THERE IS TOO MUCH MANTLE MATERIAL IN THE ASTEROID BELT. S. A. JACOBSON[1,2], F. DEMEO[3], A. MORBIDELLI[2], B. CARRY[2], D. FROST[1] and D. C. RUBIE[1], [1]Universtät Bayreuth (Bayerisches Geoinstitut, Bayreuth, Germany), [2]Observatoire de la Côte d'Azur (Laboratoire Lagrange, Nice, France), [3]Massachusetts Institute of Technology (Department of Earth, Atmospheric and Planetary Sciences, Boston, MA, USAf).

Introduction: The low relative abundance of olivine-rich meteorites, presumably mantle material, compared to iron meteorites, presumably core material, and the low relative abundance of A-type asteroids, again presumably mantle material, compared to M-type asteroids, again presumably core material, has been referred to as the "missing mantle" problem. The "battered to bits" solution proposes that since silicates are significantly weaker than metals, mantle material is ground to dust whereas core material survives [1].

We examine mantle material in the asteroid belt from a different perspective using recently completed surveys of not-Vestoid V-type asteroids [2], presumably crust material, and A-type asteroids [3] to show that there is too much mantle material relative to crust material in the asteroid belt. This cannot be satisfactorily explained by "battering to bits" differentiated planetesimals, because crustal material is not significantly weaker than mantle material. Indeed, the Vestoid V-type family has survived for about 1 Gyr [4].

To solve this new conundrum, we propose that most differentiated silicate material in the asteroid belt was deposited there during planet formation as ejecta [5] from giant impact events between planetary embryos, which grow into the observed terrestrial planets.

Asteroid populations: Using the Sloan Digitial Sky Survey (SDSS) moving object color survey with high spectral resolution follow-up [2] and [3] as well as earlier surveys [6], the total volume of not-Vestoid V-type and A-type asteroids is estimated to be 1.1×10^5 and 2.2×10^6 km^3, respectively. The total estimated volume of M-type asteroids is estimated to be 2.5×10^7 km^3 [7], but only approximately 38% of M-types are consistent with a metal-rich surface from radar albedo measurements [8]. Withholding a discussion of the uncertainties until the next paragraphs and making conservative assumptions relative to our conclusions, the volume ratio of crust, mantle, and core material in the asteroid belt is $1{:}\,20{:}\,88$.

The 1.1×10^5 km^3 estimate of not-Vestoid V-type material is a conservative upper limit of the total volume of crust material, because it undoubtedly includes a significant number of Vestoid family members even after we remove identified family members from hierarchical clustering methods [9]. We exclude Vesta and its family members, because Vesta is an intact planetesimal, so it did not contribute mantle or core material to the asteroid belt. The middle and outer regions of the asteroid belt are likely devoid of Vestoid contamination, and these regions contain only about 3.6×10^4 km^3 of V-type material. Using this lower bound the volume ratios of crust, mantle, and core material in the asteroid belt are $1{:}\,61{:}\,265$.

The 2.2×10^6 km^3 estimate of A-type material has an uncertainty of approximately 40% mostly from the volume uncertainties of the largest members. Indeed, 354 Eleonora contains about 88% of the total volume, the other 12% is pre-dominately spread amongst six other asteroids. However, the total volume of A-type material is a likely lower bound on the total volume of mantle material in the asteroid belt, since Sa-type asteroids may be altered A-type asteroids. The other differentiated asteroid types such as R- and O- contain very little volume and so do not effect the results of this analysis.

The 9.6×10^6 km^3 estimate of metal-rich M-type asteroids is still a conservative upper limit of the total volume of core material [7], because about 64% of these radar metal-rich M-type asteroids display a hydrated mineral spectral feature, which could be a secondary feature from subsequent implantation of carbonaceous material or indicative of the bulk composition. If hydration features are indicitave of bulk composition, then the total volume ratios of crust, mantle, and core material in the asteroid belt are $1{:}\,20{:}\,32$.

From this assessment, the nominal volume ratio of crust, mantle, and core material in the asteroid belt may be $1{:}\,20{:}\,88$, but the expected range of possible volume ratios are about $1{:}\,8-85{:}\,32-\ 265$.

Differentiated planetesimals: The "battered to bits" hypothesis posits that these differentiated materials are the direct consequence of disrupted differentiated planetesimals (Ceres- and Vesta-sized or smaller) [1]. Differentiation models based on the assumption of different pure chondrite parent bodies predict volume ratios of crust, mantle, and core material to be [10]:

Chondrite	*Crust:*	*Mantle:*	*Core*
H	1	0.78	0.27
L	1	1.1	0.18
LL	1	1.2	0.14
CO/CV	1	4.0	0.40

Considering only the crust to mantle ratios, the best fit to the observed V- and A-type asteroids appears to be a

CO/CV chondrite parent body, especiall the largest, 354 Eleonora, is ignored. However, the only preserved differentiated planetesimal, Vesta, appears to differ significantly from these estimates, when different investigators have tried to explain both bulk properties of the body and the HED meteorite evidence:

Model	*Crust:*	*Mantle:*	*Core*
[11]	1	0.11	0.05
[12]	1	0.99	0.26
[13]	1	0.31	0.17
[14]	1	0.21	0.16

It has been hypothesized that Vesta may not be an intact planetesimal [15], but in order to match the nominal volume ratio of crust, mantle, and core material in the asteroid belt of $1:20:88$, and incredible volume equal to many times the mass of Vesta must have been lost even in the most favorable cases.

Differentiated planets: Unlike small planetesimals, larger planets have much more mantle and core material relative to crust material:

Planet	*Crust:*	*Mantle:*	*Core*
Current Mars	1	9.1	1.6
Early Earth	1	44	8.8
Current Earth	1	88	17

The crust to mantle ratio for differentiated planets is much more similar to the ratios observed in the asteroid belt. Indeed, the best estimate for the asteroid belt would seem to match a planet somewhat larger than Mars.

Imperfect accretion: The 'Giant Impact' phase of terrestrial planet formation has long been identified in both numerical simulations. Furthermore, the giant impact hypothesis is the leading model for the formation of the Moon. These giant impacts likely produce impact ejecta that escapes into heliocentric orbit. Indeed, hit'n'run impacts can produce significant masses of debris even projectile core material.

A large variety of different ejecta outcomes can occur given the specifics of each giant impact event. In low impact angle but high impact energy events, large amounts of crust and mantle material may be ejected. The ratio fo crust to mantle material has not been reported but likely spans from crustal dominance for small impacts that do not excavate deeply, but the volume ratio of ejected materials will approach the crust to mantle ratio of the entire planet as impacts grow in size. Since the largest impacts create the most debris, the crust to mantle ratios set by these impacts dominate the final ratio amongst all of the ejecta.

Unlike low impact angle impacts, high angle hit'n'run impacts generate most of their debris from the projectile. In this case, core material may not just be present but in much higher relative abundance relative to crust and mantle material than in the planetary parent body, since a large fraction of the silicate material may be sheared away and accreted by the target body while the remaining crust, mantle and core material is tidally ripped into a 'string of pearls' configuration of smaller bodies.

These giant impacts are unlikely to have occurred locally in the asteroid belt since that would require a comminution of a half-Earth sized body (roughly the right crust to mantle ratio) by a factor of 3×10^{-6}. Instead, we propose that this ejecta is transported, albeit inefficiently, from the terrestrial planet forming region into the asteroid belt via scattering events with the planetary embryos present in the terrestrial disk. In the terrestrial planet forming regions large quantities of debris should be generated, but only this small portion needs to be transported to match the observed quantities of differentiated asteroids.

Conclusion: The not Vestoid V- and A-type asteroids likely originate from the growing planets including Earth as indicated by (1) their relative abundances, which are consistent with the interiors of differentiated terrestrial planets, (2) their very low absolute abundances, which are consistent with inefficient dynamical transport, and (3) their absence in known disrupted planetesimals (i.e. asteroid families) with the exception of the Vestoids.

We do not discard the 'blasted to bits' hypothesis, but present it in a cleaner format. This hypothesis is still necessary to explain the longer cosmic ray exposure ages measured on iron meteorites and the survival of planetesimal cores, but the corresponding silicate mantles of differentiated planetesimals do not need to survive in significant quantities.

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