THE GRAND TACK, VESTA, AND THE MISSING OLIVINE PROBLEM

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The formation of Jupiter and its subsequent migration are believed to have triggered the clearing of material interior to Jupiter's orbit, including at least 99.9% of the mass from the region now populated by main belt asteroids and a significant fraction from Mars' feeding zone [1]. The basaltic meteorites in our collection were formed during this time, probably concurrent with Jupiter's formation, as evidenced both by Hf-W ages in the metals and the presence of excess ^{26}Mg, the decay product of ^{26}Al [2]. In fact this ^{26}Al would produce widespread differentiation of accreting planetesimals of all sizes down to a radius of a few tens of kilometers. Mutual collisions incited by Jupiter's migration are expected to shatter many of these early-formed protoplanets [3].

There must have been many differentiated bodies present during this time. At least 50 different parent bodies are needed to account for the range of iron meteorite types in our collections that sample the cores of such differentiated bodies [4]. Given that these ~50 bodies are the survivors from the clearing of the asteroid belt, one could extrapolate to ~50,000 such bodies in the early solar system. In addition there are a wide variety of basaltic meteorites including HEDs, angrites, aubrites, ureilites, and others that sample a wide variety of different differentiated bodies.

Vesta was once thought be an example of an intact primordial differentiated body; however, it is impossible to reconcile Vesta's density and core as determined by Dawn [5] with a chondritic composition. Instead, Vesta could be the product of the re-accretion of core and crustal materials from other disrupted differentiated bodies [6].

A differentiated body of chondritic composition should be dominated by olivine-rich mantle material. Although we have numerous core and crustal samples from such bodies, there is a paucity of such olivine-rich lithologies on Vesta's surface, among Vestoids or other asteroids, as well as in in our meteorite collections. Where is this olivine?

A less obvious problem is the origin of the material in the chondrites and primitive achondrites. These meteorites are younger than the differentiated meteorites, as shown both by various dating techniques [7] and the fact that they show no evidence for ^{26}Al heating or excess ^{26}Mg. Where was this material while the iron and basaltic meteorite parent bodies were differentiating? If the protoplanetary disk was very inhomogeneous, one would still need to explain their younger ages and lack of an ^{26}Mg anomaly. Did this material condense from a long-lived disk after the decay of ^{26}Al? How would such a disk survive Jupiter's formation? If it was sequestered in the smallest undifferentiated asteroids, those bodies should have been reduced to dust as the larger differentiated bodies were disrupted.

The likely solution lies in the large contrast in grain size and coherent strength between coarse-grained peridotite and fine-grained basalt. The thermal expansion of olivine is anisotropic, and so intragranular stresses develop during the cooling of peridotites from their crystallization temperature due to the increasing mismatch between individual grains. The result is pervasive micro-cracking on grain boundaries [8]. This effect is strongly grain size dependent [8] and below a critical grain size (~10 µm for olivine) micro-cracking on grain boundaries is absent. The strong contrast between peridotite and basalt is well seen in mantle xenoliths (e.g. from San Carlos, Arizona): extensive grain boundary micro-cracking in peridotite xenoliths means that the material can be crumbled easily by hand whereas the surrounding basalt has a very high cohesive strength due to its much smaller grain size and the resulting absence of micro-cracking.

Thus, it seems reasonable to expect that differentiated protoplanets would be disrupted into large cohesive fragments of basalt, perhaps meters in size, whereas mantle peridotite was disrupted into millimeter-size crystals. The small crystals would be susceptible to non-gravitational forces such as gas drag in the disk, thus allowing olivine to fractionate from crustal material. However, as collisions proceeded, it is expected that both basalt and the olivine components would be reduced to dust, along with much of the metal from the cores of such bodies [9]. We therefore hypothesize that the ordinary chondrites (and primitive achondrites) might have formed from this earlier-processed material.

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