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IMPACT HISTORIES OF VESTA AND VESTOIDS INFERRED FROM HOWARDITES, EUCRITES, AND DIOGENITES.
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Introduction: The parent body of the howardites, eucrites and diogenites (HEDs) is thought to be asteroid (4) Vesta [1]. However, several eucrites have now been recognized, like NWA 011 and Ibitira, with major element compositions and mineralogy like normal eucrites but with different oxygen isotope compositions and minor element concentrations suggesting they are not from the same body [2, 3]. The discoveries of abnormal eucrites and V-type asteroids that are probably not from Vesta [see 4] raise the question whether the HEDs with normal oxygen isotopes are coming from Vesta [3]. To address this issue and understand more about the evolution of Vesta in preparation for the arrival of the Dawn spacecraft, we integrate fresh insights from Ar-Ar dating and oxygen isotope analyses of HEDs, radiometric dating of differentiated meteorites, as well as dynamical and astronomical studies of Vesta, the Vesta asteroid family (i.e., the Vestoids), and other V-type asteroids.

Are the HEDs from Vesta? Six eucrites, NWA 011, Ibitira, Pasamonte, A-881394, PCA 91007, and NWA 1240, have been found with abnormal oxygen isotopic compositions indicating they probably come from at least three and probably five separate bodies, not from the HED body [2, 5]. (Since howardites and diogenites with abnormal oxygen isotopes are not known, we use "HED group" and "HED body" for samples with normal oxygen isotopes and their source.) Does the plausible connection between the large group of normal eucrites, howardites and diogenites and Vesta, the only large, intact basaltic asteroid, and its very prominent family of sub-10 km asteroids exclude the possibility that a eucrite with abnormal oxygen isotopes comes from Vesta and not HEDs?

Bogard's study of meteorite radiometric ages [6] suggested that the proportion of meteorites from individual parent bodies that have radiometric ages reflecting impact heating during the Late Heavy Bombardment (LHB) increases as one moves to larger parent bodies: H-type ordinary chondrites (parent body diameter $D_{PB} \sim 200$ km), HEDs ($D_{PB} \sim 500$ km), and lunar rocks ($D_{PB} \sim 3400$ km). Bogard [6] argued that smaller bodies lose impact ejecta more readily and are destroyed by the same impacts that cause most impact heating on larger bodies. For example, the maximum impact energy per kg of target that can be deposited on Vesta during a near-catastrophic collision is ~100× higher than for a near-catastrophic impact on a 10 km body [7]. Over 85% of HEDs are breccias and nearly all of these have Ar-Ar ages between 3.5 and 4.1 Gyr, whereas only ~20% of ordinary chondrites have ages in this range. Thus, we infer that most HEDs were derived from a body which was much larger than the OC parent bodies, i.e., >200-300 km in diameter and presumably Vesta-sized. By contrast, the six anomalous eucrites are unshocked, only one is a breccia (Pasamonte) and only one of the four with determined Ar-Ar ages lies in the 3.5-4.1 Gyr range (Pasamonte) [8]. This indicates that during the LHB, most were probably located in bodies smaller than the HED body. The anomalous eucrites most likely formed on Vesta-sized bodies but were collisionally ejected prior to the 3.5-4.1 Gyr epoch in a similar way to the unbrecciated eucrites with normal oxygen isotopic compositions (see below). Their parent bodies and most of their sister precursors were probably lost in the dynamical scattering events that ejected over 99% of the main belt's primordial mass between ~3.9-4.5 Gyr [e.g., 9].

Impact histories of HEDs: Shock and breccia properties and Ar-Ar ages allow most HEDs to be divided as follows. Brecciated HEDs have Ar-Ar ages of 4.1-3.5 Gyr and are commonly shocked. Unbrecciated eucrites (both cumulate and non-cumulate) account for ~7% of HEDs and are largely unshocked [10]. About half (12 are known) have Ar-Ar ages of 4.48±0.02 Gyr; the rest show 4.2-3.4 Gyr Ar-Ar ages [8].

Fig. 1 argues that brecciated eucrites were impact heated in as few as four major events at 3.5, 3.8, 3.9, and 4.0 Gyr. Some breccias like polymict eucrite Y-75011 have uniform ages for clasts and matrix consistent with a single impact heating at 3.95±0.05 Gyr [11]. Since anhydrous breccias are lithified by interstitial impact melt that cements the clasts, the 3.95 Gyr impact probably lithified this rock. Other breccias like howardite EET 87509 (and the paired 87531) were lithified by gentler shocks so that their clasts preserve diverse ages, in this case 4.05±0.02 to 3.70±0.03 Gyr [see 6] implying lithification at ≤3.7 Gyr. Lithification of most HED breccias probably occurred during the 3.5-4.0 Gyr impacts.

The unbrecciated eucrites with 4.48±0.02 Gyr Ar-Ar ages (Fig. 1) are puzzling as the HED body globally differentiated by ~4565 Myr [12] and fully crystallized soon afterwards. Why should about half the unbrecciated eucrites have 4.48±0.02 Gyr Ar-Ar ages? (A more precise ^{40}K halflife may increase this age to 4.51 Gyr, but this is still 50 Myr after crystallization.)

One explanation is that the unbrecciated cumulate and non-cumulate eucrites were excavated from the hot crust by an impact so they cooled rapidly [8]. To account for the absence of subsequent brecciation and impact heating, Bogard and Garrison [8] suggested that these rocks were ejected to form a small asteroid (~10 km across). Assuming that their similar Sm-Nd ages reflect earlier isotopic closure, the eucrites could have cooled rapidly from ~400°C (the Ar closure temperature) following an impact that created unshocked fragments by spallation [13]. The small asteroid could be one of the rare V-types having similar semimajor axes to the Vestoids but lower inclinations [14]. But if the mass of the asteroid belt was about 10× its current mass prior to the LHB [9], we should expect at least 10 Vesta-like bodies in the belt at that time. Why should Vesta, which was plausibly the sole survivor at 3.6 Gyr, contribute a major fraction of the unbrecciated eucrites with ages >4.4 Gyr?

Alternatively, the ejected fragments from the 4.48 Gyr impact may have been deposited on Vesta's surface and somehow escaped the damage inflicted during the LHB [8]. Then samples could have been launched with the brecciated HEDs, although further consideration is required of the mechanism and its plausibility. A third possibility is that the 4.48 Gyr old eucrites come from a body with an oxygen isotopic composition that is indistinguishable from that of Vesta. If mesosiderites and HEDs come from separate parent bodies (see [15] for a dissenting view), a third body with Vestan oxygen isotopic composition cannot be excluded. Cosmic-ray exposure age distributions for brecciated and unbrecciated eucrites appear similar, suggesting one source [16], but more ages are needed for the 4.48 Gyr eucrites to test these hypotheses.

Origin and Age of the Vesta Family: The largest craters on Vesta are 460, 160 and 150 km in diameter [17]. Given Vesta's high escape velocity (0.35 km/s), it seems likely that most Vestoids came from the 460 km crater. Numerical simulations of the main belt's dynamical evolution [9] suggest that if the Vestoids had formed before the LHB, their orbits would be scattered much more than they are today [14]. This implies that Vesta's largest basin and most Vestoids were produced nearer the end of the 3.5-4.0 Gy period. The HED Ar-Ar ages suggest that the major impacts on Vesta after the crust had cooled occurred at 3.5-4.0 Gyr. Assuming that most HEDs come from one or a few Vestoids and not directly from Vesta itself, as seems likely, most of the Vesta family was probably created in the 3.5 Gyr impact, but some could have been created in earlier events.

Vesta's Surface Today: Only howardites among HEDs have solar wind gases, implying that unless they are grossly unrepresentative, which seems unlikely as impacts must have spread ejecta globally, all the material on Vesta's surface at 3.5-4.0 Gyr that was fine enough to be lithified consisted of well-mixed eucrite and diogenite fragments with only trivially small regions of one lithology. It seems very unlikely that remnants of the pristine basaltic crust will be seen on Vesta by the Dawn spacecraft, although boulders of this crust may be visible. Determining the relative ages of the large craters will be an important task for Dawn.

References: [1] Pieters C. M. et al. (2005) In ACM, *Proc. IAU Symp.* **229**, 273-288. [2] Yamaguchi A. et al. (2002) *Science* **296**, 334-336. [3] Mittlefehldt D. W. (2005) *MAPS* **40,** 665-677. [4] Moskovitz N. A. et al. (2008) *Icarus* **198**, 77-90. [5] Scott E. R. D. et al. (2009) *LPS* **40**. [6] Bogard D. D. (1995) *Meteoritics* **30**, 244-268. [7] Love S. G. and Ahrens T. J. (1996) *Icarus* **124**, 141-155. [8] Bogard D. D. and Garrison D. H. (2003) *MAPS* **38**, 669-710. [9] Gomes R. et al. (2005) *Nature* **435**, 466-469. [10] Mayne R. G. et al. (2009) *GCA* in press. [11] Takeda H. et al. (1994) *EPSL* **122**, 183-194. [12] Lugmair G. W. and Shukolyukov A. (1998) *GCA* **62**, 2863-2886. [13] Asphaug E. (1997) *Icarus* **32**, 965-980. [14] Nesvorný D. et al. (2008*)* *Icarus* **193**, 85-95. [15] Greenwood R. C. et al. (2006) *Science* **313**, 1763-1765. [16] Wakefield K. et al. (2004) *LPS* **35**, 1020. [17] Thomas P. C. et al. (1997) *Science* **277**, 1492-1495. [18] Bogard D. D. and Garrison D. H. (2009) *LPS* **40**.

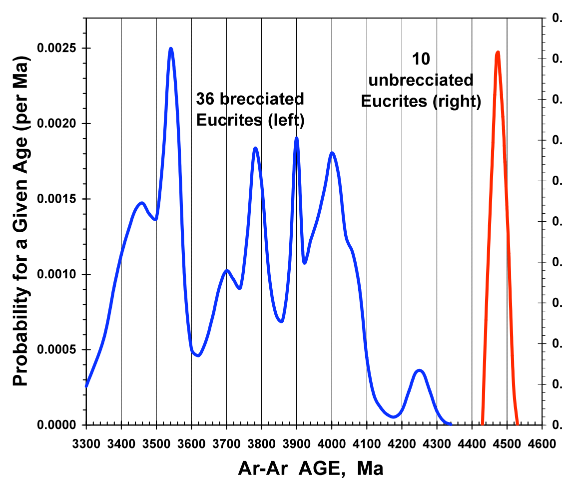

Fig. 1. Probability plots of Ar-Ar ages for 36 brecciated eucrites or eucritic clasts in howardites showing prominent impact heating peaks at 3.5, 3.8, 3.9 and 4.0 Gyr [6, 18] and for 10 unbrecciated eucrites (cumulate and non-cumulate) that peak at 4.48±0.02 Gyr. [8, 18].