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Authors	Consolmagno, G. J., Golabek, G. J., TURRINI, Diego, Jutzi, M., Sirono, S., Svetsov, V., Tsiganis, K.
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Is Vesta an intact and pristine protoplanet?

G.J. Consolmagno [a,*], G.J. Golabek [b,c], D. Turrini [d], M. Jutzi [e], S. Sirono [f], V. Svetsov [g], K. Tsiganis [h]

[a] Specola Vaticana, V-00120, Vatican City State
[b] Institute of Geophysics, ETH Zurich, Sonneggstrasse 5, CH-8092 Zürich, Switzerland
[c] Bayerisches Geoinstitut, University of Bayreuth, D-95440 Bayreuth, Germany
[d] Istituto di Astrofisica e Planetologia Spaziali INAF-IAPS, Via Fosso del Cavaliere 100, 00133 Rome, Italy
[e] Physics Institute, Space Research and Planetary Sciences, Center for Space and Habitability, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland
[f] Earth and Environmental Sciences, Nagoya University, Tikusa-ku, Furo-cho, Nagoya 464-8601, Japan
[g] Institute for Dynamics of Geospheres, Leninskiy Prospekt 38-1, Moscow, Russia
[h] Unit of Mechanics, Section of Astrophysics, Astronomy & Mechanics, Department of Physics, Aristotle University of Thessaloniki, GR 54 124 Thessaloniki, Greece

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ABSTRACT

It is difficult to find a Vesta model of iron core, pyroxene and olivine-rich mantle, and HED crust that can match the joint constraints of (a) Vesta's density and core size as reported by the Dawn spacecraft team; (b) the chemical trends of the HED meteorites, including the depletion of sodium, the FeO abundance, and the trace element enrichments; and (c) the absence of exposed mantle material on Vesta's surface, among Vestoid asteroids, or in our collection of basaltic meteorites. These conclusions are based entirely on mass-balance and density arguments, independent of any particular formation scenario for the HED meteorites themselves. We suggest that Vesta either formed from source material with non-chondritic composition or underwent after its formation a radical physical alteration, possibly caused by collisional processes, that affected its global composition and interior structure.

1. Introduction

The Dawn mission was designed to explore "remnant intact protoplanets from the earliest epoch of solar system formation" (Russell et al., 2012). Asteroid Vesta was of particular interest because, together with its associated Vestoid asteroid family, it was identified as the likely source of howardite, eucrite, and diogenite (HED) basaltic achondrite meteorites (McCord et al., 1970; Consolmagno and Drake, 1977). These basaltic meteorites have some of the oldest formation ages of any meteorite samples: they are believed to come from a parent body that differentiated within three million years after the condensation of calcium–aluminum rich inclusions (CAIs), and traces of the daughter products of the radioactive isotopes ^{26}Al and ^{60}Fe have been found in the HED meteorites, indicating that they were formed at a time when live ^{26}Al and ^{60}Fe would have been available to melt the parent body and produce the observed basalts (cf. Tera et al., 1997; Bizzarro et al., 2005; Misawa et al., 2005; Schiller et al., 2010, 2011). This period coincides with the formation and early evolution of the giant planets (Scott, 2006), which is an important but poorly understood phase of Solar System evolution. Thus the HED parent body should have been present during any large-scale planetary migration, such as the primordial episodes proposed by the "Jovian Early Bombardment" model (Turrini et al., 2011, 2012; Turrini, 2014; Turrini and Svetsov, 2014) and the "Grand Tack" scenario (Walsh et al., 2011, 2012), and the later episodes proposed by the various Nice models (Tsiganis et al., 2005; Levison et al., 2011). Having survived all these events intact it was expected that Vesta, perhaps uniquely, could provide a preserved record of that period in early Solar System history.

However, the results of the Dawn mission detailing Vesta's mass, volume, density, surface characteristics and possible core size (cf. Russell et al., 2012; Ermakov et al., 2014), and the excavation depth implied for the large south pole basins (Jutzi et al., 2013; Clenet et al., 2014) discovered by Dawn have provided serious challenges for modeling the structure of this asteroid while matching the chemical and physical evidence provided by the HED meteorites. How does the lack of olivine on Vesta's surface constrain the volume of material in the howarditic crust, and is this consistent with the bulk abundance of trace elements and aluminum in a parent body with chondritic abundances? How does the large core constrain the density and composition of the mantle and crust, and is this consistent with a parent body with chondritic abundances of the major elements?

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* Corresponding author at: Vatican Observatory Research Group, Steward Observatory, University of Arizona, Tucson, AZ 85721, USA.

E-mail address: gjc@as.arizona.edu (G.J. Consolmagno).

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This work thus addresses the question: is Vesta both an "intact and pristine protoplanet" and the source of the HED meteorites in our collection today? Let us define what is meant here by "intact and pristine protoplanet" – we define it as a planetesimal formed within the protoplanetary disk, typical in composition of materials being accreted in its part of the solar nebula, that satisfies the following two conditions. First, its present bulk composition should not be too different from cosmic abundances of the major planet-forming elements, subject of course to the characteristic condensation nature of the region in which it was formed. In the case of Vesta, this means that its global composition should not have been altered with respect to the one recorded by the HEDs (hence the "pristine"). Second, it should not be a shattered and re-accreted rubble pile (hence the "intact"). If a protoplanet is undifferentiated, its porosity may be quite high, representing the primordial porosity of a newly accreted body. However, if like Vesta it is melted and differentiated, one should expect that its overall porosity should be significantly lower (and thus its average density much higher) than that of a typical rubble pile asteroid.

The question then becomes whether it is possible to construct a model Vesta that matches the mean density and core size constraints of Vesta as reported by the Dawn team, including the lack of exposed mantle material, and which is also capable of producing the HED meteorites. If not, what does this imply for the genesis of these meteorites and for the environment in which they were formed?

2. The HED meteorites

In order to understand the nature of Vesta, we need to take advantage of the extensive knowledge we have about the HED meteorites and what their chemical and physical nature can tell us about the parent body where they were formed.

2.1. The geochemical nature of the HEDs

The HED meteorites (howardites, eucrites, and diogenites) are a class of genetically linked basaltic achondrites. *Eucrites* are primarily fine-grained basalts of anorthite-rich plagioclase and clinopyroxene; some larger-grained cumulate eucrites also have been found. *Diogenites* are cumulate orthopyroxenites with trace olivine; among them, a handful of olivine-rich diogenites have been discovered, such as MIL 03443, discovered in Antarctica in 2003 (discussed by Beck et al., 2011), and NWA 5480, found in Mali in 2008 (discussed by Tkalcec et al., 2013). The olivine in these rare samples may be associated with the formation of the diogenites, and not necessarily a sample of any putative mantle. *Howardites* are breccias containing fragments of all these components. Nearly 1600 HED meteorites are known in our collections, representing 5% of all fall meteorites, and just under 2% of all Antarctic meteorites (statistics are from the Meteoritical Bulletin database, http://www.lpi.usra.edu/meteor/metbull.php); of these, roughly 900 are eucrites, just under 400 are diogenites, and some 300 are howardites.

The linked relationship among these meteorite classes has long been recognized by the fact that howardites are themselves breccias consisting of a physical mixture of eucritic and diogenitic fragments. Howardites display a wide range of compositions, but on average one can assume a roughly 2:1 eucrite/diogenite proportion, based on the whole-rock average grain density of 28 howardites compared to eucrite and diogenite average densities (Macke et al., 2011). This ratio also matches the observed fall statistics of eucrites and diogenites, and the abundances of trace elements in regolithic howardites, which lie on a mixing line between the abundances of those elements in eucrites and diogenites (cf. McCarthy et al., 1972; Warren et al., 2009). As would be expected for material generated in a common parent body, oxygen isotope measurements show that virtually all of these meteorites (with rare but significant exceptions) fall on the same $\delta^{17}O$–$\delta^{18}O$ fractionation line (Scott et al., 2009).

Concerning the petrogenesis of the eucrites and diogenites, there is no consensus. Many different schemes (cf. Mason, 1962; Stolper, 1977; Longhi and Pan, 1988; Ruzicka et al., 1997; Righter and Drake, 1997; Mandler and Elkins-Tanton, 2013; Barrat and Yamaguchi, 2014; Mizzon et al., 2014; Greenwood et al., 2014) have been devised to explain the geochemical origins of these igneous rocks and show how a common source region could produce both the major element (especially FeO abundance) and trace element trends seen in both the eucrites and diogenites.

Likewise, many papers have attempted to determine the bulk composition of the eucrite and diogenite parent body. These include early work by Dreibus et al. (1976) and Morgan et al. (1978) who used the technique of "correlated elements," where abundances of different components (refractory, volatile-rich, etc.) are determined from the relative abundances of trace elements, selected because they have different condensation behaviors but similar geochemical behavior, and the models of Consolmagno and Drake (1977) to reproduce the trace rare earth element (REE) abundances in the eucrites which allowed them to put limits on possible bulk compositions of the HED source regions.

Though the details of petrogenesis remain controversial, most models conclude that the eucritic basalts were formed in a source region of roughly chondritic abundances of the major rock forming elements (except, notably, sodium) which, like the ordinary chondrites themselves, ought to be rich in olivine and metal – components that are not actually seen in any significant abundance in the HEDs themselves.

With this in mind, most models for the structure of Vesta (cf. Ruzicka et al., 1997; Righter and Drake, 1997; Mandler and Elkins-Tanton, 2013) have assumed a three-layer structure for the HED parent body, with an iron core and olivine-rich mantle underlying a crust of essentially howarditic composition, i.e. eucrites and diogenites. That crust may originally have been formed in separate layers of eucrites and diogenites via a magma ocean, or in a series of plutons within the crust (cf. Mittlefehldt, 1994; Barrat et al., 2010); in any event, today it occurs as a well-mixed regolith (De Sanctis et al., 2012; Prettyman et al., 2012).

2.2. The Vesta-HED connection and the missing olivine

McCord et al. (1970) first pointed out the excellent match between the telescopic spectrum of Vesta and laboratory spectra of the howardites. Furthermore, their work on the brightest asteroids showed that, among large bodies at least, Vesta's spectrum was unique. This was consistent with Vesta as an HED parent body, but it did not prove that all the HED meteorites in our collections uniquely came from Vesta; one could not rule out on the basis of spectra alone the possible existence of other, similar parent bodies that produced such meteorites but were subsequently destroyed or ejected from the Solar System. Still, this spectral match did indicate that there was at least one asteroid remaining in the asteroid belt that must have undergone an evolution including melting and differentiation that produced HED-like material.

Consolmagno and Drake (1977) made one further, crucial, observation. They pointed out that (i) both their models and the other bulk composition calculations of the HED parent body, and (ii) cosmic abundances of the major rock-forming elements, indicated that the parent body of the HED meteorites was likely to have been rich in olivine and metal. If nothing else, the seven to ten times enrichment of the rare earth elements (REE) in the eucrites demanded, by simple mass balance, that within a parent body with bulk cosmic abundances of the trace elements there must be seven to ten times as much REE-depleted residual material as there is REE-enriched eucrites. However, although some 1600 eucrites, diogenites, and howardites have been found in our meteorite collections, no meteorites exist in our collection that can be unambiguously identified as representing this olivine-rich, REE-depleted mantle.

Furthermore, although asteroids have been found whose spectra are dominated by olivine (A-type asteroids), such olivine-rich asteroids are small and rare. Only on the order of thirty A-type asteroids have been discovered to date, even after intense searching for such (DeMeo et al., 2013). By comparison, it has been estimated that more than 5% of all main belt asteroids are V-type "Vestoids", most of them dynamically linked to Vesta.

From the paucity of olivine-rich samples, Consolmagno and Drake (1977) reasoned that the HED parent body must still be intact: in this way, the "missing olivine" would be hidden beneath the parent body's intact crust. Since Vesta is the only large intact asteroid with a spectrum consistent with HED mineralogy, they concluded that Vesta itself was the only candidate parent body. In other words, they argued that Vesta is not merely *similar* to the HED parent, but in fact it must be the very source of these meteorites. The later discovery of Vestoid family members (Binzel and Xu, 1993) reinforced this connection, as it showed a pathway by which samples of Vesta could be perturbed into orbits that would eventually encounter Earth.

3. Constraints on the nature of Vesta

The Dawn mission to Vesta (Russell et al., 2012, 2013) has given us significant constraints on the nature of Vesta's internal structure and composition. Likewise, the HED meteorites provide strong constraints on the nature of their parent body. If Vesta is indeed the parent body of the HEDs, then one should see a convergence of these constraints.

3.1. The constraints from Vesta's bulk density and core size

The fundamental values of Vesta's volume, mass, and average density were first reported by Russell et al. (2012), who also reported that the gravity data were consistent with a Vesta metallic core of 110 km radius assuming that the density of Vesta's core is consistent with the density of iron meteorites. More recent work by Ermakov et al. (2014) has updated this calculation, suggesting a range of core radii as a function of core densities: the core may have a radius 110 km if its density is 8000 kg/m^3 as is typical of iron meteorites, or a radius of 140 km if the density is 5500 kg/m^3 as would be expected for a mixture of metal and sulfide, and they plot the range of acceptable core densities and radii between these values (see Fig. 1).

Using these results, Toplis et al. (2013) argued that Vesta has a bulk composition not too dissimilar from that of a sodium-depleted H chondrite. We come to a similar conclusion in a slightly different way, as illustrated in Fig. 1. If one takes the metal and sulfide abundances of average H and L chondrites as given by Jarosewich (1990) and from them calculate the core density and radius assuming no core porosity and a total mass equal to Vesta's, one finds that such a core plots on two points straddling the Ermakov et al. (2014) core line. The H chondrite composition is much closer to that core composition than the L chondrite, but in fact has slightly more metal than their data indicate for Vesta.

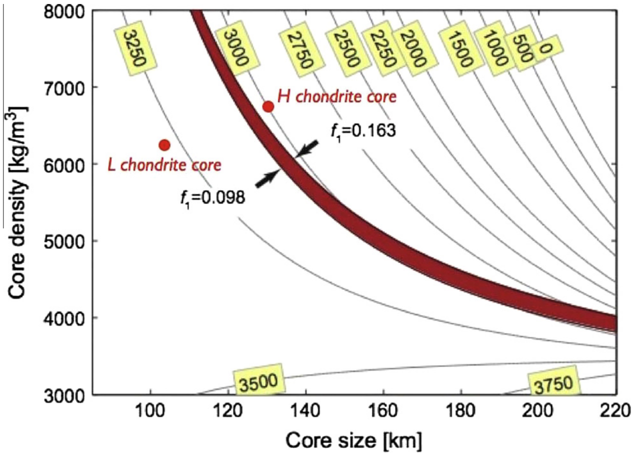


Fig. 1. The thick red line indicates the range of possible core radius versus core density according to the Dawn team, adapted from Fig. 9 of Ermakov et al. (2014); the other lines show the density of the remaining non-core parts of Vesta needed to match its overall mass. To this figure we have added the red dots to indicate the size and density of a core with the metal and sulfide content of an L or H chondrite, as indicated, based on the average chondrite compositions of Jarosewich (1990). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. Constraints from the sodium abundance

The abundant lithophile elements Si, Mg, Ca, and Al are all expected to condense into the solid phase at similar high temperatures (greater than 1500 K) in the solar nebula. Thus it is not surprising that they are found in roughly constant proportions across all the undifferentiated meteorites, such as the ordinary chondrites. By contrast, the relative abundances of these major elements in the HED meteorites are completely different from the chondritic ratios; the mass ratio of Al_2O_3/MgO in howardites, for instance, is ten times greater than the ratio seen in cosmic abundances. This difference is an expected consequence of the chemical differentiation that produced melts from which the eucrites and diogenites crystallized. If Vesta is an intact protoplanet, one would expect that its bulk composition would reflect cosmic abundances; if so, then the chemical abundances of the mantle must complement those seen in the HED crust: those elements absent from the howarditic crust must be contained in the mantle (and/or the core).

Sodium, potassium, and calcium are the cations that make up the three end members of the feldspar group of minerals. While calcium can also be found in clinopyroxenes, sodium and potassium are generally present only in feldspars (neglecting minor phases). Orthoclase, the potassium-bearing feldspar, is rare in all meteorites and completely negligible in the HEDs. However, plagioclase, the solid solution of sodium and calcium feldspars, makes up about ten percent by mass of a typical ordinary chondrite (McSween et al., 1991) and makes up nearly half the mass of a typical eucrite. One can assume that all the plagioclase in the HED parent body will be found in the eucrites. Since the abundance of plagioclase depends on the abundance of aluminum – aluminum is the essential element in all types of feldspar – one should be able to tie the thickness of the eucritic crust to the abundance of aluminum in the parent body.

The plagioclase in the HED meteorites provides a powerful constraint on its bulk composition. Perhaps the most striking chemical feature of the HED parent body composition is the strong depletion of sodium in the plagioclase. The Na_2O/Al_2O_3 mass ratio in ordinary chondrites is 0.4 for H chondrites and 0.42 in L and LL chondrites, but typically only 0.02–0.03 in the eucrites and howardites. This change from 0.4 to 0.02 represents a 95% depletion of the sodium content in these plagioclases. As a result, while the anorthite (calcium end member) fraction of the plagioclases in typical chondrites is 0.15–0.20, the anorthite fraction in eucrite plagioclases is greater than 0.80, and can be as high as 0.95 (cf. Mayne et al., 2009).

Compared to these elements, sodium is known to be mildly volatile in the solar nebula, with a condensation temperature around 1000 K (Grossman, 1972). However, the HED meteorites themselves are also rich in iron oxide, whereas condensation models predict that FeO should be stable as a solid only at temperatures much lower than the condensation point of minerals bearing sodium. One must invoke some more complex condensation/vaporization scenario to account for the presence of FeO and absence of sodium if one wants to rely on nebular processes alone to account for the depletion of sodium.

Does this conundrum of low sodium but high FeO in and of itself rule out a "cosmic" HED parent body, and thus invalidate its identification as a "primordial protoplanet"? Probably not. The fact is, such a depletion of sodium in the presence of iron oxide is seen in many other extraterrestrial samples.

For example, the angrite class of basaltic achondrite meteorites are known (Mittlefehldt and Lindstrom, 1990) to be even more depleted in sodium than the HED meteorites, while being even more enriched in FeO (with an Mg# at or below 0.50, compared to 0.56 for the average howardite). On the other hand, the Messenger mission to Mercury – a planet presumably representing high temperature condensates – found the exact opposite situation there: Mercurian basalts are rich in sodium, but essentially depleted in FeO (cf. Evans et al., 2012; Peplowski et al., 2014). In fact, the closest analogs to the sodium and FeO abundances of the HEDs are found in lunar samples.

From this variety of sodium versus FeO abundances, one can at least recognize that while the sodium depletion requires explaining, such depletion is not unique, and not by itself grounds for disallowing the term "pristine protoplanet" for the HED parent body. It appears that, for whatever reasons, sodium did vary among many different meteorite parent bodies.

The absence of sodium has an important effect on the overall composition of the HED parent body, however. Compared to cations like magnesium, silicon, or iron, sodium is not a particularly abundant element; the total mass abundance of sodium oxide in an ordinary chondrite is less than one percent (Jarosewich, 1990). But the depletion of sodium in the HEDs makes a remarkable difference in the bulk mineralogy of the HED parent body.

The tale can be seen in the chemical formulae for the plagioclase end members. The sodic plagioclase, albite, has a chemical formula of $NaAlSi_3O_8$ while the calcium end member, anorthite, is $CaAl_2Si_2O_8$. In ordinary chondrites, 80–85% of the aluminum oxide is combined with sodium to make the sodium-rich end member, albite, leaving most of the calcium free to combine with magnesium, silicon, and iron oxides to form clinopyroxene. However, in the HED parent body, the absence of sodium means that the aluminum oxide must take up the vast majority of the calcium to make anorthite, leaving less calcium available for clinopyroxene. Thus the source region of a sodium-depleted parent body will be richer in orthopyroxene than is seen in ordinary chondrites.

But also notice that in albite each mole of aluminum takes up three moles of silicon; by contrast, in anorthite, aluminum and silicon are in a one-to-one molar ratio. Thus the presence of anorthite instead of albite frees up a significant amount of silica. This silica combines with olivine to make even more orthopyroxene. As a result, the initial composition of a sodium-depleted body is likely to be significantly depleted in olivine and enriched in orthopyroxene compared to chondritic abundances of these minerals. Thus the bulk composition of an ordinary chondritic parent body that has been depleted in sodium would be dominated by orthopyroxene, rather than olivine.

Finally, the FeO content within the eucrites and diogenites puts limits on the acceptable FeO content of any complementary mantle olivine. Models indicate that source regions capable of producing the observed FeO contents should lie within a limited range of values for the mole fraction of magnesium in the olivine, MgO/(MgO + FeO), known as the magnesium number (Mg#). The Mg# suggested by Stolper (1977) for the bulk HED parent body was 0.65, while Mandler and Elkins-Tanton (2013) derived an Mg# of 0.8 within the mantle once a significant amount of FeO has been removed into the crust.

We have no undisputed direct samples of the HED parent body olivine mantle. It may be of interest, however, to compare these Mg# values with other olivine-rich meteorites. The typical Mg# for LL chondrites is 0.73, that for L chondrites is 0.77; H chondrites are at 0.83. The olivine in the olivine-rich diogenites MIL 03443 and NWA5480 have an Mg# of 0.74 and 0.70 (Beck et al., 2011; Tkalcec et al., 2013) and the Mg# for the SNC olivine-rich meteorite Chassigny is 0.79 (Lodders, 1998). The olivine in ureilites typically has an Mg# of 0.8–0.85 (Berkley et al., 1980; Takeda, 1991). By contrast, only the olivine in pallasites is significantly different from this range, being strongly depleted in iron with Mg# as high as 0.90 (Wasson and Choi, 2003).

The Mg# is important for several reasons. Besides being a constraint on petrogenesis, it also affects how one can use density to determine the abundance of mantle material, since the lower the Mg#, the higher the iron abundance and thus the higher the density of the unseen mantle material. And, as can be seen in the metal abundance trends among ordinary chondrites, as more iron is placed into the silicates as FeO, there is less left available as metal to be put into the core. Thus a large metallic core implies a relatively high Mg#, while a low Mg# implies a smaller metallic core.

3.3. The constraints from HED trace elements

Along with sodium depletion and FeO content, trace element abundances add a third constraint on the bulk composition of the HED parent body. If one assumes a chondritic initial abundance of the REE elements, the 7–10 × chondritic REE abundances seen in the bulk of the eucrites (first reported by Schmitt et al., 1963, 1964; since that work similar REE abundance measurements for about 100 eucrites can be found in the literature, cf. Mittlefehldt and Lindstrom, 2003) indicate that these basalts were crystallized from a melt that represented 10–14% of the mass of the source region.

Furthermore, the enrichment of the REE pattern occurs uniformly across all the REEs, with little difference seen from low mass to high mass elements and essentially no europium anomaly. This indicates that materials that are uniformly inert with respect to the rare earths, such as metal or olivine, must dominate the source region. By contrast, other minerals (especially plagioclase and clinopyroxene) are known to fractionate the REE in a nonuniform manner, either enriching or depleting them according to their atomic number. Furthermore, at the low oxygen fugacities of these materials, europium will be present in both +2 and +3 valence states, and so the presence of unmelted plagioclase and clinopyroxene (which are sensitive to +2 cations) would result in an anomalous fractionation of europium from the other REE in the melt. (These fractionations are one of the factors that make diogenite petrogenesis particularly difficult to model.) The absence of such fractionations in most of the eucrites is most easily explained by concluding that their source region did not contain any unmelted plagioclase or clinopyroxene: instead, at the time the eucritic material was present as a molten magma within the parent body, all the plagioclase and clinopyroxene originally present in the parent body is presumed to already be present in this magma.

The actual history of the source region before the eucritic lavas were erupted may have been simple, or complex; the only constraint here is that no plagioclase or clinopyroxene could have been fractionated away from the bulk eucrite region, since such a fractionation would have visibly altered the rare earth abundance patterns in the eucrites.

The Consolmagno and Drake (1977) paper which modeled these REE abundances took advantage of Stolper's (1977) work, but it should be emphasized that this conclusion from their REE model for the eucrites is independent of the nature or history of the origin of those meteorites, or of the precise values of the partition coefficients used in the model. Since the REE elements are essentially incompatible with most mineral phases, an enrichment of these elements by ten times chondrites suggests that the eucrites represent one tenth the mass of the source region from which they were derived. This is simply a result of mass balance, regardless of the ultimate way the trace elements found their way into these basalts – assuming that the source region was chondritic.

3.4. The constraints from the crust thickness and the missing olivine

Given the presence of a large olivine-rich source region, consistent with cosmic abundances and necessary to explain the REE abundances in the eucrites, one can then ask whether evidence of such material from deep within the HED parent body can be seen on Vesta. Early telescopic spectra had raised hopes that perhaps the deep impact feature at Vesta's south pole, inferred from Hubble images, might be an expression of this olivine (Thomas et al., 1997). However, the spectra returned by the Dawn mission found no such olivine in that region, and little elsewhere on the surface of Vesta (Russell et al., 2012; Ammannito et al., 2013; Clenet et al., 2014).

In fact, Dawn revealed that the large impact basin at the south pole of Vesta, Rheasilvia, itself overlaps an older but comparably large impact feature, named Veneneia. Ivanov and Melosh (2013) and Jutzi et al. (2013) calculated that this Rheasilvia impact basin, formed within the pre-existing large basin Veneneia, should have excavated material from a depth of 50 km to 80 km or more below Vesta's surface. More recent calculations by Clenet et al. (2014) place this boundary at a minimum of 85 km and more likely 100 km. If the howardite crust were much thinner than 85 km, a significant amount of olivine-rich material, derived from depth, should have been exposed within this basin. These models further suggest that such olivine would also be distributed both on Vesta's surface, outside the basins, and in space among the meteorite-source Vestoids.

Rare spots where olivine features are seen on the surface have been reported in Vesta's northern hemisphere (Ammannito et al., 2013), far from the southern impact basin. But the rarity of these spots and the low abundance of olivine-rich material are completely consistent with these spots having arisen from the infall of a small number of rare olivine-rich A-type asteroids (Turrini et al., 2014a). What are definitely *not* seen (Ammannito et al., 2013) are layers of olivine in the walls of the southern impact basins or widespread deposits of olivine in the surface material. Nor have any Vestoid family asteroids that show olivine spectral features been seen in telescopic surveys that looked specifically for such objects (Shestopalov et al., 2008). Such olivine is absent on Vesta and among the Vestoids; and, as noted above, it is also essentially absent from our meteorite collections.

3.5. The macroporosity constraint

The HED parent body was molten and differentiated. Vesta, which is covered with HED-like material, also possesses a core and thus is likewise differentiated. But is it an *intact* differentiated body? To determine if Vesta is an intact body, one can ask to what degree is Vesta well compacted, and to what degree it shows significant macroporosity?

The porosity of meteorites is well understood. Both scanning electron microscope backscatter images (see Fig. 2) and 3-D body scans (cf. Friedrich and Rivers, 2013) reveal that most meteorites are riddled with microcracks, which can be explained as the result of shock passage through the rocks. This porosity is referred to as microporosity, and presumably is present in a meteorite even if its parent body itself is intact.

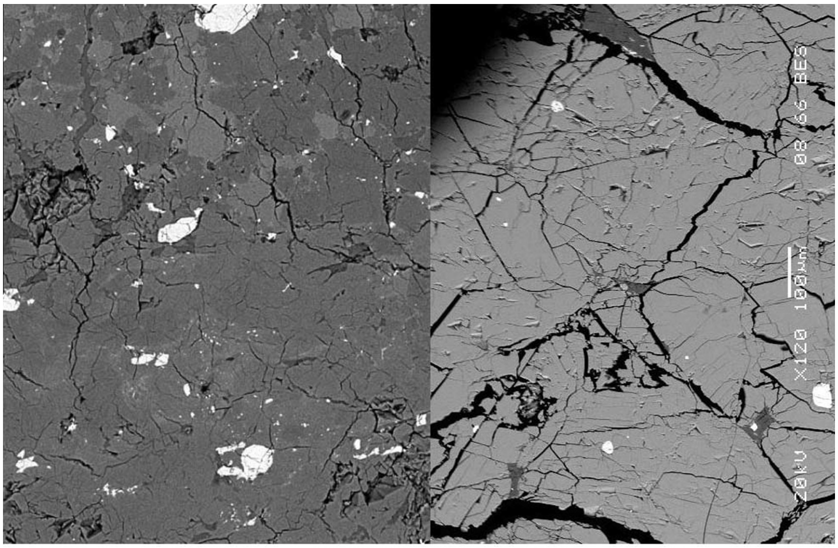
The event that broke these meteorites from their parent body and sent them on an Earth-crossing trajectory would certainly have been sufficient to produce such shocks. It is also certainly possible that these samples were equally shocked, and porous, while still in their parent body; that is what we have assumed in our calculations in the previous sections. Given the narrow range of porosities in most stony meteorite falls, including both HEDs and ordinary chondrites (cf. Consolmagno et al., 2008; Macke, 2010), one can argue that multiple shock events do not substantially change the porosity of a meteorite; presumably each shock closes as many cracks as it opens. But without sample returns from either Vesta or whatever vestoid served as the ultimate parent body of a given HED, that assumption is impossible to test.

If a parent body is found to have a significantly lower density than the bulk density of the meteorites derived from that parent body, one can infer that it has a large degree of macroporosity (i.e. porosity in addition to the shock cracks), due to voids created when it was catastrophically destroyed by a large impact and then reaccreted. It has long been recognized that most asteroids are quite porous; typically, S-type asteroids have a macroporosity on the order of 20%, while many C-type asteroids exhibit 50% macroporosity, indicative of a loosely reaccreted pile of rubble (Britt et al., 2002). This porosity is usually pointed to as evidence that such asteroids are not intact bodies, but shattered and reaccreted rubble piles.

Can there be significant macroporosity within Vesta? The very process of melting and differentiation that must have occurred within Vesta if it were the source of the HED meteorites should also have removed any macroporosity resulting from its original accretion. Any macroporosity found within Vesta today would therefore have to be the result of impacts long after Vesta solidified, impacts so large and so numerous as to have uniformly gardened and rubblized Vesta to a depth of at least tens of kilometers. If the mantle is also to have significant macroporosity, this gardening would have had to extend to a depth of more than one hundred kilometers.

The relatively low lithostatic pressures inside Vesta are certainly consistent with the possible maintenance of significant porosity within a body of its size, and Ermakov et al. (2014) suggest that variations in macroporosity of Vesta's surface layers could account for higher-order variations in Vesta's gravity field. In addition, some macroporosity could be created by the Veneneia/Rheasilvia impacts, though unfortunately current impact simulations are not yet able to estimate either bulking or dilatancy of the material, so it is difficult to estimate the resulting porosity at depth. (Given the significant overburden pressure in the deeper layers, however, it seems unlikely that a significant amount of macroporosity would be created in the mantle by these impacts.)

The question thus can be put this way: is it possible to produce a significant degree of porosity deep within Vesta after its differentiation was complete? The HED parent body must have been at least partially molten, and thus free of any macroporosity, during the first few million years of its history. Thermal models relying on short-lived radioactive heat sources (cf. Ghosh and McSween, 1998; Formisano et al., 2013; Tkalcec et al., 2013), and the inferred ages of the HED meteorites themselves (cf. Tera et al., 1997; Misawa et al., 2005; Schiller et al., 2011) indicate that Vesta must



Howardite, Dhofar 018 Mantle analog, Chassigny

Fig. 2. Scanning electron microscope images of the howardite meteorite Dhofar 018 (left) and the martian dunite Chassigny (right), which could be used as an analog for the physical state of Vesta mantle material. Both images are at similar scales, indicated on the Chassigny image. Both meteorites contain a network of cracks a few microns wide permeating all grains and materials. Similar cracks are seen in ordinary chondrites, and they can account for the majority of the porosity measured in these samples; thus we conclude that these cracks are the result of effects from outside the parent bodies, most likely the shock from impacts – including at the very least the impact that launched these samples from their parent bodies into Earth-crossing orbit. (Dhofar 018 image courtesy of Melissa Strait.)

have been molten to some degree over the first three million years after the formation of CAIs, concurrent with the time when Jupiter was forming and its orbit was evolving. But this period was the very time when such protoplanet-shattering impacts would have been most likely (Bottke et al., 2005), the era of the Jovian Early Bombardment (JEB) when Jupiter and the other outer planets were forming and perhaps undergoing significant orbital migration (Turrini et al., 2011, 2012). By the time Vesta was frozen, this era would also likely have ceased.

Instead, we must look to a later period for when significant macroporosity could have been imposed on Vesta. Are the sorts of impact events needed to produce such porosity at depth consistent with our understanding of the impact environment around Vesta during the Late Heavy Bombardment (LHB), roughly half a billion years after Vesta's formation? Can one see evidence for or against the occurrence of such deeply fracturing impacts in the crater features seen today on Vesta? One would expect that such deeply penetrating impacts on Vesta should have brought significant mantle olivine to the surface. And if Vesta were turned macroporous by the reaccretion of material following numerous catastrophic impacts, it would by definition no longer be an "intact protoplanet." Thus we argue that, while the crust of Vesta may have macroporosity, it is less likely that such macroporosity extends all the way to the iron core.

3.6. Summary

The Dawn mission's constraints on Vesta's structure include Vesta's overall density; the size of Vesta's core; and the absence of significant olivine visible on Vesta's surface. The large amount of metal in Vesta's core is consistent with a bulk composition close to that of an H chondrite. However, the bulk density and core size put a strict limit on the density of the rocky portion of Vesta, which (see Fig. 1) must be near or just under 3000 kg/m^3 – close to the bulk density of howardite meteorites, and significantly lower than the density of olivine or orthopyroxene.

It is unlikely that one can explain this low density via large degrees of macroporosity, because the molten state of the HED parent body during its first three million years after formation would presumably have removed any macroporosity at that time; this was the time during the Jovian Early Bombardment, the time when large planetesimals would have been most subject to the kinds of large impacts that could produce significant, deep macroporosity. Instead, the rocky portion of Vesta is more likely to be rich in relatively low density aluminous minerals.

The lack of surface olivine also implies that any olivine within Vesta lies at a depth of at least 85 km, and more likely 100 km, below the surface of Vesta. This is also consistent with a thick aluminum-rich howarditic crust.

The eucrite meteorites are enriched by roughly ten times chondritic abundances of aluminum oxide and rare earth elements. Assuming the howardites are made of eucrites and diogenites in a two to one ratio, simple mass balance demands that a howarditic crust can only make up about 15% of the total mass of Vesta. In addition, the FeO abundance in the eucrites suggests they were formed in equilibrium with a mantle with a magnesium number no greater than Mg# = 0.8, while the essentially flat REE abundance pattern implies that the mantle in which they were in equilibrium was essentially depleted in plagioclase and clinopyroxene.

Another important constraint on the eucrites is the strong depletion of sodium in the plagioclases, compared to what would be expected for a body with initially chondritic abundances. A large sodium depletion is also found in some other meteorites and in lunar rocks; it may be the result of high condensation temperatures, or post-formation heating. However, the lack of sodium significantly changes the mineralogy of the remaining material, if one assumes chondritic abundances of the other major rock forming elements.

The challenge to be addressed in the following section is to determine if the constraints of Vesta's thick crust and large core can be made consistent with an HED parent body of chondritic abundances of the major elements.

4. A chondritic HED parent body

One of the primary constraints we have imposed for an "intact and pristine protoplanet" is that at least the refractory rock forming elements should be present in cosmic abundances. Given that constraint, if one assumes that Vesta is a pristine protoplanet, one can combine this chondritic composition with Dawn's observed density and allowed core radii to put limits on the size and composition of the mantle and crustal regions of Vesta.

4.1. Crustal thickness

Most eucrites have REE abundances that are uniformly enriched by seven (Case A) to ten times (Case B) relative to the abundances found in chondrites. If one assumes that the original abundance of these elements throughout the entire parent body was chondritic, but that after differentiation the REE are concentrated in the crust, then regardless of how one envisions the eucrites being formed, simple mass balance tells us there must exist somewhere in the parent body seven times to ten times as much REE-depleted material as exists in the HEDs. Thus the total mass of a howarditic crust, two-thirds by mass eucritic, cannot be more than 15% (Case B) to 21% (Case A) of the total mass of Vesta.

This constraint gives us the maximum mass of the crust. The density of that crust can be inferred based on the measured howardite density and porosity. Thus one can calculate the volume of the crust; from that volume, the average crustal thickness can be derived. Then the mass of the mantle in such a model can be found by subtracting the mass of the crust and the mass of the core (using the possible densities and core radii reported by Ermakov et al. (2014)), from the total mass of Vesta. For a given core radius and density, the density of the resulting mantle can also be found as a function of the porosity of the crust: the more porous (and hence thicker) the crust, the smaller and thus more dense the mantle must be.

The results of such calculations are shown in Fig. 3. (Note that all our density calculations model Vesta as a sphere with a radius fixed so that its volume matches the observed Vesta volume.)

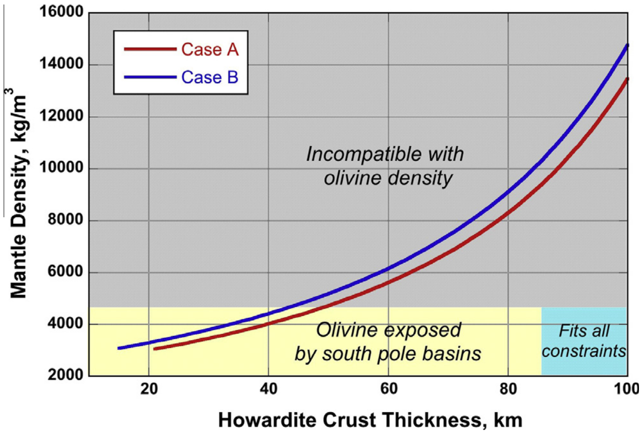


Fig. 3. The thickness of the crust determines the volume available for the mantle, given a core size. The red and blue lines indicate the maximum (case A) and minimum (case B) howardite crusts, based on average REE enrichments. The thickness of the crust depends on its macroporosity. As the crust macroporosity and thickness increases (horizontal axis), the corresponding density of the mantle is shown on the vertical axis. The densest form of olivine, fayalite, has a grain density of 4500 kg/m^3; thus the gray shaded regions above that density are ruled out. The yellow shaded region below 85 km is less than the crustal thickness needed to prevent material below the crust from being excavated via the south pole impact basins. Only the blue region allows for a sufficiently thick crust with a possible mantle density. As can be seen, no combination of crust macroporosity and mantle density allows for such a thick crust. These results assume a 110 km metal core, but the conclusions are independent of core radii and density because all acceptable core radii and densities from Dawn data result in the essentially the same total density for the non-core component. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

These calculations assume a metallic core of 110 km radius; since the Dawn range of core radius and density values suggest a nearly constant density for the non-core component, as shown in Fig. 1, similar results can be found for an FeS rich core of 140 km radius and density 5500 kg/m^3.

The maximum density of the iron endmember of olivine, fayalite, is 4500 kg/m^3; the density of olivine with an Mg# of 0.8 is closer to 3600 kg/m^3. Fig. 3 indicates that the thickness of a crust representing 15–21% of Vesta's mass cannot be higher than 45–50 km even with a fayalite mantle. Furthermore, note that a crustal porosity greater than 50% would be needed to make such a thick crust. A more reasonable olivine density puts the crustal thickness between 25 km and 30 km. This is much thinner than the crustal thickness required to hide olivine inside Vesta (indicated in the shaded region at the far right of Fig. 3). We conclude that it is impossible to explain the thick crust of Vesta inferred from the absence of expose olivine by making it very porous, because in such a case an unrealistically high mantle density would be required.

4.2. Mantle composition of an H chondrite analogue Vesta

Another way to put chondritic limits on the size of mantle and crust is to recognize that aluminum is an essential ingredient of plagioclase, and to calculate the amount of crustal material based on the total aluminum abundance found in chondrites.

As we noted above (and as suggested by Toplis et al., 2013) the size of Vesta's core is best matched by a bulk composition similar to an H chondrite. Assume therefore that the HED parent body started with the same molar abundances of the major oxides as is seen in H chondrites, but with all the sodium removed from the system. The metal and sulfide content of this composition is assumed to form the core of our parent body. The remaining oxides will go into the crust and mantle, which we will call the bulk rock composition. One can determine the molar abundance of aluminum in this bulk rock composition, and scale the molar abundances of the major oxides in howardites such that the molar abundance in the howardites matches this aluminum molar abundance. One then subtracts these moles of aluminum, calcium, magnesium, silicon, and iron present as iron oxide from the bulk rock composition. The remaining number of moles of these oxides can be converted to weight percents, and via the CIPW calculation (Hess, 1989) a mineralogy and density of the complementary mantle can be modeled.

Our calculated mantle composition is 51% olivine, 48% orthopyroxene, and 1% clinopyroxene (see Fig. 4). The Mg# calculated for this model source region is 0.85, higher than that seen in other olivine-rich meteorites, such as MIL 03443, NWA 5480 or Chassigny, or that calculated for the HED parent body mantle by Mandler and Elkins-Tanton (2013).

The thickness of the crust in this model can be calculated by assuming a porosity of the crustal material. If the crustal material's microporosity is 12.5% as is seen in howardite meteorites, the crust would be 25 km thick. In order to match the overall density of Vesta, the mantle would have to be 9% porous as well. To drive the mantle porosity to zero would require a 30 km thick crust with 28% porosity. Even this crust is far too thin to prevent the exposure of olivine in the Rheasilvia basin.

Note that the mantle is roughly half orthopyroxene, half olivine. Is it possible that these minerals lie in two layers, with the olivine hidden not only beneath the howardite crust but also beneath a diogenitic upper mantle? Assuming that the olivine lower mantle has a density of 3600 kg/m^3, typical of olivine with an Mg# of 0.8, the thickness of the combined howardite crust and this additional orthopyroxene mantle layer is still only 70 km for the howardite thickness case outlined above.

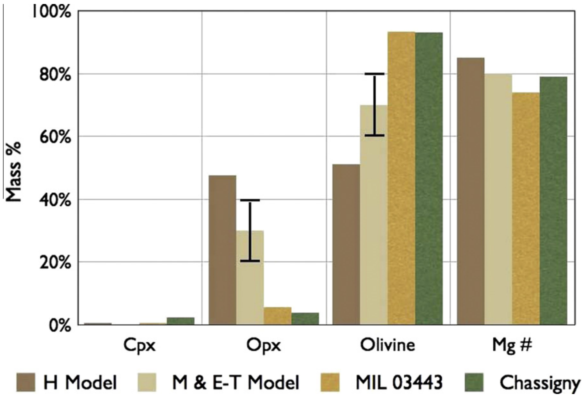


Fig. 4. An attempt to model the mantle of a "chondritic" HED parent body based on an H chondrite composition, less sodium, fails to produce a composition compatible with previous suggestions for the HED parent mantle composition. While all compositions are depleted in clinopyroxe (Cpx), as expected, the calculated mantle based on H chondrite major element abundances (leftmost bars) is more enriched in orthopyroxe (Opx) and depleted in olivine than the range of compositions (indicated by the error bars) suggested by Mandler and Elkins-Tanton (2013) (second bar from left, labeled "M & E-T Model"); the observed composition of the olivine-rich diogenite MIL 03443 (second bar from the right); or the martian dunite Chassigny (green bars, to the right) which has been suggested by Mandler and Elkins-Tanton (2013) as a Vesta mantle analogue. In addition, the magnesium number Mg# is higher for the H-chondrite model than any of these other suggested compositions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Making the crust and upper mantle layers any thicker (by, for example, increasing their porosity even further) does not allow enough room between mantle and core to accommodate the amount of olivine needed to match the overall mass of Vesta and the requirement of chondritic abundances. This is illustrated in Fig. 5. Assume our Cases A and B, set by the REE constraints as described above: howarditic crusts making up 15% and 21% of Vesta's mass. Let half the mantle mass beneath that crust be orthopyroxene with the grain density of a diogenite. By increasing the macroporosity of these two layers one can make them very thick; but in that case, the density of the olivine-rich layer at the bottom of the mantle must increase in order to maintain the total mass of Vesta. In Fig. 5 we show the resulting density required for the olivine in these scenarios. (Only one line is visible since the result of lower mantle density as a function of crustal thickness is essentially the same for both Case A and Case B.) As can be seen in the figure, it is just possible to have an 85 km thick crust and upper mantle overlying the olivine layer, but only if the olivine is essentially pure fayalite (i.e., a magnesium number Mg# of 0.0, compared to Mg# = 0.85 expected for a mantle derived from an H chondrite composition) and the crust and upper mantle layers would have to have a macroporosity of about 25%.

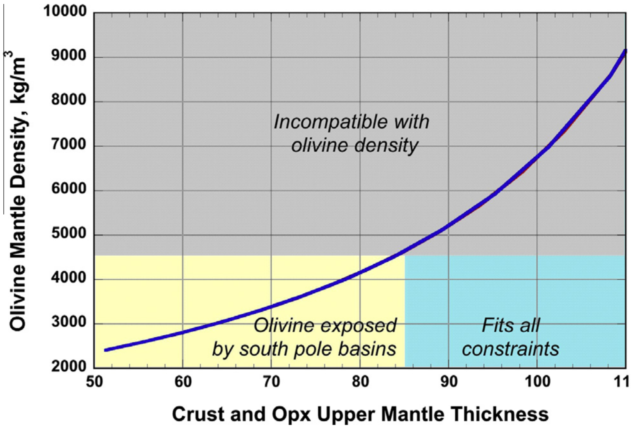


Fig. 5. Density required for a lower olivine mantle hidden by a howardite crust and orthopyroxene upper mantle. The gray shaded region denotes an olivine density greater than pure fayalite; the blue shaded region is the thickness required to hide the lower olivine mantle from exposure during the formation of the south pole basins. Note that even the minimum thickness still requires the olivine layer to be essentially pure fayalite in density, which is very unlikely. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In addition, if Vesta did have such a thick upper mantle rich in orthopyroxene, presumably similar in composition to diogenites, one might expect to see a larger proportion of diogenites within our meteorite collection, inconsistent with meteorite fall statistics. In the same way, one might expect to observe numerous diogenitic asteroids among the Vestoids; such are not observed.

Finally, one might argue that the multi-layer model of Vesta adopted in our calculations is a oversimplification and that some of the olivine we assumed to be in the mantle could actually be present as plutons amidst the vestan crust (cf. Mittlefehldt, 1994). Such a scenario could naturally explain the presence of olivine at shallower depths and would increase the thickness of an initially thin vestan crust (similarly to the case of the porous crust we considered, only with olivine instead of voids). However, to increase the crustal thickness by adding olivine means that olivine plutons should be abundant in the crust (otherwise their effect on the crustal thickness would be limited): in this case we should see the signature of these plutons inside Rheasilvia (in the walls, in the floor, or on the central peak) or in other large craters on Vesta, which we do not. Furthermore, olivine is much denser than crustal material; if large amounts of olivine were somehow hidden in the crust in this manner, it would be a challenge to match the overall density of Vesta with such a model. And in addition, the issue of the unrealistic Mg# in that olivine discussed above would remain.

4.3. Other "chondritic" models

"Chondritic" does not necessarily have to mean "identical to a known chondrite type." We know from oxygen isotopes alone, which are significantly different between the chondrites and the HEDs, that one cannot simply melt a large H chondrite to make eucrites even if the sodium could somehow be removed. Rather, by "chondritic" we merely mean that we are looking for a parent body with relative abundances of the major elements – silicon, magnesium, aluminum, and calcium – that are the same as the ratios seen in chondrites.

That being the case, note also that a large metal core is not required for the model to be considered "chondritic". In fact, there is significant variation among chondritic meteorite types in both the amount and oxidation state of the iron. One could, ad-hoc, create any number of possible bulk compositions that were enriched in FeO but depleted in metallic iron and FeS, such that the total iron content remained within the range of cosmic ratios. If there were less iron metal but more FeO present, this FeO would serve to convert the orthopyroxene back into olivine while lowering the Mg# well into the range more typical of geochemical models and olivine-bearing meteorites.

As an example, we have constructed one such ad-hoc model by arbitrarily increasing the FeO content compared to the abundance seen in ordinary chondrites; instead of the 10–14% seen in H and L chondrites, respectively, we postulate an abundance of 18%. At the same time, we assume no iron sulfide is present, and drop metallic iron content to roughly half that seen in chondrites. The other major element ratios stay the same, and the total Fe content remains in the range seen in chondrites. Given such a parent body composition, our calculated mantle would consist of about 70% olivine, 30% orthopyroxene, similar to the composition proposed by

Mandler and Elkins-Tanton (2013). The calculated mantle would have an Mg# of 0.73 and a density of 3500 kg/m^3; close to the values of MIL 03443. The density of a Vesta with this core and mantle and a 25-km thick crust of howarditic material would match the observed density of Vesta.

Of course, a parent body constructed in this way would have a core that is less than half the mass of the iron core indicated by Ermakov et al. (2014) for Vesta, and the resulting crust would be much too thin to explain the lack of mantle material on the surface of Vesta. To increase the core to the mass seen by Ermakov et al. (2014), but maintain the extra FeO in the mantle needed to produce the required olivine abundance, would demand that Fe would be more than half again as abundant in Vesta than would be expected from cosmic abundances.

This is not a pointless calculation; it demonstrates that it is certainly possible to make HED meteorites in a relatively simple parent body whose composition contains the major rock-forming elements (except sodium) in chondritic proportions. Many other such ad-hoc models for the HED parent body could be constructed, if one ignores the constraints of the Dawn results. Our difficulty is not in finding a reasonable parent body composition that can produce the HEDs. Rather, our difficulty is matching the necessary constraints of that parent body to the constraints that Dawn has observed at Vesta.

5. Discussion and conclusions

Until the arrival of the Dawn mission, the available observational data and the HED meteorites suggested the following story: Vesta was a differentiated asteroid and the progenitor of the HED meteorites, which represented the upper and lower layers of a relatively thin basaltic crust and diogenitic upper mantle that topped a large lower mantle dominated by olivine. The absence of large quantities of olivine in the HED collection was consistent with the global survival of the vestan basaltic crust as indicated by spectral data provided by remote observations. At the same time, the presence of some olivine on Vesta suggested by remote observations was in agreement with the existence of a giant impact basin at the vestan south pole that could have locally excavated the crust and extracted material from the olivine-dominated mantle. The existence of the Vestoids and the lack of members of this family exhibiting a clear olivine signature also fitted nicely in the previous picture, as on one hand it supported the idea that the giant impact basin now known as Rheasilvia excavated mainly the basaltic surface of Vesta, and on the other it provided a dynamical path for bringing the HEDs from Vesta to the Earth.

The observations and finding of the Dawn mission confirmed the identification of the HEDs with the material composing the surface of Vesta, the keystone assumption of the previously described scenario. At the same time, however, the Dawn mission revealed to us three other pieces of information that contradict that simple scenario.

The first observation is that Rheasilvia is not the only giant impact basin at the south pole of Vesta: a second, older basin also exists and the regions excavated by the two basins partially overlap.

The second observation is that olivine is present only in a handful of spots having extensions of the order of one hundred meters and almost all of it is located outside of Rheasilvia. Impact simulations can properly reproduce the morphology of the two impact basins but indicate that quantities of olivine-dominated mantle material far larger than those observed should be present on the surface of Vesta and in the two basins themselves. All searches for olivine inside Rheasilvia, in particular on its central peak (which represents the uplift of material originally located at depth) and in the region where Rheasilvia and Veneneia overlap (which represents the region of deepest excavation), gave negative results.

The third observation is the large size of the dense metal-rich core revealed by Dawn, which puts severe limits on the density and FeO content of the remaining rocky material making up Vesta's crust and mantle regions. While the puzzle of the large impact basins and the lack of olivine have been noted before, the full implications of demanding both such a thick crust and a large core on the necessary density structure of Vesta have not been appreciated up to now.

All these facts, once put together, are seriously at odds with our pre-Dawn understanding of Vesta. Our pre-Dawn idea of Vesta is proving to be like a blanket that is too short to cover everything at the same time. As we showed in the previous sections, there is too little olivine on Vesta's surface to be consistent with the thin crust suggested by geochemical models based on the HEDs and the surface morphology and interior structure of the asteroid constrained by Dawn. This issue becomes even more critical if some or all of the olivine identified by Dawn is actually an exogenous contaminant brought on the asteroid by impacts as different works are suggesting (Turrini et al., 2014a; Le Corre et al., 2015), as it implies that even less olivine was excavated from the mantle. At the same time, the existence of a thick crust and large core does not leave enough space within Vesta to accommodate all of the olivine needed to explain the enrichment patterns of the HEDs based on our cosmochemical understanding of meteorites.

The results of our work, once put in the context of the data from Dawn and the HEDs, therefore suggests that something must be wrong with the assumptions on which our pre-Dawn ideas on Vesta were based. Unless one questions the data themselves or the Vesta-HEDs link (which we do not), the only possibilities left are a) that Vesta formed from a non-chondritic source material or b) that the Vesta we see today is not the same as the Vesta where the HED meteorites formed; it must have been significantly altered in its global composition and interior structure. Note that it is possible to merge these two possibilities into a single one if Vesta were altered after its differentiation: it would be enough to affect only one component, e.g. the crust, and not the other, e.g. the mantle, to alter its global composition.

The aim of this paper is to explicitly point out the mismatch between our pre- and post-Dawn understanding of Vesta. Assessing the root of this mismatch is going to require several dedicated investigations in the years to come and is therefore far beyond our scope here. However, we can already point out here that, while contradicting our pre-Dawn ideas, the possibility that Vesta was altered in some way during its lifetime is consistent with our current understanding of the data on the iron meteorites (Goldstein et al., 2009) and, more generally, with our understanding of the evolution of the asteroid belt.

More than 1000 different iron meteorites are known, which can be classified into more than 50 different chemical and isotopic groups. This suggests that they sample the cores of at least 50 different differentiated, and destroyed, parent bodies (Goldstein et al., 2009). The iron meteorites come to us from the current asteroid belt – their cosmic ray exposure ages are all less than one billion years (see Eugster, 2003) – and thus they sample an asteroid belt not all that different from what we see today. But the asteroid belt that they sample is only a fraction of the original asteroid belt: the mass of the asteroids today represents less than one part in a thousand of the original mass of the region in which the asteroids, including differentiated asteroids, formed (Weidenschilling, 1977; Petit et al., 2002 and references therein; O'Brien et al., 2007; Walsh et al., 2011). Instead of fifty different parents, one might extrapolate from the variety of iron meteorites in our collections to the existence of perhaps 50,000 individual protoplanets

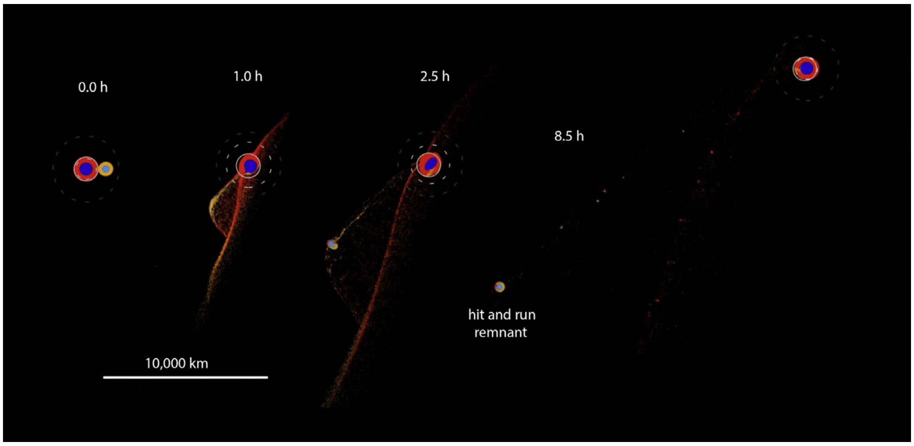


Fig. 6. Four snapshots through the symmetry plane of a collision where an 0.0002 Earth mass impactor (about 800 km diameter), impacts an 0.001 Earth mass target (about 1400 km diameter), at 2.5 times their mutual escape velocity (0.93 km/s), at an impact angle of 22.5° (from Asphaug and Reufer, 2014). Both bodies start out as completely differentiated chondritic spheres, where light/dark blue are the iron cores of the projectile/target, and yellow/red are their silicate mantles. Resolution ($h \sim 30$ km) in this model is not sufficient to resolve a separate crust and mantle. The projectile is ripped apart into a tidal arm that partly reaccretes around an undisrupted core, drawing out a plume of escaping material and changing the final mass balance of all components of the planetesimal. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

that were differentiated, and destroyed, at the time when the HED meteorites were being formed.

Whatever event caused the destruction and shattering of these 50,000 protoplanets should have been a large scale event that affected all the asteroid belt, if not all the inner Solar System: therefore, it would be unreasonable not to think that it should have left some marks on Vesta as well. Our current understanding of the primordial evolution offers several good candidates for such kinds of events: the phase of excitation and depletion of the asteroid belt (see Petit et al., 2002 and references there; O'Brien et al., 2007), the formation of Jupiter and the bombardment it triggers (Turrini et al., 2011, 2012) and the possible large-scale dynamical rearrangement of the orbits of the giant planets in the circumsolar disk (Walsh et al., 2011). All these events occurred during the violent early phases of the life of the Solar System, when Vesta was already differentiated and likely still in a molten state; these events were all associated with an enhanced rate of collisions between the existing planetary bodies.

A series of papers by Asphaug et al. (2006), Asphaug (2010) and Asphaug and Reufer (2014) on the nature and outcome of grazing or "hit and run" collisions offers one possible mechanism through which Vesta could have been altered in a desirable way during this violent early epoch. These authors shows that not only could asteroids be completely destroyed but in fact a more likely outcome of collisions would be the stripping of asteroidal surfaces from their mantles and cores (see Fig. 6). A single hit and run collision such as this would cause minimal shock heating, but considerable frictional heating and other modes of mechanical and gravity-driven energy input and advection. One (unpublished) calculation they performed suggests that one can in fact eject a significant amount of the mantle from the projectile body while retaining a large fraction of its original crust; the process leaves intact two partial hemispheres of crust because material is not stripped orthogonal to the Roche lobes on the rotating tidally distorted object (E. Asphaug, personal comm.).

Our own preliminary calculations (cf. Turrini et al., 2014b and references therein for information on the collisional model) suggest that, over the first 20 Ma of the life of the Solar System, the depletion rate of the asteroid belt estimated by O'Brien et al. (2007) and the impact probabilities computed by Bottke et al. (2005) would lead to a Vesta-sized body having a probability of ~1% of impacting a 1000 km diameter body, i.e. roughly the size range needed for the hit-and-run stripping of the mantle. This is comparable to the survival rate for the depletion process of the asteroid belt (5% to 1%, see O'Brien et al., 2007 and references therein). In other words, a comparatively large fraction of the Vesta-sized objects that survived the depletion process and were not ejected from the asteroid belt could have undergone the kind of impact discussed by Asphaug and Reufer (2014).

Before concluding, we want to emphasize once again that here we are not arguing in favor of one specific scenario over the other, nor are we attempting to find the final answer to the mismatch between the pictures of Vesta depicted by the HEDs and by Dawn's data. We are simply pointing out that this mismatch exists and it is not inconsistent with what we know about the history of the asteroid belt and the processes that govern its evolution.

Indeed, our current understanding already opens up several possible ways in which the mismatch can be explained. Finding the answer to this riddle should provide us with a new and deeper insight on the very earliest evolution of the Solar System.

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