Jacobsen B. et al. (2008) *EPSL, 272, 353-364.* [2] Amelin et al. (2002) *Science, 297, 1678.* [3] Srinivasan et al. (1999) *Science, 284, 1348*. [4] Clayton R. N. (1993) *Ann. Rev. EPS, 21, 115.* [5] Binzel R. & Xu S. (1993) *Science 9, 186.* [6] Mittlefehdlt (2003) *Treatise on Geochemistry 1, 11* [7] Bizzarro et al. (2006) *Astrophys. J., 632, L41.* [8] Schiller et al. (2010) *GCA, 74, 4844.* [9] Yin et al. (2002), *Nature 418, 949.* [10] Lugmair & Shukolyukov, (1998) *GCA*, 62, 2863. [11] Scott et al. (2009), *GCA, 73, 19, 5835.* [12] Wadhwa et al. (2009) *GCA, 73, 5189.* [13] Nyquist et al (2003), *EPSL, 214, 11* [14] Wadhwa et al (2011) *MetSoc, A5417* [15] Villeneuve J. (2009) *Science, 325, 985.* [16] Norris et al. (1983) *JGR-Proc. LPSC 14, B331.* [17] Greenwood et al. (2005) *Nature, 435, 916.* [18] Lodders (2003) *Astrophysical J. 591, 1220*.