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Iron meteorites as remnants of planetesimals formed in the terrestrial planet region

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Iron meteorites are core fragments from differentiated and subsequently disrupted planetesimals[1]. The parent bodies are usually assumed to have formed in the main asteroid belt, which is the source of most meteorites. Observational evidence, however, does not indicate that differentiated bodies or their fragments were ever common there. This view is also difficult to reconcile with the fact that the parent bodies of iron meteorites were as small as 20 km in diameter[2,3] and that they formed 1–2 Myr earlier than the parent bodies of the ordinary chondrites[4–6]. Here we show that the iron-meteorite parent bodies most probably formed in the terrestrial planet region. Fast accretion times there allowed small planetesimals to melt early in Solar System history by the decay of short-lived radionuclides (such as ^{26}Al, ^{60}Fe)[7–9]. The protoplanets emerging from this population not only induced collisional evolution among the remaining planetesimals but also scattered some of the survivors into the main belt, where they stayed for billions of years before escaping via a combination of collisions, Yarkovsky thermal forces, and resonances[10]. We predict that some asteroids are main-belt interlopers (such as (4) Vesta). A select few may even be remnants of the long-lost precursor material that formed the Earth.

In this view, inner Solar System planetesimals or their fragments, presumed to be the parent bodies of most iron meteorites, are scattered into the main asteroid belt early in its history. To investigate this, we used numerical simulations to track thousands of massless test bodies (planetesimals) evolving amid a swarm of Moon- to Mars-sized planetary embryos spread between 0.5–3.0 AU (see Fig. 1 for computational details). Figure 1 shows a representative snapshot of a thousand of our test bodies after 10 Myr of evolution, with subgroups having initial semimajor axis a values between 0.5–1.0 AU, 1.0–1.5 AU and 1.5–2.0 AU. We find that planetary embryo perturbations increase the mean displacement of particles from the centre of each group over time; for test bodies that maintain eccentricity $e < 0.3$ and inclination $i < 15°$, we find, for each subgroup, $\langle \Delta a \rangle \approx 0.2$ AU at 4 Myr and 0.3–0.4 AU at 10 Myr. These results are consistent with the observed semimajor axis spread of large S- and C-type asteroids in the main belt[13].

The most intriguing part of Fig. 1, however, are the outliers who enter the main-belt zone through a combination of resonant interactions and close encounters with planetary embryos. Figure 2 shows that nearly 0.01–0.1%, 1% and 10% of the particles respectively started with $a = 0.5$–1.0 AU, 1.0–1.5 AU, and 1.5–2.0 AU achieve main-belt orbits. Once there, these objects are dynamically indistinguishable from the rest of the main-belt population; while many may be ejected over time via interactions with planet embryos, resonances, and so on[14,15], the proportion of interloper to indigenous material in the main belt should stay the same. Figure 1 also shows that much of this material is delivered to the inner main belt, where meteoroids are dynamically most likely to reach Earth (ref. 16; see also Supplementary Discussion). We infer from these results that interloper material should be an important component in the meteorite collection.

If planetesimal material from the terrestrial planet region were actually in the main belt, we can guess at its nature by examining the main-belt population. Observations show a broad-scale taxonomic stratification among large main-belt asteroids, with S-type asteroids, believed to be analogous to metamorphosed but unmelted ordinary chondrites, dominating the inner main belt and C-type asteroids, believed to be analogous to more primitive carbonaceous chondrites, dominating the outer main belt[1,13,17]. This trend, if followed inward towards the Sun, implies that inner Solar System planetesimals experienced significantly more heating than S- and C-type asteroids, with the most plausible planetesimal heat source being radionuclides like ^{26}Al and ^{60}Fe (refs 7, 8, 9). Because the half-lives of these isotopes are only 0.73 Myr and 1.5 Myr, respectively, bodies that accrete quickly stand the best chance of undergoing differentiation. Although precise accretion timescales across the inner Solar System are unknown, modelling work suggests they vary with swarm density and a, such that accretion timescales increase with increasing heliocentric distance (at least until the so-called 'snowline' is reached)[18–20]. Accordingly, if main-belt interlopers are derived from regions closer to the Sun, their shorter accretion times would lead to more internal heating[17] and thus they would probably look like heavily metamorphosed or differentiated asteroids.

At this point, a plausible connection can be made between our putative interlopers and iron meteorites. Cooling rate and textural data from irons indicate that most come from the cores of small differentiated asteroids (diameter $D \approx 20$–200 km; refs 2, 3); very few are thought to be impact melts or fragments from larger differentiated bodies (for example, the $D = 530$ km asteroid (4) Vesta)[2,21]. Isotopic chronometers also indicate that core formation among iron meteorite parent bodies occurred 1–2 Myr before the formation of the ordinary chondrite parent bodies[4,5,6]. The paradox is that if small asteroids differentiated in the main belt at such early times, it would be reasonable to expect larger bodies forming near the same locations to have differentiated as well (ref. 17; see also Supplementary Discussion). Hence, if iron meteorites are indigenous to the main belt, large numbers of differentiated bodies and their fragments should reside there today. This is not observed. Instead, we argue that a more natural formation location for most iron-meteorite parent bodies is the terrestrial planet region, where accretion occurs quickly and thus differentiation is more likely to occur among small bodies[17]. A small fraction of this material would then be scattered into the main belt by interactions with planetary embryos.

The paucity of intact differentiated asteroids (or their fragments) in the main belt today, particularly in the inner main belt where numerous meteorites come from[16], is an important constraint for our scenario. For example, despite extensive searches[22], only one asteroid is known to sample the crust of a non-Vesta but Vesta-like

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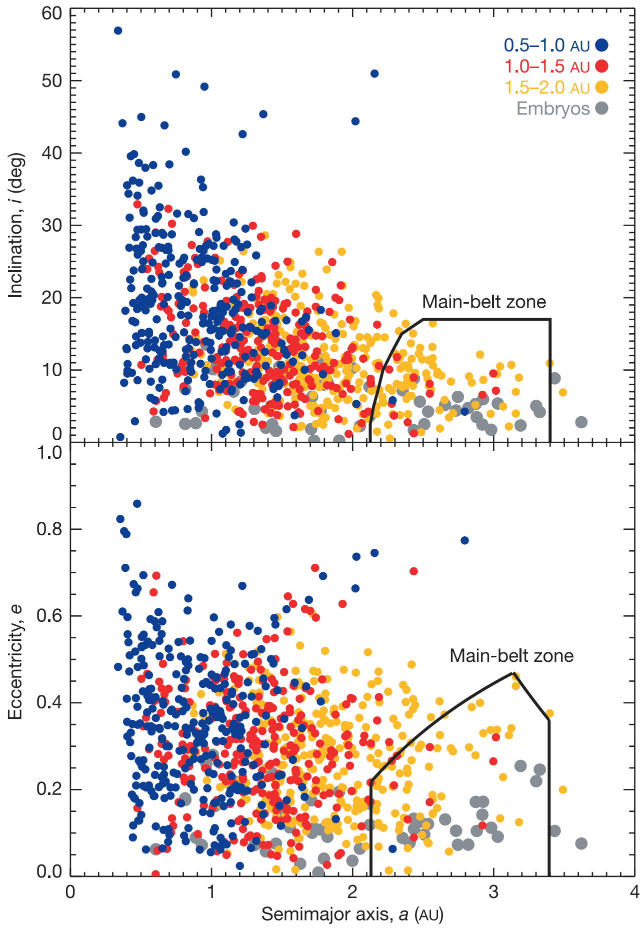

Figure 1 | A snapshot of inner Solar System planetesimals and planetary embryos after 10 Myr of dynamical evolution. The starting conditions and methods used were the same as in ref. 11. We assumed that the jovian planets, if they existed, had a negligible effect on the early dynamical history of these bodies. Gas drag and dynamical friction between the embryos and planetesimals were neglected. Tests indicate that these approximations, while imperfect, mainly affect the details of our model rather than the overall story (see Supplementary Discussion). Four sets of 100 embryos (grey dots) were distributed over 0.5–3.0 AU such that their surface density varied as the heliocentric distance $r^{-3/2}$, with 8.0 g cm^{-2} at 1 AU. Each embryo was 0.04 Earth masses. Their initial (e, i) values were chosen randomly from a uniform distribution $e = \{0.5, 5.0\}$ (a/r_H) and $\langle i \rangle = 0.5 \langle e \rangle$, where r_H is an embryo's Hill radius. The planetesimals were given uniform a between 0.5–2.0 AU and random e, i according to a Rayleigh distribution ($\langle i \rangle = 0.5 \langle e \rangle$, with $\langle e \rangle = 0.02$). The blue, red and yellow dots show what happens to 1,000 planetesimals started with 0.5–1.0 AU, 1.0–1.5 AU, and 1.5–2.0 AU, respectively. The black line is the location of the main asteroid belt (2.0 AU $< a <$ 3.5 AU, e is such that the objects do not cross the orbits of Mars or Jupiter, i is below the ν_6 resonance for 2.0 AU $< a <$ 2.5 AU, and $i < 17°$ for 2.5 AU $< a <$ 3.5 AU)[12]. Numerous planetesimals (one blue and several red/yellow) were driven into the main belt by gravitational interactions with embryos, with the highest concentration in the inner main-belt region.

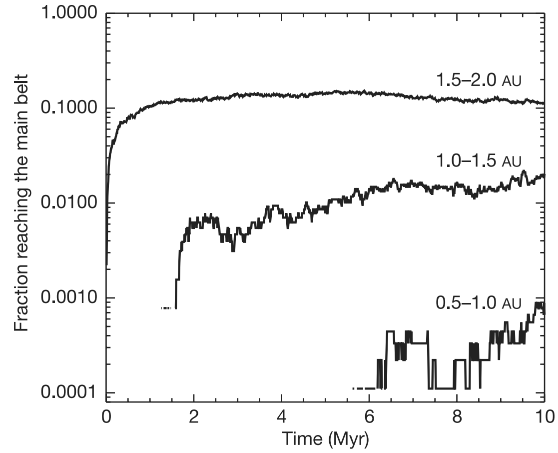

Figure 2 | The fraction of inner Solar System planetesimals scattered into the main-belt zone by gravitational interactions with planetary embryos. Computational details are given in Fig.1. The curves were generated by tracking 17,000 test bodies for 10 Myr across four planetary embryo simulations. To compute accurate statistics, >60% of the test bodies were started in the 0.5–1.0 AU zone. The remainder were equally distributed in the 1.0–1.5 AU and 1.5–2.0 AU zones. The proportion of test bodies reaching the main belt from the 1.5–2.0 AU zone is ~10% after 1 Myr of evolution. This value quickly reaches a steady state and remains that way for the remainder of the runs. For the 1.0–1.5 AU zone, 0.8–2% are injected into the main belt after a longer delay of 2 Myr, while for 0.5–1.0 AU we find >0.01–0.1% after 6 Myr. Thus, it is plausible that the current main belt contains samples from the feeding zones of Mercury, Venus, Earth and Mars, with the limiting factor being the formation times of the terrestrial and jovian planets.

differentiated asteroid: (1459) Magnya, a $D = 20$–30 km V-type asteroid located in the outer main belt[23] (though see also ref. 24 and Supplementary Discussion). Moreover, main-belt asteroid families, which contain fragments produced by the disruption of over fifty $D \approx 10$–400 km asteroids, show little spectroscopic evidence that their parent bodies were heated enough to produce a distinct core, mantle and crust (other than those associated with Vesta)[25]. These data, which suggest that differentiated material from small parent bodies is rare in the main belt, must be reconciled with the following facts: (1) iron meteorites represent over two-thirds of the unique parent bodies sampled among all meteorites[1] and (2) iron meteorites were probably extracted from the cores of $D \approx 20$–200 km parent bodies through catastrophic impacts[2,3].

We investigated this apparent contradiction by modelling the impact history of inner Solar System planetesimals using a well-tested collision evolution code[26,27] (see Fig. 3 for computational details). Figure 3 shows the fraction of $D = 20$, 100 and 500 km planetesimals that survive intact between 0.5 AU $< a <$ 2.0 AU as a function of time. Ideally, these results should be coupled to thermal models describing the minimal size needed for differentiation in each zone as a function of time. This cannot be done, however, until accretion times are better quantified. For this reason, our thermal modelling results are only used to guide the discussion below.

In the 0.5–1.5 AU zone, most $D = 20$–100 km planetesimals disrupt after a few Myr. Because the break-up of a single planetesimal can produce millions of fragments, however, some of this material should be scattered into the main belt (Fig. 2). Accordingly, we predict that many iron meteorites come from these planetesimals: they form close to the Sun, so they are likely to be differentiated, and very few survive intact, explaining the paucity of small but intact differentiated bodies in the main belt. We note that larger $D = 500$ km planetesimals from this zone, although more difficult to disrupt, are limited in number, such that none are likely to survive the dynamical events that depleted the main belt of much of its population early in its history[14,15,26,27]. The surviving remnants of this differentiated population are therefore more likely to be fragments than intact objects.

Alternatively, 1.5–2.0 AU planetesimals are increasingly likely to both survive comminution and be scattered into the main belt (Figs 2 and 3). Their longer accretion times, however, mean that only the largest, most insulated ones differentiate. Thus, $D < 100$ km interlopers from this zone are more likely to resemble heavily metamorphized S-type and E-type asteroids than differentiated bodies. Interestingly, these heating trends may help us deduce where Vesta

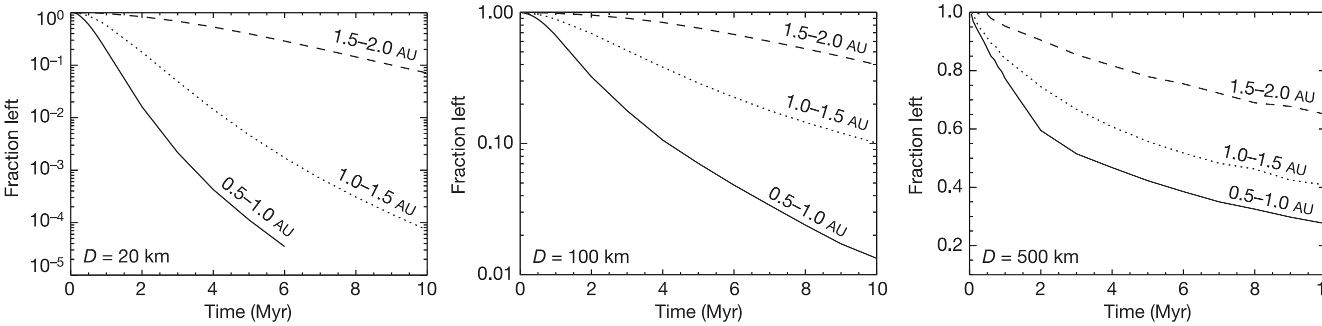

Figure 3 | The fraction of inner Solar System planetesimals that survive the first 10 Myr of collisional evolution. Using an established code[26,27], we computed how various-input size frequency distributions (SFDs) started at 0.5–1.0 AU, 1.0–1.5 AU, and 1.5–2.0 AU undergo comminution as a function of time. The collision probabilities (P_i) and impact velocities (V_{imp}) of the planetesimals striking one another were computed using data from Figs 1 and 2 (ref. 28). Typical values for our three zones were $P_i \approx 75$, 45 and $17 \times 10^{-18}\,\mathrm{km}^{-2}\,\mathrm{yr}^{-1}$ and $V_{imp} \approx 12$, 10 and $8\,\mathrm{km\,s}^{-1}$, respectively. The input SFD for each zone was assumed to follow the same trends as those determined for the primordial main belt[14,26,27]. Large planetesimals (diameter $100 < D < 1{,}000$ km) were given a differential power-law index $q \approx -4.5$, the same as that observed in the main belt (and Kuiper belt). The number of $D > 100$ km bodies was set to ~200 times the current main-belt population. Smaller planetesimals ($D < 100$ km) were given a shallow initial slope ($q = -1.2$). The results shown here focus on $D = 20$, 100 and 500 km objects. We found that $D = 20$ km planetesimals disrupt quickly enough between 0.5–1.5 AU that only their fragments are likely to reach the main-belt zone. Intact $D = 100$ km planetesimals from 0.5–1.5 AU have a better chance of reaching the main belt, but few then go on to survive the dynamical events that deplete the primordial main belt of its material[14,15]. Relatively few $D = 500$ km bodies disrupt in any zone. Their limited numbers, however, imply that only those formed in the 1.5–2.0 AU zone are likely to be in the main belt today.

formed. If $D = 500$ km bodies were close to the minimum size needed to differentiate in the main-belt region ($a > 2.0$ AU), numerous smaller bodies ($D \leq 500$ km) should have differentiated in the adjacent 1.5–2.0 AU zone; according to Fig. 2, many should have been injected into the main belt. We consider it unlikely that collisional and dynamical processes would have eliminated all the evidence. Alternatively, if $D = 500$ km bodies were close to the minimal size needed for differentiation in the 1.5–2.0 AU zone, the paucity of differentiated material in the main belt is more naturally explained, with Vesta perhaps the lone differentiated survivor from that zone.

If samples of crust, mantle and core material from differentiated planetesimals were implanted in the main belt early in its history, why do we find so few olivine and basaltic meteorites from sources other than Vesta[1]? To examine this issue, we tracked the evolution of a hypothetical population of mantle-type material in the inner main belt over the lost 4 Gyr in response to comminution and dynamical (Yarkovsky) depletion (see ref. 29 and Supplementary Discussion for details). Our results indicate that there are insufficient A-type asteroids in the inner main belt to keep a large flux of olivine meteoroids continually replenished over several Gyr through a collisional cascade. Thus, while olivine-rich A-type asteroids clearly exist in the inner main belt, they are statistically unlikely to produce a significant number of present-day meteorites. Iron meteoroids, on the other hand, have several advantages over stones: (1) their cosmic-ray exposure ages suggest they are roughly an order of magnitude stronger than stones[30], meaning they are less susceptible to comminution and are more likely to survive atmospheric entry, and (2) their high thermal conductivities mean they evolve more slowly by the Yarkovsky effect than do stones[10]. Together, these factors mean that the population of small iron asteroids in the inner main belt has probably experienced minimal changes over the last ~4 Gyr.

These results have important implications for asteroid and meteorite studies. For example, it is plausible that some iron meteorites are remnants of the precursor material comprising the terrestrial planets. Hence, by locating and studying crust or mantle fragments associated with these objects in the main belt, we may be able to deduce the composition of the primordial Earth. Note that observable remnants of Earth's precursor material may still be located in the inner main belt, although extensive spectroscopic surveys will be needed to identify them among the background population (see Supplementary Discussion). Our model may also help to explain some curious inconsistencies in the main belt. For example, the largest main-belt asteroid Ceres ($D = 930$ km) and Vesta have very different compositions and thermal histories, despite only being separated by ~0.4 AU. As described above, one possible explanation for the difference is that Vesta is a main-belt interloper. A second and equally likely possibility, however, is that Ceres formed far from the Sun and was scattered inward by planetary embryos. We conclude that the main belt may be the last, best place to look for the long-lost precursors of many Solar System planets.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Supplementary Discussion for:

Iron Meteorites As Remnants of Planetesimals Formed in the Terrestrial Planet Region

W. F. Bottke *et al.*, Nature Manuscript 2005-09-10730A

Summary

We argue that the presence of intact asteroid (4) Vesta, the spectroscopic homogeneity seen among individual asteroid families, and the paucity of small intact differentiated bodies in the main belt means that Vesta was close to the minimal size for differentiation in its formation region. The observed differentiated fragments in the main belt and the iron meteorites, however, provide clear evidence that differentiated bodies once existed. We reconcile these two aspects by postulating that the parent bodies of many iron meteorites did not form in the main belt but instead formed closer to the Sun, where planetesimal accretion is faster and hence differentiation is more likely to occur among small bodies. After their parent bodies experienced extensive melting and comminution early in Solar System history, the fragments were scattered into the main belt via interactions with planetary embryos. Iron meteorites, representing core fragments from differentiated planetesimals, are common because they are hard to disrupt, they migrate slowly by Yarkovsky drift, and their immediate precursors are predominately located near resonances that efficiently deliver material to Earth. Conversely, crust and mantle fragments, being stones, are both weaker than irons and more susceptible to Yarkovsky drift; few survive 4.6 Gy. Thus, some asteroids and meteorites escaping the main belt today may not actually be indigenous to the main belt zone (see also [1]). Moreover, it is possible that Vesta itself is a main belt interloper, although perhaps from a region closer to the main belt than the iron meteorite parent bodies.

1. Where do most meteorites come from in the main belt, and how is this related to iron meteorite record?

Most meteorites are fragments of main belt asteroids that have reached Earth through combination of processes that includes collisions, slow semimajor axis drift

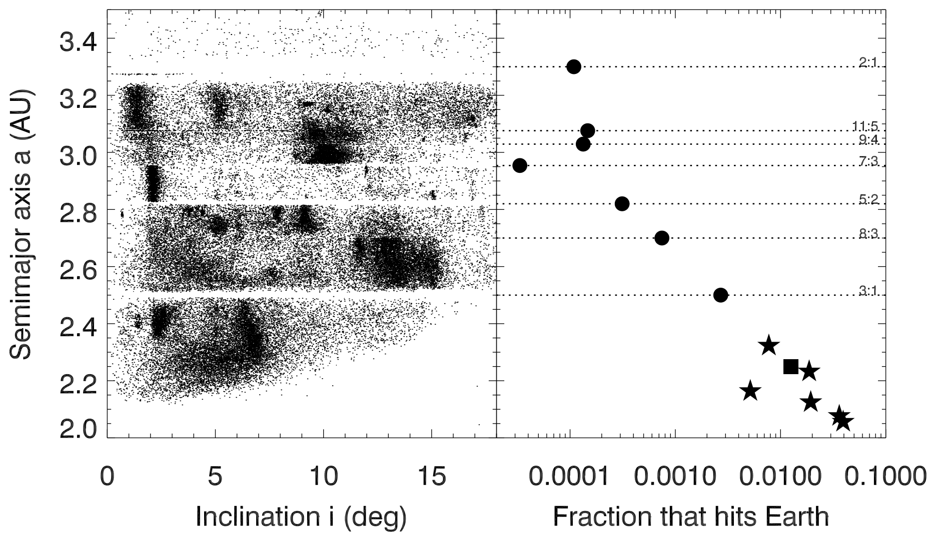

Figure S1: The delivery efficiency of test bodies from various main belt resonances striking the Earth. To create this plot, we updated the work of [4] and tracked the dynamical evolution of thousands of test bodies started in all major main belt resonances. For reference, we have also plotted the proper semimajor axis a and inclination i of 71,323 numbered asteroids with absolute magnitude $H < 15$ [5]. The stars represent values taken from test bodies started in the ν_6 secular resonance. In order of increasing a, we gave them $i = 2.5°$, $5°$, $7.5°$, $10°$, $12.5°$, and $15.0°$ [6]. The filled square represents test bodies placed in the intermediate-source Mars-crossing region located adjacent to the main belt between a = 2.0-2.5 AU [6]. Most objects in this zone escape the main belt via numerous tiny mean motion resonances (MMR) with Mars or three-body MMRs. The filled circles are values from tests bodies placed in numerous MMRs with Jupiter. Here we supplemented our impact statistics by applying Öpik-like collision probability codes to the evolutionary paths of our test bodies [7, 8]. Objects escaping the main belt with $a \leq 2.3$ AU are more than 2 orders of magnitude more likely to strike Earth than those with $a \geq 2.8$ AU. This implies that that our meteorite collection is significantly biased toward the innermost regions of the main belt.

via thermal radiation (Yarkovsky) forces, dynamical resonances, and close encounters with the terrestrial planets [2, 3]. To determine where these objects come from in the main belt, we updated results from [4] and tracked the dynamical evolution of thousands of test bodies started in all major main belt resonances.

The results, shown in **Fig. S1**, indicate that meteoroids escaping from $a <$ 2.3 AU have a 1-4% chance of striking the Earth. This fraction drops by 2 orders of magnitude, however, as we move to resonances in the central and outer main belt. Thus, if the material flux escaping out of various main belt resonances are within a factor of several of one another, as suggested by numerical experiments [6], the meteorite collection should be strongly biased toward inner main belt material.

The connection to iron meteorites can be seen **Fig. 1** in the main text, which shows that most interlopers are delivered to the innermost region of the main belt. This may explain why two-thirds of the unique parent bodies sampled in worldwide meteorite collections are represented by iron meteorites (i.e., 27 chondritic, 2 primitive achondritic, 6 differentiated achondritic, 4 stony-iron, 12 iron groups, and 60 ungrouped irons) [9, 10]. For reference, there are currently more than 20,000 known stony and iron meteorites [9].

2. How much differentiated material exists in the main belt that is not associated with Vesta?

Fragments of putative differentiated bodies have been identified in the main belt, but so far only in limited numbers. For example, only one asteroid is known to sample the crust of a Vesta-like but non-Vesta differentiated asteroid: (1459) Magnya, a $D = 20$-30 km V-type asteroid located in the outer main belt [11]. Note that this body could also be an intact differentiated body. Similarly, main belt spectroscopic surveys have only identified 22 A-type asteroids, which many believe are mantle fragments from Vesta-like bodies, out of a sample of 950 objects [12]. This material, which is likely composed of olivine-rich metal-free silicates, is mostly missing from our meteorite collection; this deficiency is colloquially known as the "great dunite shortage" (e.g., [13]). There have been spectroscopic searches for the exposed cores of differentiated asteroids, which many believe are analogous to M-type asteroids. The majority of large M-types ($D > 65$ km), however, show evidence for hydrated minerals, low densities, and/or radar signatures inconsistent with iron-rich material (e.g., [14, 15]). The most prominent examples of differentiated core material may be (16) Psyche and (216) Kleopatra, $D = 250$ and 120 km M-type asteroids, respectively, with metal-like radar signatures [15, 16] (see also [17, 18]).

Note that some differentiated material may deviate from our preconceived notions of what such asteroids should look like. For example, recent work indicates that S-type asteroids with a high-calcium pyroxene component and minor amounts of olivine may have experienced igneous differentiation [19]. To date, several asteroids in the central main belt have been found with this spectral signature (i.e., 17 Thetis, 847 Agnia, 808 Merxia, and members of the Agnia and Merxia families). A close examination of Agnia and Merxia family members, however, shows that they have nearly identical spectra. Sunshine et al. claim this homogeneity means they are likely secondary families formed from the breakup of basaltic fragments from a primary asteroid parent body [19]. Note that neither family is particularly large (i.e., the Agnia parent body was $D \sim 40$ km; Merxia was $D \sim 100$ km; Durda, Bottke et al., in preparation), which would be consistent with this scenario.

While high-calcium pyroxene S-type asteroids (and putative meteorites from these bodies) need to be further investigated, lets assume for the moment that they are indeed fragments from differentiated asteroids. Where did these objects come from? Using insights gleaned from collisional and dynamical models, it is possible to make some interesting connections. Consider the following:

- The Agnia and Merxia parent bodies in the central main belt presumably were derived from large differentiated bodies. Given their spectral similarities, they may have even come from the same parent body [19]. The disruption event(s) that produced the Agnia and Merxia parent bodies had to occur prior to the last dynamical depletion event that shaped the main belt (e.g., [20, 21]) or the family members would be dynamically related to other asteroids in proper element space. We can infer from this that the high-calcium pyroxene S-type fragments produced by this large disruption event (or events) were scattered throughout the central main belt (and perhaps further) by the last dynamical depletion event. While many of these objects would have been ejected from the main belt, some must have survived.

- The asteroids (16) Psyche and (216) Kleopatra, if they are indeed iron cores, had to have been produced by the disruption at least one very large differentiated asteroid (i.e., possibly Vesta-sized). These objects, like Agnia and Merxia, are located in the central main belt and are not associated with any known family. For this reason, we can assume that the breakup event that produced these objects, like the one that produced the Agnia and Merxia families, occurred prior to the last dynamical depletion event that shaped the main belt (e.g., [20, 21]). Note that the location of the crust and mantle material associated with these iron cores has long been a mystery [16].

Given this information, we postulate that the largest M-type asteroids and high-calcium S-type asteroids represent the core, mantle, and crust of a putative Vesta-size body that disrupted long ago. If true, some meteorites may be linked to this material (i.e., a few HEDs may not come from Vesta [19]). Because meteorites from central/outer main belt asteroids are unlikely to reach Earth (**Fig. S1**), however, the total number should be small. For this and other reasons, we believe that only a limited number of unique iron meteorites are derived from this source material.

Finally, we point out that unidentified remnants of other differentiated planetesimals may still be found in the inner main belt. At present, 5-color data from the Sloan Digital Sky Survey suggests there are some asteroids in the inner main belt with Vesta-like colors that are unassociated with either (4) Vesta or the Vesta family [22]. These objects are prime candidates for new observations.

3. Could space weathering effects help "hide" a population of small differentiated bodies in the main belt?

Space weathering is thought to be caused by the formation of nanophase iron particles in asteroid regolith, where silicate vapor is deposited on surrounding grains via micrometeorite impact heating and/or solar wind sputtering [23]. This process, while reddening and diminishing the band depths of S-type asteroid spectra, does not significantly affect the spectral features of Vesta-like bodies, whose surface is dominated by pyroxene rather than olivine (and thus has a lower abundance of nanophase metallic iron; [24]). This explains why basaltic material over a vast size range (i.e., Vesta, multi-km members of the Vesta family, km-sized V-type asteroids in the near-Earth asteroid population, HED meteorites) are spectroscopically similar to one another [25]. For this reason, we expect non-Vesta but Vesta-like basaltic material to be similarly unaffected by space weathering (though see **#2** and [19]).

4. Why does the meteorite record contain so few non-Vesta samples of crust/mantle from differentiated asteroids?

The model presented in the main text implies that disrupted differentiated planetesimals from the terrestrial planet region should have injected representative samples of crust, mantle, and core material in the main belt. The meteorite record, however, is deficient in meteorites made of basaltic or olivine-rich material other than those believed to be linked with (4) Vesta and its family [9, 13]. A possible explanation for the missing crustal material could be that it was never there to begin with; basaltic melts on small asteroids may contain enough entrained volatiles that they are readily vented into space by volcanism [26]. This scenario, however, does not explain what happened to the mantle material.

To investigate this apparent shortage, we modeled the evolution of a hypothetical population of olivine (A-type) asteroids in the inner main belt using a code designed to track how comminution and dynamical depletion via the Yarkovsky thermal drag and chaotic resonances affect size-frequency distributions (SFDs) evolving inside the main belt population [27]. **Fig. S2** shows our results. For testing purposes, we chose an extreme example; we assumed these bodies followed a power-law SFD, with the low-D end containing the same number of $D \sim 1$ m bodies as the current main belt and the high-D end set to a diameter twice the size of the largest known A-type asteroid in the inner main belt (i.e., (1126) Otero; $D \sim 12$ km).

Following the evolution of this SFD from 4 Ga to today, we find the population of potential olivine meteoroids drops by ~ 3 orders of magnitude (**Fig. S2**). This occurs because there are not enough large A-type asteroids in the inner main belt to keep the population of meter-sized olivine bodies replenished through a collisional cascade. Instead, the meteoroids are steadily eroded over time by comminution and dynamical depletion. Thus, while olivine-rich A-type asteroids clearly exist in the inner main belt, they are statistically unlikely to produce a significant number of present-day meteorites. The same analysis can be used to explain what happened to the non-Vesta crustal fragments from differentiated asteroids (though see [26]); they too lack a reservoir of large bodies capable of sustaining a large meteoroid flux over several Gy.

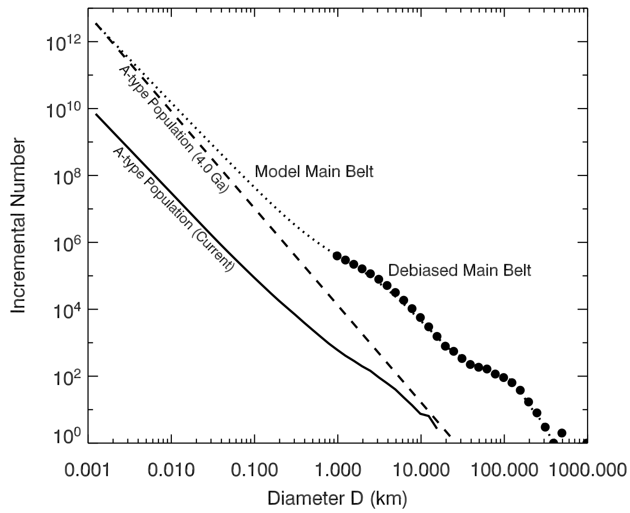

Figure S2: Collisional and dynamical evolution for a hypothetical population of olivine-rich A-type asteroids placed in the inner main asteroid belt. For our initial A-type asteroid population, we chose the largest body to be twice the size of the largest known A-type asteroid in the inner main belt (i.e., (1126) Otero; $D \sim 12$ km), while we set the number of meter-sized objects equal to those in the main belt. The latter, while an exaggeration, is useful for demonstration purposes. Linking the low and high ends, the rest of the population was given a power-law SFD with differential index $q = -3.9$. The solid line shows what happens to the A-type population after 4 Gy of evolution. The population of meteoroids, represented by bodies in the $D \sim 0.001$ km size bin, decreases by ~ 3 orders of magnitude, mainly because there are too few collisions among larger A-type asteroids to keep them replenished. Thus, our "extreme" population is statistically unlikely to produce many meteoroids, consistent with the absence of olivine-rich meteorites in our collection.

5. Could small differentiated asteroids (iron meteorite parent bodies) have formed in the main belt zone and then been eliminated by collisional and dynamical processes?

We argue the answer is 'no'. The accepted view is that iron meteorites come from small differentiated bodies ($D \sim$ 20-200 km) that formed in the main belt early in Solar System history. These bodies were then almost entirely eliminated by (i) dynamical interactions with planetary embryos and sweeping resonances (e.g., [20, 21]) and (ii) main belt collisions (e.g., [13]). Thus, the iron meteorites would be one of the few surviving remnants of this putative population. When this scenario is considered in detail, however, several potential problems come to light:

- Collision evolution models, now calibrated against a wide range of constraints (e.g., the wave-shaped main belt size-frequency distribution, the number and distribution of asteroid families produced by the disruption of $D > 100$ km parent bodies over the last 3-4 Gy, the single $D \sim 400$ km basin observed on asteroid (4) Vesta, the cosmic ray exposure history of stony meteorites, the relatively constant crater production rate of the Earth and Moon over the last 3 Gy), indicate that only a limited fraction of $D \sim$ 20-200 km bodies ever disrupted in the primordial main belt population [17, 18]. These results suggest it would be difficult to eliminate a substantial population of differentiated asteroids without violating numerous constraints (i.e., producing a main belt size-frequency distribution with a shape different than that observed; creating too many asteroid families over the last 4 Gy, etc.).

- Dynamical models of main belt evolution are more successful at eliminating objects than collisions, with $\sim 99.5\%$ of the primordial main belt population ejected prior to or during the so-called Late Heavy Bombardment that occurred ~ 3.9 Gy ago [17, 20, 21, 18]. These model results imply the number of intact differentiated bodies in the primordial main belt was limited to roughly 200 (i.e., 1/0.5%). The problem, however, is that this makes Vesta's survival a remarkable fluke; dynamical removal mechanisms should not have a preference for Vesta over its smaller and more numerous brethren (assuming these bodies follow a reasonable size distribution).

- The paucity of differentiated material in the main belt is discordant with expectations based on planetesimal formation and meteoritical data. Isotopic chronometers indicate that core formation among most iron meteorite parent bodies occurred 1-2 My before the formation of the ordinary chondrite parent bodies [28, 29]. If small bodies differentiated in the main belt at these early times, it is reasonable to expect larger bodies forming near the same locations to have differentiated as well (e.g., [30]). Hence, if iron meteorites are indigenous to the main belt, large numbers of differentiated bodies and their fragments should reside there today. At the least, chondrites and asteroid families should show some signs that their parent bodies were significantly heated or that their parent bodies agglomerated some of these differentiated planetesimals during accretion. None of these conspicuous items has yet been observed. (See main text for additional details: for families, see [31]; for chondrites and other meteorites, see [9, 10, 32, 33]).

6. What are some of the limitations of this model?

The model presented here, while the best that can be done with current planet formation codes, can still be improved. Here we briefly discuss how the inclusion of dynamical friction and gas drag in future planet formation/planetesimal evolution codes might impact our conclusions. We also describe why we do not predict in the main text the fraction of interloper material existing in the current main belt.

Dynamical Friction. Preliminary results by our team using codes that include dynamical friction between planetary embryos and a limited number of smaller bodies suggest: (i) the disruption rate of small differentiated planetesimals in the terrestrial planet zone is somewhat diminished when compared to the results in the main text and (ii) the length of time the fragments have to become trapped in the main belt in increased. Because these two effects roughly balance one another, the overall story presented here should remain the same, albeit with longer timescales. Potential constraints on these timescales may be found in iron meteorite cooling rate data [32, 34].

Gas Drag. The effects of gas drag on our scenario have yet to be modeled. Still, insights gleaned from numerical results and observational data allow us to predict its importance.

- Our model results are consistent with the (limited) degree of semimajor axis mixing observed among large S- and C-type asteroids in the main belt (see main text and [20, 35]). For this reason, we believe the effects of gas drag in the inner Solar System were similarly limited; either it did not significantly affect planetesimal mixing, or the gas went away early enough that planetary embryos still had time to stir the remaining planetesimals before being removed from the inner Solar System.

- Planet formation models invoking strong gas drag models are likely to produce results that are inconsistent with the taxonomic stratification seen among main belt and Hungaria asteroids [35]. For example, if gas drag dominates planetesimal evolution, the main belt should be literally overrun with bodies formed beyond the snowline (e.g., [36]). Asteroids made from this material are much more likely to resemble the primitive C-type asteroids that dominate the outer main belt (analogous to carbonaceous chondrites) than the water-poor and metamorphosed S- and E-type asteroids that dominate the inner main belt and Hungaria regions, respectively (analogous to ordinary and enstitite chondrites).

Thus, main belt observations not only place strong constraints on the effects of gas drag in the inner Solar System, but they also suggest that leaving gas drag out of our model runs may not significantly impact our conclusions.

Other Model Limitations. A common question asked about our model results is why we do not estimate the fraction of interloper material existing in the current main belt. This calculation, while admittedly important, is difficult to do correctly; it requires the construction of a coupled collisional and dynamical simulation capable of tracking individual planetesimals and their fragments as they experience both comminution and interactions with planetary embryos. There is also the issue of constraining such a model when we have yet to attain a thorough understanding of the physical and spectroscopic properties of smaller main belt asteroids. For these reasons, we leave this critical but computationally expensive problem for future work.

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