LETTERS

Iron meteorite evidence for early formation and catastrophic disruption of protoplanets

Jijin Yang[1], Joseph I. Goldstein[1] & Edward R. D. Scott[2]

In our Solar System, the planets formed by collisional growth from smaller bodies. Planetesimals collided to form Moon-to-Mars-sized protoplanets in the inner Solar System in 0.1–1 Myr, and these collided more energetically to form planets[1]. Insights into the timing and nature of collisions during planetary accretion can be gained from meteorite studies. In particular, iron meteorites offer the best constraints on early stages of planetary accretion because most are remnants of the oldest bodies, which accreted and melted in <1.5 Myr, forming silicate mantles and iron-nickel metallic cores[2–4]. Cooling rates for various groups of iron meteorites suggest that if the irons cooled isothermally in the cores of differentiated bodies, as conventionally assumed, these bodies were 5–200 km in diameter[5,6]. This picture is incompatible, however, with the diverse cooling rates observed within certain groups, most notably the IVA group[7,8], but the large uncertainties associated with the measurements do not preclude it. Here we report cooling rates for group IVA iron meteorites that range from 100 to 6,000 K Myr^{-1}, increasing with decreasing bulk Ni. Improvements in the cooling rate model, smaller error bars, and new data from an independent cooling rate indicator[9] show that the conventional interpretation is no longer viable. Our results require that the IVA meteorites cooled in a 300-km-diameter metallic body that lacked an insulating mantle. This body probably formed ~4,500 Myr ago in a 'hit-and-run' collision between Moon-to-Mars-sized protoplanets[10]. This demonstrates that protoplanets of ~10^3 km size accreted within the first 1.5 Myr, as proposed by theory, and that fragments of these bodies survived as asteroids.

We investigated the group IVA iron meteorites, which come from a single asteroid[5,6], because they present the biggest challenge to existing formation models for iron meteorites. Studies of the formation of the Widmanstätten pattern—the microstructure in which kamacite forms on the close-packed planes of the parent taenite at high temperatures—have concluded that cooling rates for the group IVA iron meteorites decrease by a factor of 10–100 with increasing bulk Ni concentration[7,8], although samples from a mantled core should have indistinguishable cooling rates[11]. In addition, two IVA members contain abundant silicates, which should have floated out of a mantled core before it crystallized. If the observed correlation between cooling rate and Ni concentration is not an artefact of poor sampling (see ref. 12), either the cooling rates (often called metallographic cooling rates) are flawed[5,13], or there is an essential feature in the genesis of IVA iron meteorites ('irons') that has not yet been recognized.

We first determined the cooling rates at 1,000–700 K for ten IVA irons using recent models for nucleation and growth of the Widmanstätten kamacite[14] (see Methods). These range from 100 to 6,600 K Myr^{-1} and decrease monotonically with bulk Ni, as previously reported[7,8], but exceed previous estimates (see Fig. 1, Table 1). Next, we investigated the cloudy zone microstructure at the periphery of lamellae of taenite in seven unreheated and low-shock IVA irons using a transmission electron microscope (TEM) (see Fig. 2), as the dimensions of these microstructures depend on cooling rate at 600–500 K. The apparent absence of any systematic variation of the dimensions of the cloudy zone microstructure with Ni for six IVA irons[9] was interpreted as evidence that the diverse cooling rates determined by the metallographic cooling rate method were flawed[5,13]. We found, however, that the sizes of high-Ni particles in the cloudy zones of IVA irons range from 10 to 29 nm, increasing in size with increasing bulk Ni (Fig. 1, Table 1). As the particle dimensions and metallographic cooling rates are inversely related (Fig. 3), these data are consistent with the cooling rate variation in IVA irons inferred from the Widmanstätten pattern. Although cooling rates cannot be derived directly from cloudy taenite particle sizes because there is no effective model available for spinodal growth, the relative cooling

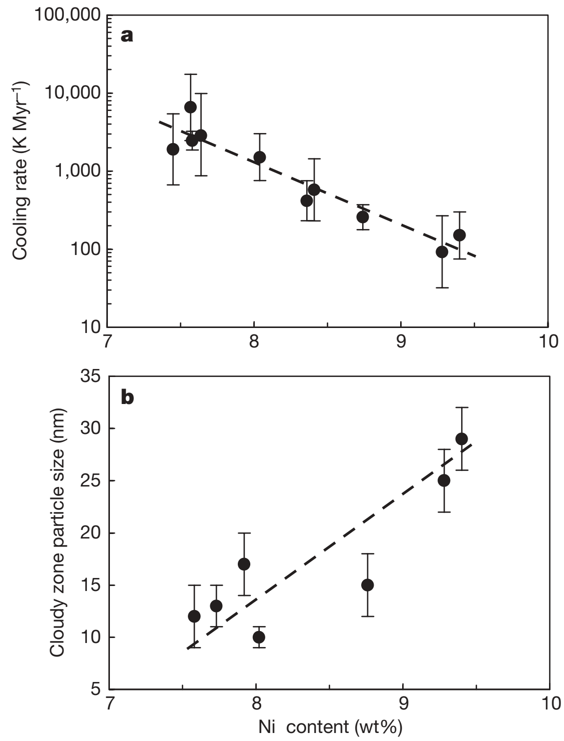

Figure 1 | Dependence of cooling rate and cloudy zone particle size of IVA irons on the bulk meteorite composition. Metallographic cooling rates at 1,000–700 K inferred from kamacite growth modelling (**a**) and the size of cloudy zone particles of low-shock irons (**b**) are plotted as a function of bulk Ni concentration. Error bars: **a**, 2σ uncertainty factors; **b**, $\pm$1 s.e.m. (see Table 1).

[1]Department of Mechanical and Industrial Engineering, University of Massachusetts, Amherst, Massachusetts 01003, USA. [2]Hawaii Institute of Geophysics and Planetology, University of Hawaii at Manoa, Honolulu, Hawaii 96822, USA.

Table 1 | Measured and calculated properties of IVA iron meteorites

Meteorite	Ni* (wt%)	Cooling rate ($K\,Myr^{-1}$)	2σ uncertainty factor†	Shock level (GPa)	Size of CZ particle‡ (nm)
Obernkirchen	7.64	2,900	3.3	40§	
Jamestown	7.45	1,900	2.8	13–40§	
La Grange	7.57	6,600	2.6	13–75§	
Bishop Canyon	7.58	2,500	1.3	<13‖	12 ± 3
San Francisco Mountains	7.73			<13‖	13 ± 2
Bristol	7.92			<13‖	17 ± 3
São João Nepomuceno	8.02			<13‖	10 ± 1
Gibeon	8.04	1,500	2.0	>13‖	
Seneca Township	8.41	580	2.5	13–75§	
Altonah	8.36	420	1.8	13–75§	
Bushman Land	8.76	260	1.4	<13‖	15 ± 3
Steinbach	9.40	150	2.0	<13‖	29 ± 3
Duchesne	9.28	100	2.9	<13§	25 ± 3

* Ref. 13.
† The 2σ uncertainty factors for the cooling rates of individual irons, which range from 1.3 to 3.3, represent a combination of measurement errors and possible errors due to the basic assumptions of the computer model[14], such as chemical homogeneity and uncertainties in the kamacite nucleation temperature. Uncertainties at the 2σ level for the cooling rates of individual irons are 10–20 times smaller than the total range observed within the IVA group.
‡ Data show mean of 4–10 measurements ±1 s.e.m. CZ, cloudy zone.
§ Ref. 29.
‖ Shock level estimated using optical microscopy and SEM.

rates of two meteorites, (CR_1) and (CR_2), can be estimated from the ratio of their respective high-Ni particle sizes (PS_2/PS_1), namely: $(CR_1/CR_2) = (PS_2/PS_1)^n$. The parameter n obtained from Fig. 3 equals 2.4 ± 0.4. Given the threefold variation in IVA particle size (2.9 ± 0.5; Table 1), we estimate that cooling rates at 600–500 K varied by a factor of ~15, decreasing with increasing bulk Ni.

Our data for cloudy zone microstructures in IVA irons are more accurate than previously published data[9]. We used a TEM to directly image the cloudy zone, whereas the earlier study used a scanning electron microscope (SEM) and samples that had been etched to make the cloudy zone visible[9]. In addition, we measured IVA irons that experienced only low shock, <13 GPa, whereas the previous study used some samples that were heavily shocked or showed signs of plastic deformation. Six of the ten IVA irons selected for cooling rate analysis of their Widmanstätten patterns experienced shock pressures >13 GPa and were not used in this study because their cloudy zones were damaged or obliterated. However, shock heating only caused compositional changes at the submicrometre level and did not affect compositions at the micrometre level that were used to derive the cooling rates in Table 1.

Our results from two different techniques show that cooling rates of IVA irons decrease with increasing Ni (7.45–9.4 wt%) by factors of ~50 and ~15 at 1,000–700 K and 600–500 K, respectively (Fig. 1), and cannot be explained by cooling in a mantled core, or by poor sampling of a disrupted and reassembled core[12]. The cooling rates of low-Ni IVA irons at 1,000–700 K are also incompatible with conventional models for asteroidal melting by ^{26}Al. To cool a mantled core at $3,000\,K\,Myr^{-1}$ would require a body only 4 km in radius, according to thermal models of differentiated asteroids[11]. However, bodies <20 km radius would not have been melted sufficiently by ^{26}Al to form a core[4]. We infer that IVA irons could not have cooled in a mantle-insulated core.

The only plausible solution to the IVA cooling rate enigma is that a metallic body with virtually no silicate mantle was formed by an early catastrophic disruption of a differentiated body and cooled in space so that it had a significant thermal gradient when kamacite nucleated at ~1,000 K. We have tested this concept with thermal modelling of cooling metallic bodies. Figure 4 shows how cooling rate varies with decreasing temperature at different distances from the centre of a metallic body with radius $R = 150$ km, assuming an initial temperature of 1,750 K. The range of cooling rates of samples between $0.4R$ and $0.97R$ decreases from a factor of ~50 during Widmanstätten

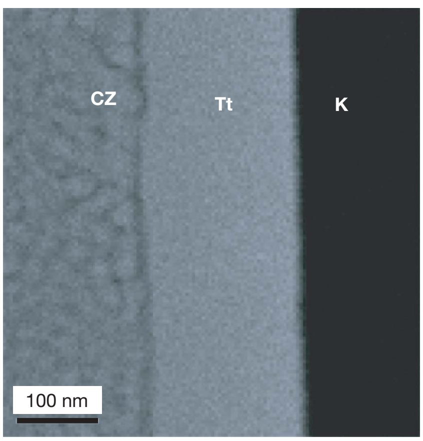

Figure 2 | Microstructure of the cloudy zone in the Steinbach IVA iron. The Ni X-ray map reveals three zones (CZ, cloudy zone; Tt, tetrataenite; K, kamacite). The cloudy zone consists of high-Ni nanoscale particles (light grey), ~50 wt% Ni, that are surrounded by regions of low-Ni phase (dark grey). The size of the high-Ni nanoscale particles in meteorites correlates inversely with cooling rate (Fig. 3). Scale bar, 100 nm.

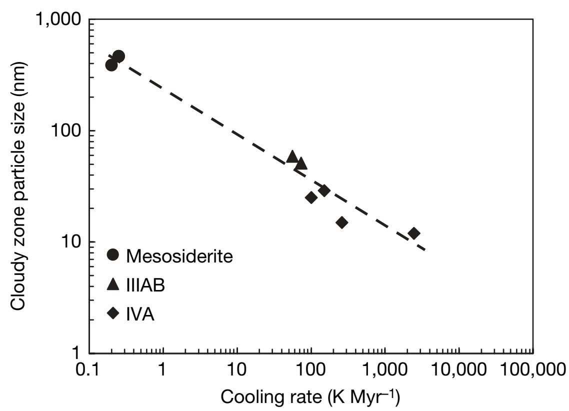

Figure 3 | Variation of the size of the cloudy zone particles in individual mesosiderites and iron meteorites with metallographic cooling rate. This updated plot, unlike the previous plot[9], shows cloudy zone particle sizes for IVA irons that are entirely consistent with the overall trend shown by iron and stony-iron meteorites. Thus, our new cloudy taenite data for IVA irons support the metallographic cooling rate variation within group IVA. Cooling rates are from ref. 30 (mesosiderites), ref. 14 (IIIAB irons) and Table 1 (IVA irons); cloudy zone particle sizes are from ref. 9 (mesosiderites and IIIAB irons) and this study (IVA irons).

growth at 1,000–700 K to a factor of ~15 when cloudy taenite forms at 600–500 K. As these values and the actual cooling rates at 1,000–700 K are very close to those observed for the IVA irons, we conclude that the IVA irons cooled in a metallic body of radius 150 km, and not in an insulated core 3–5 km in radius as previously inferred[6]. Given the inferred 2σ uncertainties in these cooling rates and the likelihood that the IVA irons are reasonably representative of the IVA body[15], the thermal models suggest that the uncertainty in the radius is ~50 km. This metallic body would have been comparable in size to the largest M class asteroid, 6 Psyche. A corollary of this model is that the metallic body crystallized inwards[16] not outwards[5], so that low-Ni irons crystallized on the outside.

We cannot infer from the thermal models whether the metal was initially solid at 1,000–1,300 K or very largely molten above ~1,750 K, as the thermal model is not very sensitive to the initial temperature (see Methods). However, two features suggest that it was initially largely molten. The presence of silicates in five IVA irons has been attributed to a major impact involving silicate melt[12,17]. If the metallic body was initially molten after the impact, the silicates may have been trapped in the metal when it started to crystallize inwards. The extremely low levels of moderately volatile siderophiles in IVA irons (Ge/Ni ratios are 0.01–0.001 times chondritic values) may also result from melting and vaporization during impact[5]. However, the colliding bodies were more likely to have been protoplanets, as proposed for the Moon and Vesta[18], rather than asteroids[5], as the former would have been more efficient at vaporizing metal. These features also suggest that the impact that formed the IVA metallic body occurred before the IVA irons crystallized, ~4,500 Myr ago[6].

Many other meteorite groups have thermal histories that are incompatible with igneous differentiation and cooling in isolated bodies, and require impact disruption at high temperatures. For example, three kinds of silicate-rich, differentiated meteorites have anomalous thermal histories requiring early disruption of molten or partly molten parent bodies: ureilites, mesosiderites and the Shallowater aubrite[19]. In addition, group IIAB, IIIAB and IVB irons have cooling rates that vary by factors of 6–12 (refs 14, 20, 21), which exceed the uncertainties in the cooling rate of individual irons. We infer that the parent bodies of the IIAB, IIIAB and IVB iron meteorites were much larger than previously inferred and cooled with little or no mantle, and that these irons did not cool isothermally inside silicate mantles as widely believed[6,21].

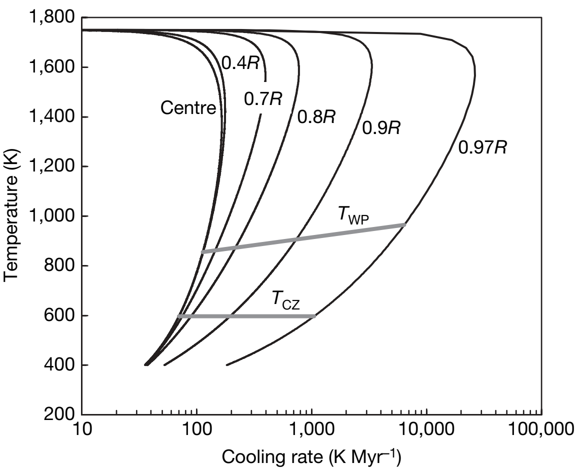

Figure 4 | Variation with radial location and temperature of the cooling rates inside a 150-km-radius solid metallic body exposed to space. We assume that the body was initially at 1,750 K and had a surface temperature of 200 K. T_{WP} and T_{CZ} indicate the respective temperatures at which the Widmanstätten pattern and the cloudy zone began to form. The T_{WP} line is drawn for the IVA irons using the relationship between bulk Ni and cooling rate shown in Fig. 1a.

If the initial mass of the asteroid belt was only a few times the current mass[22], impacts capable of forming a 150-km-radius metallic body would have been exceptionally rare. However, if the initial mass was ~10^3 times higher and many Moon-sized or larger protoplanets were present[23,24], collision rates would have been greatly enhanced while the differentiated bodies were still hot. As mantles are not efficiently stripped from cores by catastrophic impacts between asteroid-sized bodies[25], the IVA metallic body may have formed as a result of a grazing collision between protoplanets that disrupted the core of a Moon-sized body creating a string of metal-rich bodies, or possibly by tidal disruption alone during a close approach[10]. Opportunities for such collisions would have also have been enhanced if the parent bodies of the irons formed inside 2 AU from the Sun[26].

Given the Hf–W chronological constraints on the origin of iron meteorites and refractory inclusions in chondrites[2,3], we infer that protoplanets with diameters of 10^3 km accreted <1.5 Myr after Solar System formation, as dynamicists suggest[1], and that some were disrupted[10] long before the impacts that exposed the iron meteorites to cosmic rays <1,000 Myr ago. Our study provides the first evidence that fully differentiated bodies were destroyed very early, which is probably an essential factor in understanding the distribution of differentiated asteroids and the rarity of olivine-rich asteroids and meteorites[26].

METHODS

Cooling rate based on the Widmanstätten structure. The Wood method[27] was used to determine the cooling rate by plotting the Ni concentration in the centre of taenite (face-centred cubic Fe-Ni) lamellae—measured using a Cameca SX-50 electron probe microanalyser—against the orientation-corrected taenite half-width measured on the sample surface[14]. A cooling rate code[14] was applied to simulate the diffusion-controlled growth of kamacite (body-centred cubic Fe-Ni) from taenite. The required bulk concentrations of Ni of the meteorites are given in Table 1 and those of P in the Supplementary Table. We also evaluated concerns that the correlation between cooling rate and bulk Ni concentration is an artefact resulting from the use of incorrect nucleation mechanisms or other errors[5,13] (see Supplementary Notes).

Particle size in cloudy zone structure. Techniques used to measure the dimensions of high-Ni particles in IVA cloudy zones are especially critical at the 10 nm level. If etching is used to reveal the microstructure[9], this can affect the apparent size of the microstructure even in a high-resolution SEM. We prepared thin sections of kamacite–taenite interfaces without etching using a dual-beam FEI DB-235 focused ion beam instrument, and examined them in a FEI Tecnai F30ST field emission TEM operated at 300 kV. The dimensions of the high-Ni particles in seven IVA irons that experienced low shock pressure (<13 GPa) and revealed undamaged cloudy zone microstructure were measured (Fig. 1b, Table 1).

Relative cooling rates inferred from the dimensions of cloudy zone microstructures are not a function of the nucleation temperature of the Widmanstätten pattern, as the cloudy zone forms via a spinodal reaction[9]. The spinodal decomposition in meteoritic Fe-Ni metals is a diffusion-controlled reaction, which depends on the cooling rate and composition. For the IVA irons, taenite is P saturated when spinodal decomposition occurs (<600 K) so that the diffusion coefficient of Ni in taenite is the same irrespective of the initial bulk Ni and P content of the IVA meteorite.

Thermal model of an exposed metallic body. As the thermal gradient in a liquid metallic body will be very small until the metal solidifies, we assumed that a spherical solid isothermal Fe-Ni metallic body covered by virtually no silicate mantle at 1,750 K was exposed to space at 200 K following an impact. We used the thermal conductive equation[11] assuming that no heat was generated in the metal during cooling. The Crank-Nicolson approximation and the tridiagonal matrix algorithm[28] were used to describe the partial differential equation for conduction cooling and to solve the difference equation. The physical properties of metal and silicate are from ref. 11.

Our calculations show that the cooling rates at the relevant temperature range (1,000–500 K) for a 150-km-radius metallic body were insensitive to the surface temperature below a plausible maximum of ~300 K, and to the assumed initial temperature over the range 1,750–1,000 K. For example, for an initial temperature of 1,300 K, the range of cooling rates during kamacite growth (1,000–700 K) from <0.4R to 0.96R, where R is the radius of the body, is comparable to the metallographic cooling rates of IVA irons (Table 1). If the initial temperature is 1,750 K (Fig. 4), the corresponding depth range for the IVA irons becomes <0.4R to 0.97R. We use a solid body for convenience in thermal modelling, as the cooling rates at 1,000–500 K are also insensitive to the physical condition of the metal immediately after exposure of the metallic body to space, as long as the temperature was >1,000 K.

The effect of radiation from the surface of a 150-km body was also calculated. Heat was effectively radiated away from the surface of the body, so that the surface temperature decreased from 1,750 K to <300 K in only 100 yr. At depths >3 km below the surface, there was no difference between a model that included radiation and a model that assumed a fixed surface temperature of 200 K.

We also calculated the effect of silicate mantle material on the outside of a cooling metallic body of radius 150 km. If the mantle layer is >1 km thick, the cooling rate range across the metallic body is reduced and the thermal model cannot reproduce the fast cooling rates of low-Ni IVA irons near the surface (Fig. 4). A thin silicate mantle could form as a result of late accretion of silicate, incomplete removal, or incomplete separation of silicate that was mixed into molten metal by the impact.

Received 15 September 2006; accepted 26 February 2007.

1. Chambers, J. E. Planetary accretion in the inner Solar System. *Earth Planet. Sci. Lett.* **223**, 241–252 (2004).
2. Kleine, T., Mezger, K., Palme, H., Scherer, E. & Münker, C. Early core formation in asteroids and late accretion of chondrite parent bodies: Evidence from ^{182}Hf-^{182}W in CAIs, metal-rich chondrites, and iron meteorites. *Geochim. Cosmochim. Acta* **69**, 5805–5818 (2005).
3. Scherstén, A., Elliott, T., Hawkesworth, C., Russell, S. & Masarik, J. Hf-W evidence for rapid differentiation of iron meteorite parent bodies. *Earth Planet. Sci. Lett.* **241**, 530–542 (2006).
4. Hevey, P. J. & Sanders, I. S. A model for planetesimal meltdown by ^{26}Al, and its implications for meteorite parent bodies. *Meteorit. Planet. Sci.* **41**, 95–106 (2006).
5. Wasson, J. T., Matsunami, Y. & Rubin, A. E. Silica and pyroxene in IVA irons; possible formation of the IVA magma by impact melting and reduction of L–LL-chondrite materials followed by crystallization and cooling. *Geochim. Cosmochim. Acta* **70**, 3149–3172 (2006).
6. Chabot, N. L. & Haack, H. in *Meteorites and the Early Solar System II* (eds Lauretta, D. S. & McSween, H. Y.) 747–771 (Univ. Arizona Press, Tucson, 2006).
7. Moren, A. E. & Goldstein, J. I. Cooling rates of group IVA iron meteorites determined from a ternary Fe-Ni-P model. *Earth Planet. Sci. Lett.* **43**, 82–96 (1979).
8. Rasmussen, K. L., Ulff-Moller, F. & Haack, H. The thermal evolution of IVA iron meteorites: Evidence from metallographic cooling rates. *Geochim. Cosmochim. Acta* **59**, 3049–3059 (1995).
9. Yang, C.-W., Williams, D. B. & Goldstein, J. I. A new empirical cooling rate indicator for meteorites based on the size of the cloudy zone of the metallic phase. *Meteorit. Planet. Sci.* **32**, 423–429 (1997).
10. Asphaug, E., Agnor, C. B. & Williams, Q. Hit-and-run planetary collisions. *Nature* **439**, 155–160 (2006).
11. Haack, H., Rasmussen, K. L. & Warren, P. H. Effects of regolith/megaregolith insulation on the cooling histories of differentiated asteroids. *J. Geophys. Res.* **95**, 5111–5124 (1990).
12. Haack, H., Scott, E. R. D., Love, S. G., Brearley, A. J. & McCoy, T. J. Thermal histories of IVA stony-iron and iron meteorites: Evidence for asteroid fragmentation and reaccretion. *Geochim. Cosmochim. Acta* **60**, 3103–3113 (1996).
13. Wasson, J. T. & Richardson, J. W. Fractionation trends among IVA iron meteorites: contrast with IIIAB trends. *Geochim. Cosmochim. Acta* **65**, 951–970 (2001).
14. Yang, J. & Goldstein, J. I. Metallographic cooling rates of the IIIAB iron meteorites. *Geochim. Cosmochim. Acta* **70**, 3197–3215 (2006).
15. Scott, E. R. D., Haack, H. & McCoy, T. J. Core crystallization and silicate-metal mixing in the parent body of the IVA iron and stony-iron meteorites. *Geochim. Cosmochim. Acta* **60**, 1615–1631 (1996).
16. Haack, H. & Scott, E. R. D. 1992. Asteroid core crystallization by inward dendritic growth. *J. Geophys. Res.* **97**, 14727–14734 (1992).
17. Ruzicka, A. & Hutson, M. Differentiation and evolution of the IVA meteorite parent body: clues from pyroxene geochemistry in the Steinbach stony-iron meteorite. *Meteorit. Planet. Sci.* **41**, 1959–1987 (2006).
18. Halliday, A. N. & Kleine, T. in *Meteorites and the Early Solar System II* (eds Lauretta, D. S. & McSween, H. Y.) 775–801 (Univ. Arizona Press, Tucson, 2006).
19. Keil, K., Haack, H. & Scott, E. R. D. Catastrophic fragmentation of asteroids: evidence from meteorites. *Planet. Space Sci.* **42**, 1109–1122 (1994).
20. Randich, E. & Goldstein, J. I. Cooling rates of seven hexahedrites. *Geochim. Cosmochim. Acta* **42**, 221–233 (1978).
21. Rasmussen, K. L. Cooling rates and parent bodies of iron meteorites from group IIICD, IAB, and IVB. *Phys. Scripta* **39**, 410–416 (1989).
22. Davis, D. R., Durda, D. D., Marzari, F., Bagatin, A. C. & Gil-Hutton, R. G. in *Asteroids III* (eds Bottke, W. F., Cellino, A., Paolicchi, P. & Binzel, R. P.) 545–558 (Univ. Arizona Press, Tucson, 2002).
23. Petit, J.-M., Chambers, J., Franklin, F. & Nagasawa, M. in *Asteroids III* (eds Bottke, W. F., Cellino, A., Paolicchi, P. & Binzel, R. P.) 711–723 (Univ. Arizona Press, Tucson, 2002).
24. Bottke, W. F. *et al.* Linking the collisional history of the main asteroid belt to its dynamical extinction and depletion. *Icarus* **179**, 63–94 (2005).
25. Scott, E. R. D., Haack, H. & Love, S. G. Formation of mesosiderites by fragmentation and reaccretion of a large differentiated asteroid. *Meteorit. Planet. Sci.* **36**, 869–881 (2001).
26. Bottke, W. F., Nesvorny, D., Grimm, R. E., Morbidelli, A. & O'Brien, D. P. Iron meteorites as remnants of planetesimals formed in the terrestrial planet region. *Nature* **439**, 821–824 (2006).
27. Wood, J. A. The cooling rates and parent bodies of several iron meteorites. *Icarus* **3**, 429–459 (1964).
28. Von Rosenberg, D. U. *Methods for the Numerical Solution of Partial Differential Equations* (American Elsevier Publishing Company, New York, 1969).
29. Jain, A. V. & Lipschutz, M. E. On preferred disorder and shock history of chemical group IVA meteorites. *Geochim. Cosmochim. Acta* **34**, 883–892 (1970).
30. Hopfe, W. D. & Goldstein, J. I. The metallographic cooling rate method revised: Application to iron meteorites and mesosiderites. *Meteorit. Planet. Sci.* **36**, 135–154 (2001).

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

Acknowledgements Financial support from the NASA Cosmochemistry programme is acknowledged. We thank T. J. McCoy, L. Welzenbach, D. S. Ebel and J. Boesenberg for providing the meteorite samples; M. J. Jercinovic, J. R. Michael and P. Kotula for assistance and advice in obtaining electron microprobe and microscopy data; G. J. Taylor, E. Asphaug, W. F. Bottke and A. Ruzicka for discussions; and H. Haack, J. T. Wasson and J. A. Wood for critically reading the manuscript.

Author Contributions J.Y., J.I.G. and E.R.D.S. contributed equally to this work. J.Y. determined the metallographic cooling rates and established the thermal model. J.I.G. measured the cloudy zone particle size. E.R.D.S. provided the planetary science perspective. All authors discussed the results, wrote portions of the paper and commented on the manuscript.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Correspondence and requests for materials should be addressed to J.Y. (jiyang@ecs.umass.edu).