FRAGMENTATION AND REACCRETION OF DIFFERENTIATED ASTEROIDS: EVIDENCE FROM THERMAL HISTORIES OF METEORITES AND THEORETICAL CONSTRAINTS; Edward R. D. Scott[1], Stanley G. Love[1], and Henning Haack[2]; [1]Hawaii Institute of Geophysics and Planetology, SOEST, University of Hawaii, Honolulu, HI 96821; [2]Dept. of Physics, Odense University, DK-5230 Odense M, Denmark.

Abstract: For asteroids with diameters of 50-500 km, there are significant ranges of specific impact energies which will cause asteroids to be fragmented and reaccreted with scrambled interiors. Scrambling requires that specific impact energies must be ~1/2 the asteroid's gravitational binding energy with flight times around 2 hours. For asteroids >500 km in size (e.g., Vesta), fragmentation and reaccretion events are less likely to scramble asteroid interiors. Thermal histories of the IVA irons and stony irons appear to be broadly consistent with these constraints. Fragmentation and reaccretion occurred when the IVA core was at 1200°C and the asteroid had a mean temperature of 400-700°C. Other fully differentiated asteroids with sizes of 50-500 km may also have been scrambled by impacts to make S asteroids.

Introduction: Theoretical studies of asteroid collisions indicate that for a wide range of impact energies, collisions can disrupt asteroids without imparting sufficient velocities to most of the fragments to overcome their mutual gravitational attraction. Hartmann [1] discusses collisions of similar-sized asteroids, and Greenberg et al [2] consider low-velocity impacts during accretion. Disruption and reaccretion events have been invoked for ordinary chondrites [3, 4] and the Shallowater enstatite achondrite [5]. Here we investigate how the plausibility of fragmentation and reaccretion events depends on impact energy and target size and what factors control the thermal histories of fragments of hot bodies; we use these results to investigate the IVA iron meteorites.

Theoretical constraints. The specific energy required for catastrophic impact disruption of rocklike targets at laboratory size scales (~ 10 cm) is about 1000 J/kg [1, 9-12]. "Catastrophic disruption" means that the target is completely broken up, and the mass of the largest fragment is < 1/2 the mass of the original target. Asteroidal iron may have a higher disruption threshold than stone, but if asteroid cores form by dendritic crystallization [13] they should contain weak sulfide veins, along which fracturing would occur preferentially. Sulfide veins in a still-hot asteroid core may be liquid and effectively strengthless, but also better able to dissipate shock energy than solid material. Given these uncertainties, we assume that the disruption energy of asteroidal iron is equal to that of stone, accepting that the results thus obtained are not exact. Also we neglect the effect of absolute size scale on fragmentation: depending on the assumed scaling laws, the specific disruption energy of a km-scale or larger body may be the same as that of a cm-scale laboratory target, or it may be more than an order of magnitude lower (e.g., [10]). Given the current state of uncertainty on this issue, we retain the former, simpler model.

Collisional breakup requires not only enough energy to shatter the target, but also enough additional energy to disperse the fragments against their mutual gravitational attraction: $E_{grav}=-3GM^2/5R$, where M is the mass of the body and R is its radius. Figure 1 shows the specific energy necessary to *fragment* and to *fragment and disperse* asteroids of various diameters, assuming a density of 3.5 g/cm^3. At sizes less than ~ 50 km, the specific energy must fall into an implausibly narrow range in order to shatter the asteroid while still allowing its fragments to reassemble. Breakup and reassembly events are more likely for larger asteroids. Use of a size-dependent model [10] would lower this size limit by a factor of ~ 3 for every factor of 10 drop in the disruption threshold energy. To scramble the asteroid interior, an impact must be capable of launching rocks at least halfway around the body, and onto a large enough variety of trajectories such that surface rocks can reaccrete with core materials. Satisfying both criteria requires typical launch speeds on the order of the circular orbit speed at the surface of the asteroid (with ~ 2 hour flight times), and an impact energy ~ 1/2 the asteroid's gravitational binding energy (Fig. 1).

Fragments of an initially hot asteroid that is shattered and reassembled might cool through two mechanisms: radiative cooling of rocks suddenly exposed to cold space, and conductive redistribution of thermal energy between fragments of different temperatures "stirred" together in the debris cloud and reaccreted side by side. Catastrophic disruption of rocks generates much dust, which may restrict radiative heat loss to cold space though allowing some thermal equilibration of debris. Subsequent conductive equilibration of asteroid fragments stirred together from different depths would generate ubiquitous anomalies in the thermal histories of the fragments. The presence of poorly conducting dust greatly hinders internal thermal equilibration as long as sintering temperatures (~800 K [14]) are not exceeded.

Group IVA irons. Fragmentation and reaccretion has been invoked to account for the microstructures of ortho- and clinoenstatite intergrowths in the Steinbach IVA stony-iron which indicate a cooling rate of ~100°C/hr through 1200°C prior to Widmanstätten pattern growth [6]. Although the IVA irons cooled slowly through 1200-1000°C (<300°C/y), the similarities of their Widmanstätten patterns and metallographic cooling rates [15, 16] to those of the IVA stony-irons require that the IVA core was also fragmented and reaccreted. We calculate that the outer 0.5 m of core fragments initially at 1200°C would cool at ~100°C/hr during the ~2 hour flight time. We infer that Steinbach was located at the surface of a larger fragment because fractures would propagate preferentially through the transition zone at the core-mantle boundary. Core fragments were >30 m in size and reaccreted with cooler mantle fragments. Our best estimate of the mean temperature of the IVA body at the time of impact is 400-700°C and depends on regolith thickness and core size. Although we have not modeled the complex thermal histories of fragments in such a reaccreted body, it seems plausible that the diversity of metallographic cooling rates in IVA irons (20-3000°C/My [7, 16]) and the apparent decrease in cooling rate with falling temperature of high-Ni IVA members reflect conditions after fragmentation and reaccretion of the IVA body.

Although IVA irons did not cool at the surface of the reaccreted body, further impacts would have mixed metal, olivine and pyroxene so that the surface mineralogy resembled that of S asteroids. Other fully differentiated asteroids with diameters of 50-500 km diameter could also have been scrambled to generate S asteroids. Abundant km-sized near-Earth S asteroids could not be manufactured in this way. If they are derived from totally differentiated asteroids, they must be well bonded fragments of previously mixed larger bodies.

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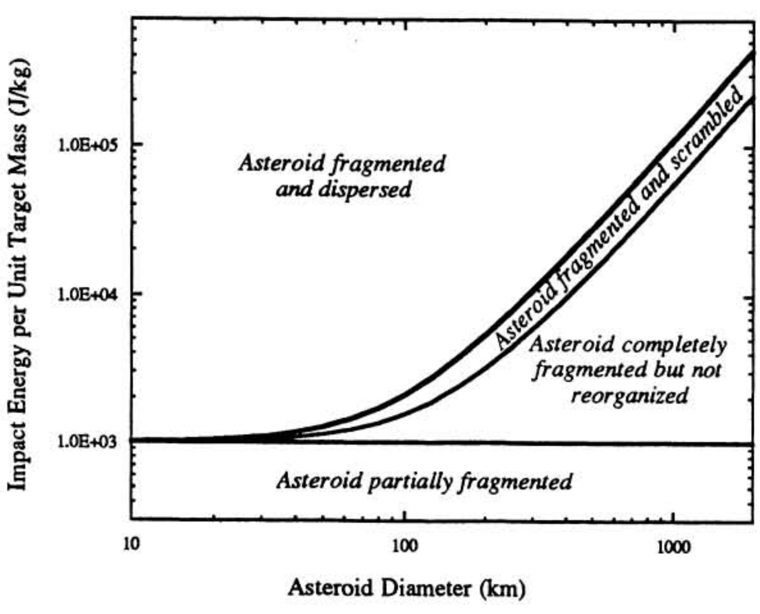

Fig. 1 Specific impact energy required for fragmentation, fragmentation and dispersal, and fragmentation and scrambling of asteroids as a function of asteroid diameter. It is unlikely that asteroids with diameters less than about 50 km suffered collisional breakup and reassembly. The range of energies yielding fragmented and scrambled asteroids is estimated from the requirement that launch velocities be sufficient for orbit around the asteroid. This corresponds to an excess impact energy (after fragmentation) equal to about one half the gravitational binding energy.