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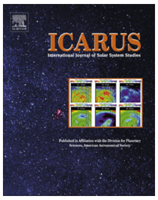

Is Vesta an intact and pristine protoplanet?

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