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LETTERS

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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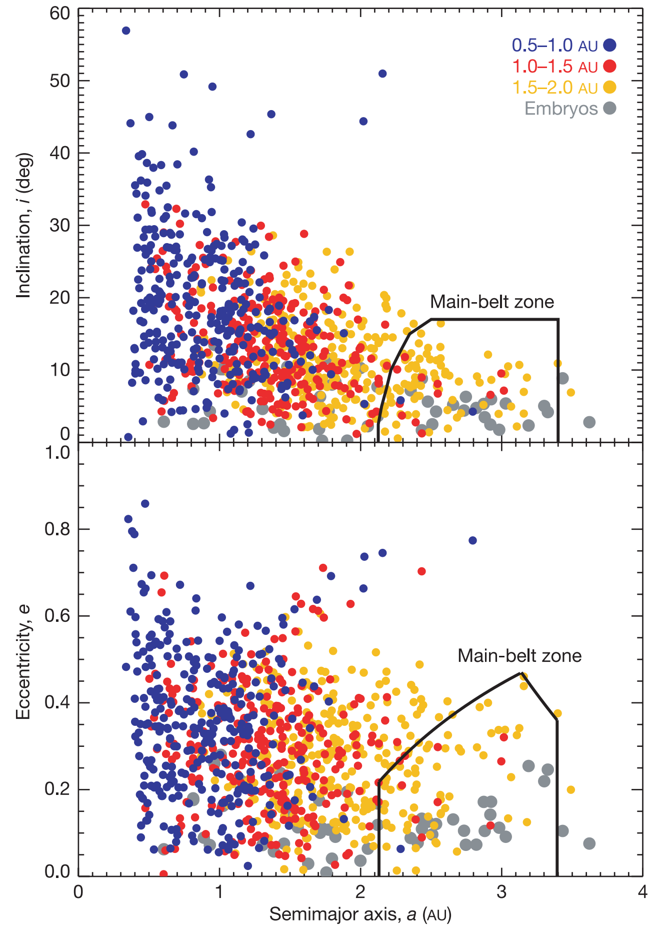

Figure 1 | A snapshot of inner Solar System planetesimals and planetary embryos after 10 Myr of dynamical evolution. The starting conditions and methods used were the same as in ref. 11. We assumed that the jovian planets, if they existed, had a negligible effect on the early dynamical history of these 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.

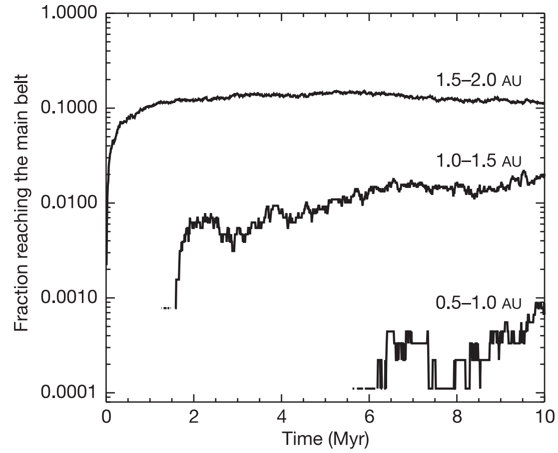

Figure 2 | The fraction of inner Solar System planetesimals scattered into the main-belt zone by gravitational interactions with planetary embryos. Computational details are given in Fig.1. The curves were generated by tracking 17,000 test bodies for 10 Myr across four planetary embryo simulations. To 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

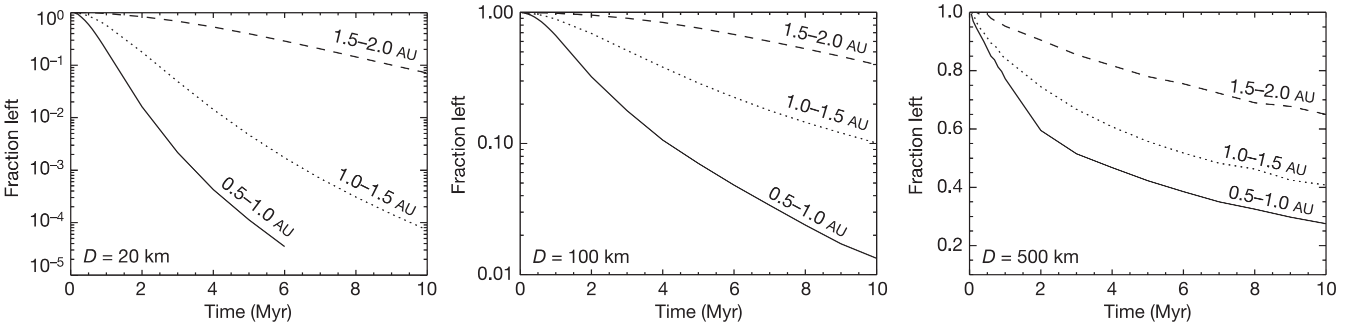

Figure 3 | The fraction of inner Solar System planetesimals that survive the first 10 Myr of collisional evolution. **Using an established code[26,27], we computed how various-input size frequency distributions (SFDs) started at 0.5–1.0 AU, 1.0–1.5 AU, and 1.5–2.0 AU undergo comminution as a function 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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