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Olivine on Vesta as exogenous contaminants brought by impacts: Constraints from modeling Vesta's collisional history and from impact simulations

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A B S T R A C T

The survival of asteroid Vesta during the violent early history of the Solar System is a pivotal constraint on theories of planetary formation. Particularly important from this perspective is the amount of olivine excavated from the vestan mantle by impacts, as this constrains both the interior structure of Vesta and the number of major impacts the asteroid suffered during its life. The NASA Dawn mission revealed that olivine is present on Vesta's surface in limited quantities, concentrated in small patches at a handful of sites not associated with the two large impact basins Rheasilvia and Veneneia. The first detections were interpreted as the result of the excavation of endogenous olivine, even if the depth at which the detected olivine originated was a matter of debate. Later works raised instead the possibility that the olivine had an exogenous origin, based on the geologic and spectral features of the deposits. In this work, we quantitatively explore the proposed scenario of a exogenous origin for the detected vestan olivine to investigate whether its presence on Vesta can be explained as a natural outcome of the collisional history of the asteroid over the last one or more billion years. To perform this study we took advantage of the impact contamination model previously developed to study the origin and amount of dark and hydrated materials observed by Dawn on Vesta, a model we updated by performing dedicated hydrocode impact simulations. We show that the exogenous delivery of olivine by the same impacts that shaped the vestan surface can offer a viable explanation for the currently identified olivine-rich sites without violating the constraint posed by the lack of global olivine signatures on Vesta. Our results indicate that no mantle excavation is in principle required to explain the observations of the Dawn mission and support the idea that the vestan crust could be thicker than indicated by simple geochemical models based on the Howardite–Eucrite–Diogenite family of meteorites.

1. Introduction

Asteroid Vesta, explored between 2011 and 2012 by the NASA Dawn mission (Russell et al. 2012, 2013), has long been identified as the source of the Howardite–Eucrite–Diogenite (HED) suite of meteorites (McCord et al. 1970; Consolmagno and Drake, 1977; De Sanctis et al. 2012a; Prettyman et al. 2012). These meteorites suggested that Vesta is a differentiated asteroid that accreted and experienced global melting (see e.g. Greenwood et al. 2014; Steenstra et al. 2016) in the first 3 Ma of the life of the Solar System (Bizzarro et al. 2005; Schiller et al. 2011; Consolmagno et al. 2015 and references therein).

Compositional models of Vesta's interior based on the information provided by the HEDs and on cosmochemical constraints (Mandler and Elkins-Tanton 2013; Toplis et al. 2013; Consolmagno et al. 2015 and references therein) indicate that eucrites and diogenites represent the main components of the upper and lower crust of the asteroid, and that the total thickness of this crust should range between 20 and 40 km (see Consolmagno et al. 2015 for a detailed discussion of the porosity of the vestan crust). A part (10–20%, Mandler and Elkins-Tanton 2013) of the lower crust

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was suggested to be in the form of olivine diogenite, i.e., diogenite minerals containing $<40\%$ olivine. Underneath this crust, a mantle rich in olivine (harzburgite containing 60–80% olivine, Mandler and Elkins-Tanton 2013; Toplis et al. 2013; Consolmagno et al. 2015) should extend down to an Fe-dominated core with an estimated radius of 110–140 km depending on its density (Russell et al. 2012; Mandler and Elkins-Tanton 2013; Ermakov et al. 2014; Consolmagno et al. 2015).

The Dawn mission, while confirming the global survival of the eucritic-diogenitic crust (De Sanctis et al. 2012a; Prettyman et al. 2012), revealed that the vestan surface is densely covered, plausibly to saturation level (Marchi et al. 2012; Turrini et al. 2014; Pirani and Turrini 2016), by craters of all sizes that testify to the violent collisional past of the asteroid. Moreover, the data provided by the Framing Camera (FC) onboard the Dawn spacecraft showed that the 500 km wide Rheasilvia basin, originally identified (Thomas et al. 1997) through the observations of the Hubble Space Telescope, partially overlaps an older 400 km wide basin, Veneneia (Russell et al. 2012; Marchi et al. 2012; Schenk et al. 2012).

According to numerical simulations and their comparison with Dawn's data, the impacts that created Rheasilvia and Veneneia should have reached depths of at least 40–80 km, in principle excavating the crust and exposing the harzburgitic mantle in the crater floor and walls, in the ejecta, or both (Ivanov and Melosh 2013; Jutzi et al. 2013). The data provided by the Visual and near-InfraRed spectrometer (VIR) onboard Dawn, however, ruled out the possibility of large exposures of olivine inside Rheasilvia and on the rest of the vestan surface (De Sanctis et al. 2012a; Ammannito et al. 2013). The lack of olivine signatures in the central mound of Rheasilvia, in particular, was attributed by Ruesch et al. (2014a) to the absence of significant quantities (i.e. $\geq$20–30%) of olivine down to the depths ($\geq$40 km, Ivanov and Melosh 2013; Jutzi et al. 2013; Clenet et al. 2014) excavated by the impacts.

After extensive searches, two olivine-rich (50–80%) sites (Ammannito et al. 2013) associated with the post-Rheasilvia craters (Ruesch et al. 2014b) Arruntia and Bellicia were identified by VIR in the northeastern hemisphere of Vesta (see Fig. 1). The distribution of the olivine outcrops observed by VIR was described as consistent with the exposure of shallow olivine deposits (Ammannito et al. 2013).

The list of olivine-rich sites was expanded by the discovery by VIR of a second set of 11 sites (see Fig. 1) containing lower concentrations of olivine (<50% but plausibly >20–30%, Ruesch et al. 2014a), all in the eastern hemisphere except for one located in the western hemisphere inside Rheasilvia (see Fig. 1 and Ruesch et al. 2014a). Most of these sites were associated with post-Rheasilvia craters and, because of the shallow depths of the latter, were interpreted as the exposition of local plutonic deposits of olivine diogenite (Ruesch et al. 2014a). A few sites were identified on the outer part of the rim of Rheasilvia and interpreted as ballistic-deposited material originating from near-by excavated craters (Ruesch et al. 2014a).

An alternative third set of 6 less olivine-rich sites was later identified through VIR, all consisting of different outcrops with olivine concentration comprised between 25% and 50% and all but one northern of the original two (see Fig. 1 and Palomba et al. 2015). One of these sites is located inside Rheasilvia and one in the western hemisphere (Palomba et al. 2015). The two sets of 11 and 6 less olivine-rich sites do not overlap between them (Fig. 1; Ruesch et al. 2014a; Palomba et al. 2015), Arruntia and Bellicia being the only regions identified in all studies performed on the VIR dataset. Nevertheless, in all sites identified by VIR (Ammannito et al. 2013; Ruesch et al. 2014a; Palomba et al. 2015) olivine is reported in outcrops hundreds of meters wide.

The survival of Vesta's crust and the exposure (or lack thereof) of its harzburgitic mantle has long been identified as a pivotal constraint for the study of the evolution of the asteroid belt (see O'Brien and Sykes 2011 and references therein; Consolmagno et al. 2015) and the whole Solar System (see Coradini et al. 2011 and references therein; Brož et al. 2013; Turrini, 2014; Turrini and Svetsov 2014; Consolmagno et al. 2015; Pirani and Turrini 2016). For this constraint to be valid, however, it is essential we understand the interior structure and geological history of Vesta, but the limited number of olivine-rich sites, together with the small sizes of the outcrops and the lack of high-concentration ($\geq$50%) outcrops inside Rheasilvia and on its central mound (Ammannito et al. 2013; Ruesch et al. 2014a; Palomba et al. 2015) cast doubts on the pre-Dawn ideas on the geophysical evolution of Vesta and the petrology of the HEDs (see Consolmagno et al. 2015 for a discussion).

The proposed association of the outcrops observed at Arruntia and Bellicia with the excavation of more surficial olivine plutons (Ammannito et al. 2013) could in principle be explained with the formation of Vesta's crust through serial magmatism in a series of shallow magma chambers instead of an extended magma ocean (Mandler and Elkins-Tanton 2013) while the lack of olivine-rich outcrops inside Rheasilvia could be the result of the deposition at depth of the olivine during the mantle crystallization, resulting in a olivine-depleted upper mantle overlying a olivine-enriched lower mantle (Toplis et al. 2013). Both these scenarios, however, have been proved not to be so straightforward in their application to Vesta once mass balance and the abundance of trace elements and rare earth elements in the HEDs are taken into account (Barrat and Yamaguchi 2014; Consolmagno et al. 2015; Steenstra et al. 2016).

The observational data from the Dawn mission recently provided a final piece of information on the subject that suggested a possible solution to this problem. A search for olivine-rich deposits performed in the dataset provided by the FC using a set of three spectral parameters (Nathues et al. 2015) resulted in the identification of a number of small outcrops, all associated with impact features. This fourth set of olivine-rich sites partly overlaps the set identified by Ruesch et al. (2014a) and partly with that reported by Palomba et al. (2015). As in the case of the previous studies (Ammannito et al. 2013; Ruesch et al. 2014a; Palomba et al. 2015), the results of Nathues et al. (2015) confirm Arruntia and Bellicia as the regions associated with stronger olivine signatures.

While the data in the visible range are less reliable than those in the infrared for the identification of olivine, the higher resolution (about a factor of three) offered by Dawn's FC with respect to that of VIR allows for more detailed information on the spatial distribution and morphology of the olivine-rich sites. Based on their results and in contrast to previous work (Ammannito et al. 2013; Ruesch et al. 2014a), Nathues et al. (2015) argued that the geologic nature and context of the vestan olivine is suggestive of an exogenous nature, a claim supported by the contemporary reanalysis of the VIR spectral data on the olivine signatures associated to Arruntia and Bellicia by Le Corre et al. (2015).

An exogenous origin of the olivine could be easily explained, from a qualitative point of view, as the natural outcome of the continuous flux of impactors on Vesta over the lifetime of the asteroid (Turrini et al. 2014) and would be supported by the results of hydrodynamic simulations of the fate of projectiles after hypervelocity impacts (Svetsov 2011; Turrini and Svetsov 2014; Svetsov and Shuvalov 2016). Recent impact experiments (Daly and Schultz 2015, 2016; McDermott et al. 2016, Avdellidou et al. 2016) have provided strong observational support to this scenario, as they confirm that, in contrast to hypervelocity ($>$20–30 km/s) impacts where stony projectiles undergo complete vaporization (e.g., Melosh 1989; Svetsov and Shuvalov 2016), a significant fraction of the projectile indeed survives the impact at the velocities characteristic of the asteroid belt (Daly and Schultz 2015, 2016; McDermott et al. 2016, Avdellidou et al. 2016).