METAL SEGREGATION IN ASTEROIDS. G. Jeffrey Taylor, Institute of Meteoritics and Department of Geology, Univ. of New Mexico, Albuquerque, NM 87131

An understanding of how metal segregated from silicates when asteroids were heated is crucial to understanding how cores formed in small bodies, the origins of iron meteorites and achondrites, and the geology of differentiated asteroids. In turn, this will lead to a more quantitative picture of early melting in the solar system, which will illuminate the nature of the heat sources. An improved comprehension of asteroidal differentiation may also lead to a better description of the nature of earth-forming planetesimals. Little work has been done on the physics of metal segregation in small bodies. The results of this preliminary study suggest that metal segregation requires substantial (> 50%) melting of the silicate assemblage.

PETROLOGIC CONSIDERATIONS Several lines of petrologic and geochemical arguments indicate that the formation of at least some achondrites and iron meteorites involved high percentages of partial melting. *Eucrites*: Newsom (1,2) has calculated that the depletions of siderophile elements in eucrites is consistent with 20-70% partial melting, with the best estimate at 40%. Constant ratios of incompatible siderophile to nonsiderophile elements over a wide range in concentration indicates that the core-forming event took place prior to the igneous fractionation events that led to the variety of eucritic lithologies observed. Jones (3) also deduced that the eucrite magmas could have formed by relatively large degrees of melting, 20-30%. These estimates differ sharply with those (4-6) based on trace lithophile elements (5-10%). *Aubrites*: Production of the series of magmas now observed as clasts in enstatite achondrites seems to require a large percentage of melting (>50%) of an ultramafic source (7,8). *Magmatic iron meteorites*: These meteorites are considered (e.g., 9) to have formed by fractional crystallization of metallic magmas (i.e., cores). High temperatures are required to melt chondritic Fe-Ni-S assemblages. For example, the Fe-S binary system (10) indicates that the metal assemblage liquidus is 1700 K in H chondrites and 1630 K in LL chondrites. These temperatures can be used to estimate the percentage of melting experienced by the associated silicates. I used two methods to estimate f, the fraction of melting; both assume a solidus temperature of 1425 K, about the liquidus temperature of eucrites (11), and a liquidus temperature of 1850 K (12). One approach assumes that the percent melting varies linearly with temperature; the other assumes it is nonlinear and uses values based on (13). Melting of the metal assemblage in H chondrites results in f = .65 (linear) and .71 (nonlinear); for LL chondrites the results are f = .49 (linear) and .59 (nonlinear). Some iron meteorite groups, such as IIIAB, may have formed from magmas containing only 20 mg/g S (14), about four times lower than H chondrites. The correspondingly higher liquidus temperature, 1743 K, requires that f = .74 (linear) or .79 (nonlinear). *Inference*: These results suggest that the fraction of silicate melting was commonly >50% during core formation in asteroids, and in some cases might have exceeded 70%.

PHYSICS OF METAL SEGREGATION If during melting, the metal-silicate melt formed an interconnected network along the triple junctions between solid grains, core formation would be rapid. For example, using Darcy's law (15, p.414), an initial grain size of 10^{-3} m, a density contrast of 3500 kg/m^3, and a viscosity for molten iron of 5 mPa s (16), I calculate a velocity of 8.6 x 10^{-6} m/sec (270 m/yr) for 10 % melting on a body 10 km in radius; for 50% melting the velocity is 1400 m/yr. This is clearly ample velocity to allow core formation in a few years. However, as Kracher (17) pointed out, whether the metal-sulfide melts are able to migrate at small percentages of melting depends on the interfacial energies between metal-sulfide melts and silicates. Experiments (18,19) show that migration is extremely sluggish. When an L-chondrite was heated to 50% melting of the silicates (18), metal-sulfide melts formed globules that did not separate from residual olivine, even though the silicate melt moved readily. Most importantly, the metal-sulfide melt did not form a continuous network, so Darcy's law is not applicable. It might be possible that concentrations of metal larger than those of ordinary chondrites, say >50 vol.% (70 wt.%), would allow the metal to form connected channels, leading to rapid core formation, but this could not apply to the eucrite parent body because geochemical calculations (2) indicate that it contained only 20-40 wt.% metal. Metal abundance would increase by continuous removal of silicate melt, but the total amount of melt would still be tens of percent of the original silicate assemblage. Furthermore, this would not give rise to eucritic melts because the metal-silicate fractionation took place prior to silicate fractionation.

It appears that the metal-sulfide globules must sink through a silicate mush to form a core. This is also an inefficient process. Even at 50% melting, Takahashi's (18) experiments show that metal-sulfide globules do not separate from residual silicates. This might be due to the yield strength (σ_0) of a crystal-bearing silicate magma. Using the empirical relation $\sigma_0 = 6500\ (1-f)^{2.85}$ developed by Ryerson et al. (20) and the method described by (21), I calculated the minimum radius of metal-sulfide globules (density contrast with silicates of 3500 kg/m^3) as a function of parent body size and f, the fraction of melt present (Fig. 1). On 100-km bodies, metal-sulfide globules will sink only if they are larger than 1 cm and 90% of the silicate assemblage is molten. Metal-sulfide globules must coalesce to form spheres 1 m in radius at f = .5, and they must be several meters in radius at f = .1. Melting experiments on chondritic materials (18,19) result in formation of globules substantially smaller than 1 mm, so it is not clear how the globules would coarsen or coalesce to meter-sized objects unless the percentage of melting was large; the process might be aided by convection. Generously taking 1 m as a reasonable globule radius, the calculations suggest that metal-sulfide globules will not sink until the percentage of melting exceeds 50% on a 100-km body or 75% on a 10-km body. Once they begin the sink, use of Stoke's law (correcting viscosity for the presence of crystals) indicates that they will fall rapidly, 5 m/s on a 100-km body (f = .5) and 3 x 10^{-2} m/s on a 10 km body (f = .75). If yield strength were not significant, at small percentages of melting metal-sulfide globules 1 mm in radius would still be inefficiently segregated. For example, using a viscosity of $\eta_0 f^{-2.5}$, where η_0 is the viscosity in the absence of crystals (2.6 Pa s; Juvinas melt at 1473 K) and f is the fraction of melt (0.1), a sphere 1 mm in radius would fall 9.5 x 10^{-8} m/s, or only 3 m/yr on a 100-km body. The percentages of melt inferred above are surprisingly high in light of the high mobility of silicate melts (22). As Jones (3) pointed out, however, smaller bodies permit accumulation of silicate melt in the source regions, and there are instances in terrestrial systems where the amount of trapped liquid exceeds 50% (23).

IMPLICATIONS Formation of eucrites and magmatic iron meteorites involved high percentages of melting. Formation of S-rich cores by eutectic melting of the metal-sulfide assemblage at 1250 K (24) is apparently not possible. High percentages of melting are mechanically easier on smaller bodies (< 10 km) than on larger ones is consistent with Scott's (25) model for differentiation in small bodies that later accreted to larger ones. If correct, this implies a heat source potent enough to overcome rapid cooling of small bodies; careful modelling of the heating and cooling of small, substantially-molten bodies might place constraints on the nature of the heat sources. If small bodies had cores, it seems likely that Earth-forming planetesimals also had them.

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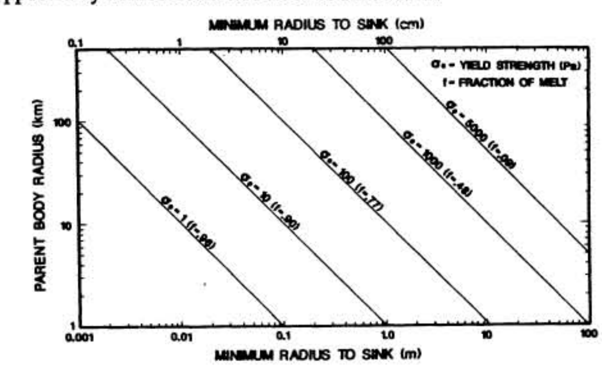

Figure 1. Minimum radius required to overcome yield strength as a function of parent body radius.