VESTA, IRON METEORITES FROM EXTENSIVELY DIFFERENTIATED ASTEROIDS, AND THE PROVENANCE OF THE HED METEORITES.

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Introduction. Since the discovery that Vesta has a basaltic reflection spectrum [1] it has been widely assumed that the HED (howardite, eucrite and diogenite) meteorites come from Vesta. However, rocks formed on the surface of Vesta have to escape from two potential wells before getting into a resonance; Vesta has a high escape velocity and Vesta's orbital position is far from those of the 3:1 or the ν6 resonances.

Vesta's reflection spectra is the strongest link with the HED meteorites, but it is not strong enough to prove that its basalts are HED-like. It therefore follows that other basalt-bearing asteroids that are closer to resonances and smaller than Vesta are more likely sources of the HEDs. The magmatic iron meteorites offer the best source of information about the number of such extensively differentiated asteroids.

The amount of basalt that can be produced on an asteroid is limited by the initial bulk Al content. If we assume a bulk Al content of 14 mg/g (which gives a CI-chondrite-like Al/Si ratio) and that 50% of the Al ends up as basalt, one calculates that basalts amount to 12% of the volume (and 4% of the radius near the surface) of the asteroid. On Vesta this would be a layer 10 km thick.

An important constraint in the following discussion is that cosmic-ray exposure ages of HEDs can mostly be explained by impacts ~20 and ~40 Ma ago but a few ages are as high as 80 Ma [2]. The cosmic-ray penetration depth is only ~1 m thus exposure ages provide lower limits on the times when major impacts occurred on the parent asteroid. A reasonable working estimate is that the major disruption that produce the HED meteorites occurred 50-100 Ma ago.

It is also of importance that isotopic evidence shows that there are additional "basaltic" meteorites (those formed as low-temperature silicate melts) such as the angrites and Ibitira from asteroids other than the HED parent.

Magmatic iron meteorites and extensively differentiated asteroids. Because irons meteorites are tough they tend to have long exposure ages, typically >200 Ma. Irons are divided into two classes roughly equal in size, the magmatic irons that originated in asteroids that experienced fractional crystallization and thus extensive melting, and the nonmagmatic irons that formed as impact melts that cooled too rapidly to permit fractional crystallization [2]. Because almost all meteorites (including the irons) come from asteroids that were located in the inner asteroid belt at the time of their breakup, our studies of 700 iron meteorites have the potential to establish a lower limit on the number of extensively differentiated asteroids in the inner belt.

Nine of the iron meteorite groups (Table 1) are magmatic; it is probable that their parent asteroids produced basalts and gabbros in the surficial regions. Each of these groups has enough members to yield compositional trends best explained by fractional crystallization. These high degrees of fractionation require slow crystallization of a continuously mixed magma which can only be achieved in a magma that cools very slowly. It is highly likely that they formed in the cores of moderately large (radii of tens of km or larger) asteroids.

Table 1. Iron meteorite groups (IIG combined with IIAB)

nonmagmatic	magmatic	magmatic	magmatic
IAB	IC	IID	IIIE
IIE	IIAB+IIG	IIF	IVA
	IIC	IIIAB	IVB

In addition to irons that are members of the groups there are about 100 ungrouped irons, small sets of 1 to 4 irons with compositions distinctly outside the compositional fields of the established groups. I therefore developed criteria for inferring which of these formed by fractional crystallization. The two main criteria are compositional evidence (very high or low compatible/incompatible ratios) or an absence of evidence that implies formation in pools of impact melt.

Perhaps half of the ungrouped irons (and especially the smaller ones) are part of the IAB complex, based on their high Au, As and Sb contents [3]; I eliminated these irons. I further reduced the list of candidates by eliminating irons with small masses (<1.9 kg) and by requiring that the structures imply cooling rates similar to those oberved in the magmatic iron groups (and thus deeply buried). Because impact melts preserve chondritic compositions, i.e., with Ir/Au mass ratios in the range 2 to 5, I eliminated irons with Ir/Au ratios in the range 0.95 to 8 g/g.

Twenty large ungrouped irons remained. One set of three (the South Byron trio) and one set of two (the Mbosi duo) showed fractional crystallization trends. The remaining fifteen were chosen because they have Ir/Au mass ratios <1 or >8; Table 2 shows their key properties including structures. Thus the nine magmatic groups and the 17 asteroids required to explain these ungrouped irons lead to a minimum estimate of the number of 26 extensively differentiated asteroids in the inner asteroid belt. Differentiated silicate fragments from these bodies have surely fallen on the Earth. However, because the set of meteorites accreting to Earth undergoes stochastic variations and some of these irons have high exposure ages (≥400 Ma), we may not have silicate samples from all these bodies in our museums. However, it is probable that 10-20% of these were liberated contemporaneously with the HEDs. There must be additional differntiated asteroids whose core materials have not yet be liberated by catastrophic disruptions.

Astrophysical observations that bear on the possible Vesta-HED connection. In plots of asteroidal orbital parameters such as the inclination, eccentricity and semimajor axis, one can recognize a dozen or so clusters; the meteorites in these clusters are called families. For the tightest clusters it is widely accepted that these sets formed by the catastrophic destruction of a "parent". In the inner belt are two large and somewhat overlapping families commonly referred to as the Vesta and the Flora families. The common view is that compact families formed by impact-induced catastrophic collisions that destroyed the larger asteroid. However, the Vesta family is not compact and may well reflect a sizable number of disruption events. In addition, Vesta is still intact; studies of lunar secondary craters [8] raise serious doubts that the impact that produced the large southern crater could have ejected large

(D≥10 km) fragments with velocities exceeding the escape velocity of Vesta.

Most bodies with basalt on the surface show degraded spectra; the pyroxene absorption at 0.9 µm is shallow, and the spectrum has been reddened. It is now widely accepted that these changes are the result of space weathering. In contrast the spectrum of Vesta is remarkably fresh and unweathered [4]. The only plausibe mechanism to account for this spectrum is a dusting of the surface by fine ejecta from an impact that occurred within the last Ma or so.

It has been suggested that a set of small (diameter of 4 to 10 km) asteroids with basaltic spectra have orbits that link them to Vesta [5]. However, as noted by numerous authors, these asteroids are redder than Vesta, however, because small asteroids cannot efficiently retain regoliths, on would expect them to be fresher (less reddened) than Vesta. In addition, recent surveys (e.g., [7]), show that basaltic (and more diogenitic) asteroids are found throughout the inner asteroid belt; many are not members of the Vesta family.

The Dawn Mission. The instruments on the Dawn Mission will provide some help in determining whether HEDs come from Vesta; especially important will be the elemental-concentration and elemental-ratio data returned from the gamma-ray and neutron-detector (GRAND) instrument. Unfortunately, the instrument is omnidirectional and the precision (for HED-like materials) is limited for elements other than Fe, Si and Mg [4]. Perhaps it can resolve K if concentrations are well above the low (~300 µg/g) concentrations in HEDs.

If this instrument returns a composition consistent with a layer of basalt on the surface it will be consistent with Vesta being a source of basalts, but it will not prove that the HEDs originated on Vesta. The value of the data may rest in their ability to show that the HEDs are unlikely to have originated on Vesta. For example, it might detect K levels above HED levels (Vesta, like Mars, may have "planetary" concentrations of alkali metals. In any case, the Fe, Si and Mg data can help test the idea that the fresh reflection spectrum is the result of a recent dusting event that deposited a very thin layer of basalt around the asteroid.

Summary: Iron meteorite data indicate that at least 26 extensively differentiated asteroids were disrupted in the inner asteroid belt. A number of other asteroids are presumably still largely intact. Because most asteroids are dynamically closer to resonances than Vesta, it is probable that one of these other asteroids was the parent of the HED meteorites.

The remarkably fresh reflection spectrum of Vesta seems best understood as a recent (last Ma or so) dusting of the surface by fine ejecta from an impact. If this is the case, the GRAND instrument on the Dawn mission will probably show relatively high Mg and low Si concentrations compared to a basalt. If the GRAND mission detects K in at planetary levels, it will confirm that Vesta is not the parent of the HEDs.

References: [1] McCord T et al. (1970) Science 168, 1445. [2] Herzog G. (2003) ToG 1, 347. [3] Wasson J. (2011) GCA.[4] Wasson J. and Kallemeyn G. W. (2002) GCA 66, 2445. [5] Pieters C. (2011) Space Sci. Rev. [6] Binzel R. and Xu S. (1993 Science 260, 186. [7] De Sanctis M. (2011) A&A 533, A77. [8] Vickery A. (1987) GRL 14,726.

Table 1. Structural and compositional properties of ungrouped iron meteorites inferred to have formed by fractional crystallization.

meteorite	str.	Co	Ni	Ga	Ir	Au	Ir/Au
		mg/g	mg/g	µg/g	µg/g	µg/g	g/g
Elton	Om	4.94	70.5	48.6	0.06	1.44	0.04
Etosha	Om	4.78	67.1	50.1	0.12	0.99	0.12
Cambria	Off	5.37	104	11.3	0.87	2.24	0.39
Morradal	Opl	4.83	195	47.1	0.68	0.72	0.94
Denver City	Of	4.03	83.4	0.91	4.88	0.54	9.0
Laguna Manantiales	Of	4.78	68.2	20.6	4.34	0.46	9.5
Bacubirito	Off	5.39	97.1	17.7	5.09	0.51	9.9
NWA 6932	Opl	6.84	123	9.45	7.87	0.78	10.0
Cowra	Opl	5.70	133	75.1	14.2	1.22	11.6
La Caille	Om	6.02	93.0	13.7	9.30	0.69	13.4
Campinorte	Og	5.80	70.7	74.0	19.6	1.30	15.1
Piedade do Bagre	Om	4.58	77.1	15.7	9.21	0.43	21
Grand Rapids	Om	5.49	92.4	17.0	16.9	0.74	23
New Baltimore	Om	5.94	62.2	20.9	9.50	0.35	27
Reed City	Og	6.33	78.0	24.8	45.2	1.31	35