Origin of igneous meteorites and differentiated asteroids

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Introduction: Igneously formed meteorites and asteroids provide major challenges to our understanding of the formation and evolution of the asteroid belt. The numbers and types of differentiated meteorites and non-chondritic asteroids appear to be incompatible with an origin by fragmentation of numerous Vesta-like bodies by hypervelocity impacts in the asteroid belt over 4 Gyr. We lack asteroids and achondrites from the olivine-rich mantles of the parent bodies of the 12 groups of iron meteorites and the ~ 70 ungrouped irons, the 2 groups of pallasites and the 4–6 ungrouped pallasites. We lack mantle and core samples from the parent asteroids of the basaltic achondrites that do not come from Vesta, viz., angrites and the ungrouped eucrites like NWA 011 and Ibitira. How could core samples have been extracted from numerous differentiated bodies when Vesta's basaltic crust was preserved? Where is the missing Psyche family of differentiated asteroids including the complementary mantle and crustal asteroids [1]? Why are meteorites derived from far more differentiated parent bodies than chondritic parent bodies even though C and S class chondritic asteroids dominate the asteroid belt?

New paradigm. Our studies of meteorites, impact modeling, and dynamical studies suggest a new paradigm in which differentiated asteroids accreted at 1–2 au less than 2 Myr after CAI formation [2]. They were rapidly melted by 26Al and disrupted by hit-and-run impacts [3] while still molten or semi-molten when planetary embryos were accreting. Metallic Fe-Ni bodies derived from core material cooled rapidly with little or no silicate insulation less than 4 Myr after CAI formation [4]. Fragments of differentiated planetesimals were subsequently tossed into the asteroid belt.

Meteorite evidence for early disruption of differentiated asteroids. If iron meteorites were samples of Fe-Ni cores of bodies that cooled slowly inside silicate mantles over $\sim$50–100 Myr, irons from each core would have almost indistinguishable cooling rates as thermal gradients across cores would have been minimal. Irons in groups IIIAB, IVA, and IVB have chemical crystallization trends showing that they cooled in three separate bodies. However, each shows a wide range of cooling rates [4]. Group IVA irons cooled through 500°C at 6600–100 °C/Myr in a metallic body of radius 150 ± 50 km with scarcely any silicate insulation [5]. The Pb-Pb age of 4565.3 ± 0.1 Myr for a IVA iron [6] confirms that these irons cooled to $\sim$300°C only 2–3 Myr after CAI formation. Multiple hit-and-run impacts may have separated core and mantle material during accretion [7] as hypervelocity impacts do not efficiently separate cores from mantles. Thermal histories and magnetic properties of main group pallasites also require early catastrophic disruption of their primary parent body [8,9].

Conclusions. The anomalous properties of differentiated asteroids and meteorites cannot be explained by concealing differentiated planetesimals under chondritic crusts [10] as meteorite breccias and the apparent compositional homogeneity of asteroid families are inconsistent with this model. Like Burbine et al. [11], we attribute the lack of olivine mantle meteorites and asteroids to collisional grinding of weaker silicate and the preferential survival of stronger metallic Fe,Ni fragments. But we infer that asteroid break up occurred very early inside 2 au, not in the asteroid belt over 4 Gyr. Vesta may have preserved its crust due to early ejection into the asteroid belt. It is the smallest terrestrial planet — not an archetypal differentiated asteroid.

References: [1] Davis D. R. et al. (1999) Icarus 137, 140. [2] Bottke W. F. et al. (2006) Nature 439, 821. [3] Asphaug E. et al. (2006) Nature 439, 155. [4] Goldstein J. I. et al. (2009) Chem. Erde 69, 293. [5] Yang J. et al. (2008) Geochim. Cosmochim. Acta 72, 3043. [6] Blichert-Toft J. et al. (2010) Earth Planet. Sci. Lett. 296, 469. [7] Asphaug E. et al. (2011) Earth Planet. Sci. Lett. 308, 369. [8] Yang J. et al. (2010) Geochim. Cosmochim. Acta 74, 4471–4492. [9] Tarduno J. A. et al. (2012) Science 338, 939. [10] Weiss B. P. and Elkins-Tanton L. (2013) Ann. Rev. Earth Planet. Sci. 41, 529. [11] Burbine T. H. et al. (1996) Meteorit. Planet. Sci. 31, 607–620.