

Impact histories of angrites, eucrites, and their parent bodies

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Abstract—Eucrites, which are probably from 4 Vesta, and angrites are the two largest groups of basaltic meteorites from the asteroid belt. The parent body of the angrites is not known but it may have been comparable in size to Vesta as it retained basalts and had a core dynamo. Both bodies were melted early by ²⁶Al and formed basalts a few Myr after they accreted. Despite these similarities, the impact histories of the angrites and eucrites are very different: angrites are very largely unshocked and none are breccias, whereas most eucrites are breccias and many are shocked. We attribute the lack of shocked and unbrecciated angrites to an impact, possibly at 4558 Myr ago—the radiometric age of the younger angrites—that extracted the angrites from their original parent body into smaller bodies. These bodies, which may have had a diameter of approximately 10 km, suffered much less impact damage than Vesta during the late heavy bombardment because small bodies retain shocked rocks less efficiently than large ones and because large bodies suffer near-catastrophic impacts that deposit vastly more impact energy per kg of target. Our proposed history for the angrites is comparable to that proposed by Bogard and Garrison (2003) for the unbrecciated eucrites with Ar-Ar ages of 4.48 Gyr and that for unbrecciated eucrites with anomalous oxygen isotopic compositions that did not come from Vesta. We infer that the original parent bodies of the angrites and the anomalous eucrites were lost from the belt when the giant planets migrated and the total mass of asteroids was severely depleted. Alternatively, their parent bodies may have formed in the terrestrial planet region and fragments of these bodies were scattered out to the primordial Main Belt as a consequence of terrestrial planet formation.

INTRODUCTION

The two main groups of basaltic meteorites that are derived from the asteroid belt, eucrites and angrites, appear to have formed contemporaneously but their subsequent histories were very different. Eucrites are largely composed of pyroxene and plagioclase feldspar and are closely associated with the diogenites, which are orthopyroxenites, and howardites—breccias composed of eucrite and diogenite material. The howardite-eucrite-diogenite (HED) meteorites, which provide our best samples of any differentiated asteroid, probably come from asteroid 4 Vesta (McSween et al. 2010).

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Angrites, which are much less abundant, have a more exotic mineralogy as the pyroxene is Al-Ti-bearing diopside-hedenbergite (formerly known as fassaite), plagioclase is essentially pure anorthite, and olivine is Ca-rich and more common than in eucrites. The angrites also differ from the eucrites in that the angrites have exceedingly low alkali contents (even lower than eucrites) and very different oxygen isotopic compositions (Greenwood et al. 2005; Mittlefehldt 2007). The only asteroid that provides a good spectral match to the angrites is the km-sized Mars Trojan asteroid (5261) Eureka (Rivkin et al. 2007; Trilling et al. 2007). The Sr-class asteroid 3819 Robinson matches some angrites in the visible region but not in the near-infrared (Burbine et al. 2006), and asteroid 3628 Boznemcová might be an unsampled angrite-like body (Cloutis et al. 2006). Both are ≤10 km in diameter.

Eucrites and angrites have similar whole-rock Al-Mg and Mn-Cr ages of 4563–4565 Myr suggesting that their parent bodies were melted by ^{26}Al and globally differentiated at approximately the same time (Lugmair and Shukolyukov 1998; Baker et al. 2005; Bizzarro et al. 2005; Markowski et al. 2007; Sanders and Scott 2007; Shukolyukov and Lugmair 2007; Schiller et al. 2010). However, their subsequent impact histories were very different. In a section called “What’s Up with Angrites?” Mittlefehldt et al. (2002) noted that although most eucrites are fragmental breccias and many show evidence for shock, like ordinary chondrites, the angrites are unshocked and unbrecciated.

Mittlefehldt et al. (2002) speculated that the lack of shock and breccia features in angrites might reflect a smaller size for the angrite parent body or a more protected formation location. They also noted that angrites appeared to be less metamorphosed than eucrites and concluded that if the angrites were representative of their parent body, there was some fundamental difference between the parent bodies of angrites and eucrites.

When Mittlefehldt et al. (2002) studied the angrites, there were only six known including three with weights of 1–11 g (Meteoritical Bulletin Database). We have reviewed the properties of the five angrites discovered subsequently and investigated possible explanations for the apparent lack of shock features and brecciation in angrites. We conclude that the original angrite parent body was probably not significantly smaller than Vesta (it may have been larger), but argue that, nevertheless, body size was the key factor responsible for the dramatically different shock and brecciation histories of angrites and eucrites.

ANGRITES AND THEIR PROPERTIES

After allowance for pairing, there are currently 11 known angrites with very diverse textures (Meteoritical Bulletin Database). These can be divided into two types: rapidly crystallized and more granular varieties (Table 1; Fig. 1). The rapidly cooled angrites crystallized about 3–5 Myr after CAIs, and the granular angrites have radiometric ages that are 4–6 Myr younger (Lugmair and Galer 1992; Lugmair and Shukolyukov 1998; Sugiura et al. 2005; Markowski et al. 2007; Amelin 2008; Kleine et al. 2009; Spivak-Birndorf et al. 2009; Amelin et al. 2011).

The rapidly crystallized angrites have porphyritic to ophitic textures, chemically zoned minerals, and, in many cases, millimeter-sized exotic forsterites and spherical vesicles (Mittlefehldt et al. 2002; Floss et al. 2003). These angrites crystallized while cooling at 10–50 °C h⁻¹ within a meter of the surface (Mikouchi et al. 2000, 2001, 2003; Floss et al. 2003). The granular angrites have relatively

Table 1. Angrites, classification, and authors who identified them as unshocked or not significantly shocked and unbrecciated^a.

Meteorite	Texture ^b	Reference
Angra dos Reis (stone)	Gran. pyroxenite	Prinz et al. (1977)
Asuka 881371	r-c	Mikouchi et al. (1996, 2001)
D’Orbigny	r-c	Mittlefehldt et al. (2002)
Lewis Cliff 86010	gran	Prinz et al. (1988), Mittlefehldt et al. (2002)
Lewis Cliff 87051	r-c	Mikouchi et al. (1996, 2001)
NWA 1296	r-c	Jambon et al. (2005)
NWA 1670	r-c	Jambon et al. (2008)
NWA 2999 ^c	Gran.	Kuehner et al. (2006), Irving and Kuehner (2007)
NWA 4590	Gran.	Irving and Kuehner (2007), Kuehner and Irving (2006)
NWA 4801	Gran.	Irving and Kuehner (2007)
Sahara 99555	r-c	Mikouchi et al. (2000, 2001)

^aA twelfth apparently unbrecciated, rapidly crystallized angrite was described by Yanai and Noda (2004) but it has not been officially named.

^bTextures: r-c = rapidly crystallized; gran. = granular.

^cIncludes paired specimens Northwest Africa (NWA) 3158, 3164, 4569, 4662, 4877, 4931, and 6291. The Meteoritical Bulletin (Weisberg et al. 2008) states that NWA 4569, 4662, and 4877 are moderately shocked, but T. E. Bunch [personal communication] reports that they are low shock stage, S1/2 to S2.

equilibrated minerals and clearly had more prolonged thermal histories; they have been called “plutonic metamorphic angrites” by Kuehner et al. (2006) and Kuehner and Irving (2007).

All but two of the angrites are unshocked (shock stage S1; Stöffler et al. 1991), and none are fragmental breccias according to the studies listed in Table 1. Mikouchi et al. (2003 and private communication) report that NWA 1670 contains shock melt veins in the groundmass, which are 1–20 μm in width. Mikouchi et al. (2003) also note that olivine megacrysts in NWA 1670 display mosaicism or undulose extinction. However, Fig. 2b in Jambon et al. (2008) shows that the large olivines appear to have a recrystallized texture and are not mosaicized as in strongly shocked stage S4 rocks (Stöffler et al. 1991). Jambon et al. (2008) also note that the overgrowths on the large crystals appear undeformed so that NWA 1670 does not appear to be strongly shocked. The second shocked angrite is NWA 2999. T. E. Bunch (personal communication) notes that some of the paired specimens are shock stage S1-S2 or S2.

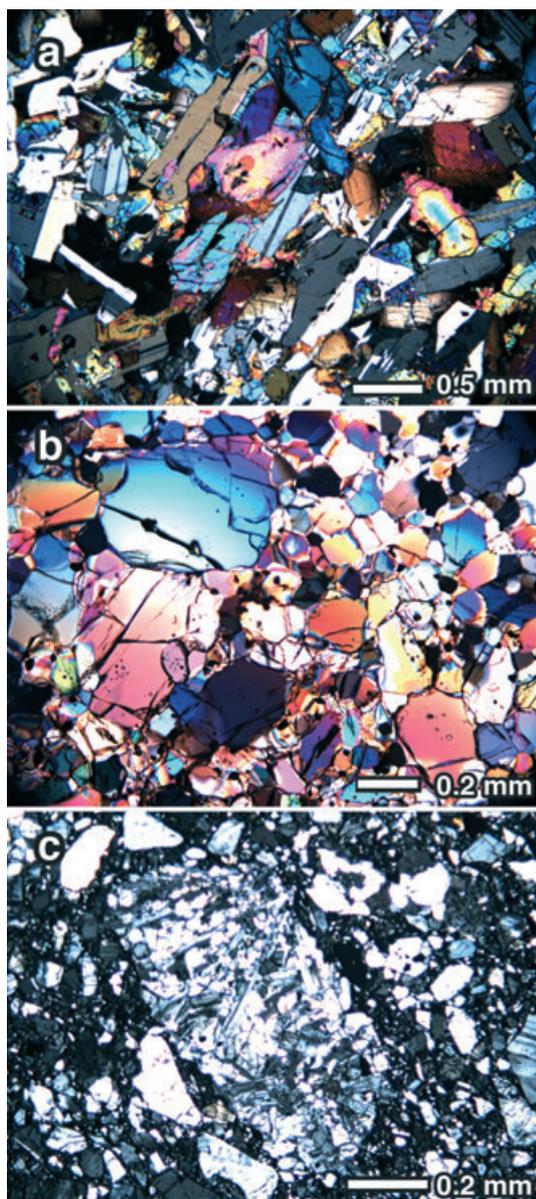


Fig. 1. Transmitted-light photomicrographs using crossed polars of two angrites, a) D'Orbigny and b) Angra dos Reis, which are both unshocked and unbrecciated, and c) eucrite clast in the Jodzie howardite, which is a breccia composed of fragments of eucrites and diogenites. D'Orbigny, which cooled rapidly near the surface of the parent body, shows pyroxene and intergrown crystals of plagioclase and olivine. The recrystallized texture of Angra dos Reis and its more equilibrated mineral compositions show that it had a more prolonged thermal history at depth.

Thus none of the angrites show very pronounced shock effects.

Angra dos Reis (stone), which is a unique pyroxenite, has a fine-grained granular texture (Prinz et al. 1977), which may result from recrystallization of a previously deformed rock or breccia. Irving and Kuehner (2007) also

suggest that NWA 2999 may represent an annealed breccia. Thus these two angrites may have been shocked and brecciated before they were metamorphosed.

Seven angrites have a wide spread in cosmic-ray exposure ages (0.2–60 Myr; see Eugster et al. 2006), suggesting that they are not a very biased sample from a single recent collision. These ages are comparable to a random sample of ages of HEDs or H chondrites, for example, so there would appear to be nothing especially unusual about the delivery mechanism for angrites.

Clasts containing anorthite and Al-Ti-bearing diopside-hedenbergite that resemble Angra dos Reis are present in three polymict ureilite breccias, one of which is a regolith breccia (Goodrich et al. 2004). Although petrogenetic links between the ureilites and the angrites have been considered, oxygen isotope data show that they are derived from entirely separate bodies and that the clasts are probably from the same source as the angrites.

Angrites have been linked to the IVB irons as both groups are highly depleted in moderately volatile elements (Campbell and Humayun 2005). However, a single parent body for these meteorites can be excluded as their Mo isotopic compositions are quite different (Burkhardt et al. 2011).

SHOCK AND BRECCIATION IN EUCRITES

Many eucrites are fragmental breccias and a significant fraction has been shocked (Metzler et al. 1995; Bischoff et al. 2006). Observable shock effects in silicates such as undulatory extinction in olivine and pyroxene, which define shock stage S2, require shock pressures of approximately 5 GPa and impact velocities of 1–2 km s⁻¹ or higher (Stöffler et al. 1991; Bischoff and Stöffler 1992; Rubin et al. 1997).

Eucrite breccias other than impact melt breccias are mostly fragmental breccias that were lithified like regolith breccias by localized shock melting at grain corners and edges at shock pressures > 5 GPa (Bischoff et al. 2006). Thus the impact velocities required to produce observable shock effects (S2 and above) and to weld fragments into breccias are a few km s⁻¹, vastly higher than the impact velocities of tens of m s⁻¹ that are needed just to fragment rock.

Some eucrite breccias were lithified instead during metamorphism or by impact heating and some were also recrystallized (Metzler et al. 1995; Yamaguchi et al. 1997). Roughly 10% of eucrites are unbrecciated (table 4 in Scott et al. 2009a) and some of these are also shocked (Mayne et al. 2009). The unbrecciated eucrites, like the angrites, include fine-grained basalts that formed near the surface as well as cumulates and other plutonic rocks from depth. However, at least two of the unbrecciated eucrites, NWA 011 and Ibitira, and possibly others have

such distinctive isotopic compositions that they are very unlikely to have been derived from the parent body of the HEDs (Yamaguchi et al. 2002; Scott et al. 2009a).

DISCUSSION

Parent Bodies of Eucrites

If a few eucrites with anomalous isotopic compositions are not derived from the HED body, as noted above, how do we know that the HEDs come from Vesta and not some anomalous eucrite? We believe one can make the following set of arguments based on what we know of this population as well as the evolution of Main Belt objects.

First, the HEDs have reflectance spectra that are an excellent match for Vesta and other V-type asteroids, nearly all of which form a broad well-defined family of several thousand asteroids near Vesta itself (Pieters et al. 2005; Moskovitz et al. 2010; Parker et al. 2008). This large family may have derived from the large crater on Vesta (Thomas et al. 1997). Moreover, while small V-type asteroids can be found scattered across the Main Belt region, there are no other prominent reservoirs of such objects at sizes larger than a few kilometers in diameter other than those near Vesta itself.

Second, like other families on plots of semi-major axis versus eccentricity or inclination, the Vesta family is sculpted and truncated by resonances, consistent with dynamical simulations that include the Yarkovsky effect, which causes the smallest members to drift in semimajor axis. The Vesta family itself stretches from the two key resonances in the inner Main Belt that produce planet-crossing objects: the ν_6 secular resonance near 2.2 AU and the 3:1 mean motion resonance with Jupiter near 2.5 AU. These resonances play a dominant role in populating the near-Earth asteroids (e.g., Binzel and Xu 1993; Bottke et al. 2002, 2006a; Nesvorný et al. 2008). Many V-type asteroids are present among the near-Earth asteroids (e.g., Marchi et al. 2005) and the majority of these are almost certainly Vesta family fragments that were removed from the Main Belt by this process.

There are a few V-type asteroids in the Main Belt that do not appear to belong to the Vesta family (e.g., Lazzaro et al. 2000) as well a few S types that may be derived from asteroids which had basaltic surfaces (Sunshine et al. 2004). However, Vesta is clearly the dominant source of basaltic asteroids (Moskovitz et al. 2008). Given that the HED meteorites collectively account for 5% of all meteorite falls and are over 100 times more abundant than the anomalous eucrites (Meteoritical Bulletin Database), it would be quite extraordinary if Vesta was limited to be the source of an anomalous eucrite and not the HEDs.

Table 2. Comparison of shock levels and abundance of fragmental breccias among angrites, eucrites, ordinary, and CO chondrites.

Meteorite	Breccias	Shock levels
Angrites	None	~80% S1
Eucrites	Common	S3–S6 common
Ordinary chondrites	Common	S3–S6 common
CO chondrites	< 2%	~95% S1

Sources: see text.

Comparison of Angrites and Eucrites

In Table 2, we have summarized the abundances of shocked meteorites and fragmental breccias among angrites and eucrites as well as the ordinary chondrites (H, L, and LL groups) and CO chondrites (Stöffler et al. 1991; Scott et al. 1992; Bischoff et al. 2006). The eucrites and ordinary chondrite groups have many members that are fragmental breccias that were lithified by shock as well as shocked members. Angrites are clearly unusual in lacking brecciated and significantly shocked members, but CO chondrites show they are not unique in this regard.

One possible explanation for the differences in the abundance of breccias and shocked rocks among the eucrites and angrites is that the angrites were stored in a relatively “safe” location in the asteroid belt, where collisions were infrequent or they occurred predominantly at low velocities. The problem is that most asteroids have orbits that cross one another, such that there is always an ample supply of objects to beat up on a given target (e.g., Bottke et al. 1994). Moreover, the orbital orientations of asteroids are constantly randomized by secular perturbations. This implies that two asteroids with similar semimajor axes, eccentricities, and inclinations would still be fairly likely to hit one another at substantial velocities. In general, most Main Belt objects have intrinsic collision probabilities with the background population within a factor of 2 or so of the mean, $2.9 \times 10^{-18} \text{ km}^{-2} \text{ yr}^{-1}$ (Bottke et al. 1994), and impact velocity distributions near the mean value of about 5 km s^{-1} (see also O’Brien 2010). Even the Hungaria asteroids, a tiny population located at high inclinations between 1.8 and 2.0 AU, cannot escape being hit by objects from the innermost region of the Main Belt. Thus, it seems unlikely that variations in collision probabilities or impact velocities could account for the angrite-eucrite differences, especially over 4 Gyr.

Radiometric ages of angrites are generally older than those of eucrites (e.g., Lugmair and Shukolyukov 1998; Markowski et al. 2007), so the angrite-eucrite shock and breccia differences cannot reflect prior crystallization of the eucrites. We infer that the angrite-eucrite differences must reflect something we have not yet considered, and

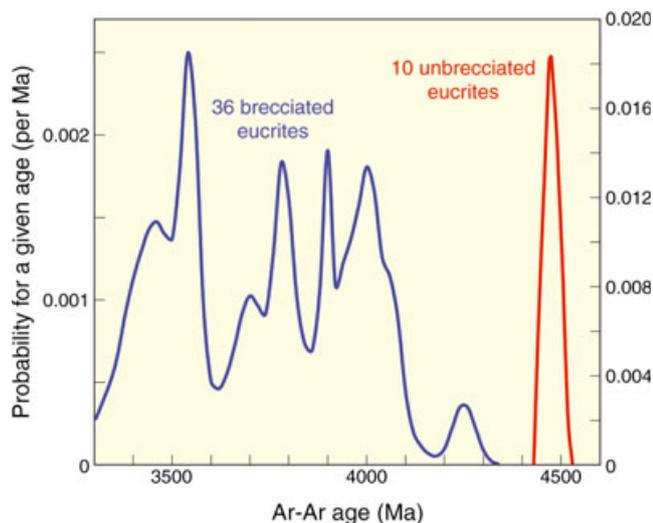


Fig. 2. Summed Gaussian probability curves of Ar-Ar ages for 36 brecciated eucrites or eucritic clasts that show prominent impact heating peaks at 3.5, 3.8, 3.9, and 4.0 Gyr, and for 10 unbrecciated eucrites (cumulate and non-cumulate) that peak at 4.48 ± 0.02 Gyr. The scale for the unbrecciated eucrites is on the right, and for the 36 brecciated eucrites on the left. Sources: Bogard (1995); Bogard and Garrison (2003, 2009); Scott et al. (2009b).

we postulate that the differences are a consequence of the sizes of the bodies in which the meteorites were formed or stored.

Effect of Parent Body Size

If shocked rocks and fragmental breccias had simply formed and accumulated on the surfaces of asteroids over long periods, we might expect that shocked meteorites and meteorite breccias would be derived preferentially from small bodies. Similarly, because most meteorites probably resided in one or more intermediate-sized precursor bodies after leaving their parent bodies, we should also expect that breccia formation and shock occurred predominantly after the destruction of their parent asteroids in family forming impacts. For example, the formation of the Bapistina family by the destruction of the parent asteroid, which may have had a diameter of 170 km, increased the surface area of bodies >0.3 km in diameter by a factor of >100 (e.g., Bottke et al. 2007). Thus if the surface-to-volume ratio of the asteroid is the dominant factor, most breccias and shocked meteorites would have formed relatively recently on small bodies.

To test this hypothesis, we need to know when meteorites were shocked above 5 GPa and when meteorite fragmental breccias were formed. For some meteorites, we cannot determine precisely when they were shocked. But many strongly shocked meteorites were also extensively heated e.g., in a hot volume of ejecta or crater basement,

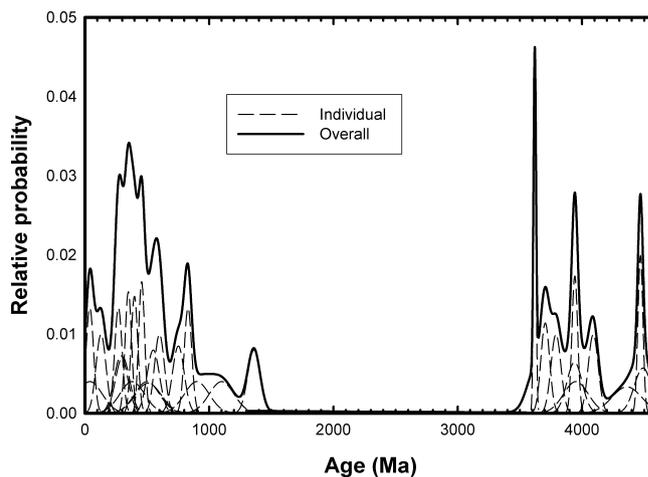


Fig. 3. Summed Gaussian probability curve of Ar-Ar ages for approximately 30 H chondrites and clasts (heavy line). The dashed lines show age probability curves for some individual samples: the peak gives the age and the spread of the curve measures the age uncertainty. Reproduced from Swindle et al. (2009) by permission of *Meteoritics & Planetary Science*, ©2009 by the Meteoritical Society.

so that they lost Ar, resetting their K-Ar radiometric clocks. Ordinary chondrites with Ar-Ar ages of 4.4–4.5 Gyr, for example, are mostly unshocked (stage S1), the others were mildly shocked to stage S2-S3, whereas ordinary chondrites with younger Ar-Ar ages were shocked to stage S3-S6 (above 5–10 GPa) (Haack et al. 1996). Thus even though the shock-reheated meteorites with reset Ar-Ar ages are only a subset of the shocked meteorites, the former should provide an excellent guide to the time when meteorites were shocked to shock stage S2 and above and fragmental and impact-melt breccias were formed (e.g., Wittmann et al. 2010). (We recognize that some ordinary chondrites, angrites and eucrites could have been shocked at 4.5 Gyr and then recrystallized during metamorphism so that they are now unshocked again.)

Ar-Ar age distributions for eucrites and H chondrites and some clasts in their breccias are shown in Figs. 2 and 3. The distribution of ages for L chondrites is broadly similar to that for the H chondrites except that the former are dominated by the 470 Myr impact event that probably demolished the L chondrite parent body and showered Earth with debris (Bogard 1995, 2011; Nesvorný et al. 2009). These figures show that shock heating did not occur predominantly on the small bodies that were the most recent parent bodies of the meteorites. For HEDs, shock heating occurred predominantly during the late heavy bombardment at 3.5–4.0 Gyr, most likely by sizable cratering events (Bogard 1995, 2011). For ordinary chondrites, shock heating occurred partly during this event but predominantly during several major impacts during the last 1500 Myr. Few if any Ar-Ar ages

date the events that exposed meteorites to cosmic rays as meter-sized rocks when they departed from their last parent body (Bogard 1995). Thus shock-reheating occurred predominantly during a few major impacts over the past 4 Gyr and not predominantly during small, far more numerous, and relatively recent cratering events. We therefore infer that asteroidal meteorites were mainly shocked on relatively large asteroids.

Bogard (1995; see also Bogard 2011) compared the abundance of impact-heated rocks with Ar-Ar ages between approximately 3.5 and 4.0 Gyr among lunar rocks, HEDs, and ordinary chondrites. For reference, the diameters of their parent bodies are 3500, 530, and approximately 100–300 km, respectively (e.g., Taylor et al. 1987; Trieloff et al. 2003). Bogard found that the abundance of samples with these reset ages was higher among lunar samples than HEDs, and lowest among ordinary chondrites. He suggested that the increase in the abundance of shock-reheated samples with these ages with increasing parent body size was due to the tendency for smaller bodies to lose their ejecta much more readily than larger bodies. Although smaller asteroidal bodies would have been preferentially destroyed during the late heavy bombardment, the proportion of shock-heated rocks on the surviving small bodies would have been lower than on the larger bodies. We call this “Bogard’s rule.” The corollary is that fragmental breccias are formed more efficiently on large bodies than on small ones.

Bogard’s rule is partly a result of the expected higher ejection speeds of many shocked rocks and the lower escape velocities of smaller bodies. For example, a 10 km diameter body has an escape velocity that is 50 times less than that of Vesta. Another important factor is that the size distribution of asteroids ensures that most impact energy is delivered by the large rare projectiles that nearly destroy the body, and not by the numerous small projectiles that merely pepper the surface. Figure 4 shows the specific impact energy, defined as the impact energy per kg of target that is needed to catastrophically disrupt a body so that the largest fragment is half the mass of the target (Q_D^*). The right side of the curve is the “gravity-scaling” regime, where fragmentation is controlled by the self-gravity of the target. Examining the gradient of the linear portion for $D > 5$ km, we find that Q_D^* is proportional to $D^{1.5 \pm 0.3}$ in this size range. (The uncertainty in the exponent comes from the diverse slopes of the curves shown by Asphaug [2009; fig. 4].) Accordingly, the specific impact energy needed to catastrophically destroy Vesta is 100–1000 times larger than for a 10 km body. The ability of big objects to sustain sizable impacts implies that if the angrites had been located on a Vesta-sized body during or after the late heavy bombardment, they would have likely been

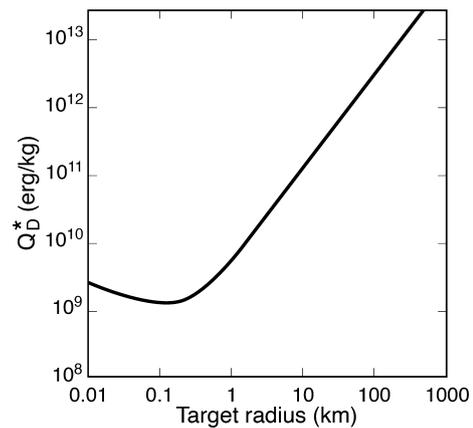


Fig. 4. The specific impact energy Q_D^* needed to catastrophically disrupt a body as a function of size (see Asphaug 2009). For bodies larger than a kilometer in radius, Q_D^* increases with size so that Q_D^* for Vesta is enormously higher than for a 10 km diameter body. This curve gives a factor of approximately 200 higher, but given the uncertainty in the curve, the factor could range between 100 and 1000 times higher.

shocked by impact events in the same manner as their HED brethren.

The effect of the asteroid’s gravity on the relative volume of shocked rock produced in impacts is analogous to what is observed for the ratio of mass melted to mass displaced for terrestrial impact craters of diverse sizes. For the smallest craters, this ratio is approximately 0.001–0.01 and it increases very roughly in proportion to the crater size so that the largest craters form almost entirely within impact melt (Melosh 1989). Given that the ratio of shocked rock to shock melt in hypervelocity impacts is ≈ 10 –20 (e.g., Stöffler et al. 1991), it is apparent that shocked rock may be a minor product of the smallest craters but the major product of large craters.

Size of the Original Angrite Parent Body

Several lines of evidence suggest that the angrite parent body was larger than previously inferred (see Busemann et al. 2006)—at least 100 km in diameter and probably closer to Vesta in size. (1) Basalts would probably have been lost explosively from the angrite parent body if it were < 100 km in radius when they erupted (Wilson and Keil 1991). (2) The presence of solar-like gases trapped in glass in the D’Orbigny angrite may imply that the parent body was large enough to retain a nebular atmosphere (see Busemann et al. 2006). (3) Paleomagnetic studies show that the angrite parent body was large enough (> 100 km radius) to sustain a core dynamo that lasted until at least about 9 Myr after CAIs formed (Weiss et al. 2008; Elkins-Tanton et al. 2011). (4) Spinel-plagioclase-pyroxene intergrowths in

one angrite, NWA 2999, resemble those produced under pressure on Earth (Kuehner et al. 2006).

Note that an origin on Mercury, as Kuehner et al. (2006) and Kuehner and Irving (2007) proposed, seems implausible, as unbrecciated and unshocked rocks with the antiquity of angrites would be unlikely to have survived intact on such a heavily cratered planet for 4560 Myr. This would be a direct violation of Bogard's rule, with Mercury's large size implying it is even more likely to keep shocked material than the Moon. In addition, Mercury's silicates contain < 2 wt% FeO (Blewett et al. 2009) whereas those in angrites are FeO-rich (Mittlefehldt 2007).

Explanation for Angrite Properties

Since the breccia and shock properties of angrites appear to be incompatible with their formation and storage on a large Vesta-sized parent body, we suggest that they were removed from their parent body soon after they formed. To avoid impact shock and brecciation, we postulate they were safely stored in bodies having diameters of approximately 10 km for several Gyr. Modeling work shows that a modest fraction of such bodies created at the dawn of the asteroid belt can survive a few Gyr of collisional and dynamical evolution (Bottke et al. 2005, 2010).

Our current understanding of meteorite delivery from the Main Belt suggests that asteroid families are more likely to be prominent sources of meteoroids than individual objects, largely because families can more easily keep resonances resupplied with small objects via a collisional cascade. Along these lines, we suspect that a major impact on the angrite parent body 4.5 Gyr ago produced a steep size distribution of "intermediate precursors" that was possibly analogous to the Vesta asteroid family. Some of these $D < 10$ km bodies, or their daughter products, may still be around today. While greatly reduced in number from their original population and potentially scattered into a myriad of Main Belt locales, the survivors are likely sufficient in number to keep up a modest supply of new fragments to resonances, enough to allow the angrites to stand out slightly compared to the unsampled background.

A similar model was proposed by Bogard and Garrison (2003) to account for the 4.48 ± 0.02 Gyr Ar-Ar ages of two-thirds of their sample of unbrecciated eucrites. Since both cumulate and basaltic eucrites were found to have this age, they suggested that a major impact on Vesta 4.48 Gyr ago had excavated these eucrites from the hot crust and removed them from Vesta allowing them to cool relatively quickly. Scott et al. (2009a) similarly inferred that eucrites with anomalous oxygen isotopic compositions like NWA 011 and Ibitira

were plucked from their Vesta-like parent bodies before the late heavy bombardment to be stored in bodies having diameters of approximately 10 km for 4.5 Gyr.

The original parent bodies of the angrites, as well as those of the anomalous eucrites that were probably formed on other Vesta-like bodies, may have been removed when resonances swept across the Main Belt due to migration of the giant planets (Minton and Malhotra 2009). Alternatively, their parent bodies formed elsewhere—perhaps in the terrestrial planet region—with fragments of these bodies scattered out to the primordial Main Belt as a consequence of terrestrial planet formation (Bottke et al. 2006b). The absence of any large asteroid with an angrite-like surface is consistent with either origin.

SUMMARY AND CONCLUSIONS

Angrites and eucrites formed contemporaneously due to ^{26}Al heating in large asteroids. The angrite parent body may have been comparable in size to Vesta as it retained basalts and had a magnetic field from a core dynamo. Despite their similar formation histories, angrites are unbrecciated and not significantly shocked, unlike most eucrites.

We suggest that angrites were less affected by shock as they were stored for 4.5 Gyr in much smaller bodies that may have been approximately 10 km in diameter. The angrites were probably extracted from their original parent by an impact, probably 4558 Myr ago, the radiometric age of the granular angrites. This impact may also account for the relatively rapid cooling of the granular angrite, NWA 4590, in approximately 0.5 Myr (Amelin et al. 2011), partial melting in this angrite during pressure release (Kuehner and Irving 2007), and the presence of angrite clasts on the ureilite body. The greater extent of metamorphism in eucrites than in angrites (Mittlefehldt et al. 2002) may simply reflect a longer residence time in a large hot body that was cooling slowly.

Small asteroids that survived the late heavy bombardment intact have proportionately fewer shock-heated meteorites from this era than larger ones ("Bogard's rule"). This is because larger bodies retain shocked rocks more efficiently and because bigger bodies can sustain larger impacts than smaller ones, with these impacts depositing vastly more impact energy per kg of target. Since most fragmental breccias are formed by shock welding of fragments, the corollary of this rule is that breccias form more efficiently on large bodies than on small ones.

Our suggested history for the angrites resembles that proposed by Bogard and Garrison (2003) for the unbrecciated eucrites with Ar-Ar ages of 4.48 Gyr, which were probably extracted from Vesta at that time and

stored in small bodies for 4 Gyr. Similarly, the anomalous eucrites like NWA 011 and Ibitira, which do not appear to have formed on Vesta, are unshocked and unbrecciated and were probably also removed from their parent bodies in a similar way (Scott et al. 2009a).

Bogard's rule provides important clues to the history of other meteorites. For example, CO chondrites, which are very largely unshocked and unbrecciated like angrites, probably had a similar history involving early extraction from their parent body and storage in smaller bodies for several Gyr. The HEDs, which have not been shock-heated since 3.5 Gyr ago, probably came from objects in the Vesta family, which was created in a large basin-forming impact toward the end of the late heavy bombardment or some time afterward (Binzel and Xu 1993; Thomas et al. 1997).

We note that although most CI and CM chondrites are breccias, they were probably lithified by precipitates from aqueous solutions. Thus we cannot infer that they were derived from large asteroids.

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