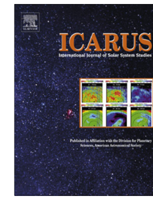
Icarus 258 (2015) 483–499

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus



Exploring exogenic sources for the olivine on Asteroid (4) Vesta

Lucille Le Corre [a,*], Vishnu Reddy [a], Juan A. Sanchez [a], Tasha Dunn [b], Edward A. Cloutis [c], Matthew R.M. Izawa [c], Paul Mann [c], Andreas Nathues [d]

[a] Planetary Science Institute, 1700 East Fort Lowell, Suite 106, Tucson, AZ 85719, USA
[b] Colby College, Department of Geology, 5800 Mayflower Hill, Waterville, ME 04901, USA
[c] Department of Geography, University of Winnipeg, 515 Portage Avenue, Winnipeg, Manitoba R3B 2E9, Canada
[d] Max-Planck-Institute for Solar System Research, Göttingen, Germany

ARTICLE INFO

Article history:
Available online 30 January 2015

Keywords:
Asteroid Vesta
Asteroids, composition
Asteroids, surfaces
Mineralogy
Spectroscopy

ABSTRACT

The detection of olivine on Vesta is interesting because it may provide critical insights into planetary differentiation early in our Solar System's history. Ground-based and Hubble Space Telescope (HST) observations of Asteroid (4) Vesta have suggested the presence of olivine on the surface. These observations were reinforced by the discovery of olivine-rich HED meteorites from Vesta in recent years. However, analysis of data from NASA's Dawn spacecraft has shown that this "olivine-bearing unit" is actually impact melt in the ejecta of Oppia crater. The lack of widespread mantle olivine, exposed during the formation of the 19 km deep Rheasilvia basin on Vesta's South Pole, further complicated this picture. Ammannito et al. (Ammannito, E. et al. [2013a]. Nature 504, 122–125) reported the discovery of local scale olivine-rich units in the form of excavated material from the mantle using the Visible and InfraRed spectrometer (VIR) on Dawn. These sites are concentrated in the walls and ejecta of craters Arruntia (10.5 km in diameter) and Bellicia (41.7 km in diameter), located in the northern hemisphere, 350–430 km from Rheasilvia basin's rim. Here we explore alternative sources for the olivine in the northern hemisphere of Vesta by reanalyzing the data from the VIR instrument using laboratory spectral measurements of meteorites. Our rationale for using the published dataset was to bypass calibration issues and ensure a consistent dataset between the two studies. Our analysis of the VIR data shows that while the interpretation of their spectra as an olivine-rich unit is correct, the nature and origin of that olivine could be more complicated. We suggest that these olivine exposures could also be explained by the delivery of olivine-rich exogenic material. This hypothesis is supported by meteoritical evidence in the form of exogenic xenoliths containing significant amount of olivine in some of the HED meteorites from Vesta. Previous laboratory work on HEDs show that potential sources of olivine on Vesta could be different types of olivine-rich meteorites, either primitive achondrites (acapulcoites, lodranites, ureilites), ordinary chondrites (H, L, LL), pallasites, or carbonaceous chondrites (e.g., CV). Based on our spectral band parameters analysis, the lack of correlation between the location of these olivine-rich terrains and possible mantle-excavating events, and supported by observations of HED meteorites, we propose that a probable source for the olivine seen in the northern hemisphere corresponds to remnants of impactors made of olivine-rich meteorites. The best curve-matching results with laboratory spectra suggest these units are HED material mixed with either ordinary chondrites, or with some olivine-dominated meteorites such as R-chondrites.

1. Introduction

Olivine is the "Rosetta Stone" of planetary differentiation. Its abundance and chemistry provide important clues into the conditions under which it forms including the composition of the starting material, redox state, temperature, etc. Olivine is also the most abundant mineral formed during planetary differentiation, normally making up the bulk of an object's mantle for inner Solar System bodies. However, olivine on asteroids remains elusive with only a handful of asteroids composed mostly of olivine identified to date (e.g., Sanchez et al., 2014). This lack of olivine in the main asteroid belt has been termed the "missing olivine problem".

Using ground-based telescopic observations, several researchers have looked for evidence for the presence of olivine on Vesta without success (Larson and Fink, 1975; Feierberg and Drake, 1980). Similarly, McFadden et al. (1977) inferred that olivine was probably very rare or absent from the surface of Vesta using data in the

* Corresponding author.
E-mail address: lecorre@psi.edu (L. Le Corre).

http://dx.doi.org/10.1016/j.icarus.2015.01.018
0019-1035/

visible wavelength range. The first possible detection of olivine with a significant surface coverage on Vesta was presented in Gaffey (1997). In this paper, the authors interpreted a drop in pyroxene Band Area Ratio (BAR) between 60 and 120°E longitude (Thomas et al. (1997) coordinate system) in rotationally-resolved spectra of Vesta as a possible indicator of the presence of olivine. This feature, nicknamed the "Leslie formation", was interpreted to be a deposit of olivine from the mantle probably emplaced by ejecta material from a large impact. With the analysis of the Dawn Framing Camera (FC) data, Reddy et al. (2013) associated this "Leslie formation" with the Oppia crater and its ejecta. Le Corre et al. (2013) ruled out the presence of olivine in this crater and concluded that the drop in BAR was due to the presence of impact melt rather than olivine. McSween et al. (2013a) reported that no large olivine deposits were detected within the Rheasilvia basin suggesting that no significant amount of olivine has been excavated by basin-forming impacts in the south polar region. Beck et al. (2013) suggested that the lack of olivine detections could be explained by the dilution of olivine abundance in harzburgitic diogenite exposures.

The scarce detection of olivine on Vesta is consistent with the rarity of olivine-rich diogenites (11 samples of olivine diogenites and 368 diogenites) in the meteorite collection (Met. Bulletin). Diogenites are generally monomineralic (orthopyroxenite) and contain less than 10% of olivine in addition to minor eucritic fragments (McSween et al., 2010). Olivine diogenites correspond to cumulate orthopyroxene-rich rocks but contain a significant amount of olivine. Among olivine diogenites, Beck and McSween (2010) identified mixtures of olivine and magnesian orthopyroxene as harzburgites, and the most common diogenites made of two distinct orthopyroxenes (Mg-rich and Fe-rich) as breccias of two different lithologies (polymict diogenites). Beck and McSween (2010) proposed new subdivisions among diogenites with dunitic, harzburgitic, and orthopyroxenitic diogenites based on the content of olivine and orthopyroxene: orthopyroxenite has <10% olivine, harzburgite can contain 10–90% olivine, and dunite is characterized by >90% olivine. Only three diogenites composed essentially of pure olivine have been described: a monomineralic dunite clast in NWA 5968 (Bunch et al., 2010) and dunite MIL 03443 (Mittlefehldt, 2008), both brecciated dunites (Beck et al., 2011a), and cataclastic dunite NWA 5784 (Bunch et al., 2010). A third achondrite (NWA 2968) with >95% olivine is also considered a dunite from Vesta (Bunch et al., 2006). Concerning the howardites, Beck et al. (2012) analyzed olivine-rich impact melt in a group of howardites that suggest the possible incorporation of dunitic and harzburgitic lithologies in the howarditic target rock. Two other groups of olivines were found in these howardites, one formed by secondary processes on Vesta (crystallized from the melt), and one possibly from exogenic origin.

Ammannito et al. (2013a) described the identification of olivine-rich units emplaced over howarditic background terrain in Arruntia (39.44°N, 221.59°E) and Bellicia (37.73°N, 197.76°E) craters (for a map with vestan nomenclature, see USGS website[1]). The location of these units comes as a surprise because one would expect olivine to be present around the Rheasilvia impact basin (e.g. Ruzicka et al., 1997; Jutzi and Asphaug, 2011), which is thought to have breached the crust–mantle boundary (Thomas et al., 1997). Olivine is found in the walls of Arruntia crater, a relatively young crater with well-defined rims and visible ejecta rays; and in the walls of Bellicia crater and nearby secondary craters that have excavated and deposited olivine on Bellicia's ejecta blanket. In addition to crater walls, Ammannito et al. (2013a) described the olivine distribution as being scattered diffusely over a broad area. Bellicia is a larger crater (41.7 km in diameter) than Arruntia (10.5 km in diameter). Bellicia appears older than Arruntia with more subdued crater rim and most of the crater walls and floor covered by regolith. In Dawn Framing Camera (FC) images made with Clementine color ratios, Arruntia exhibits orange/red material in its ejecta (i.e. with redder visible slope than average howarditic terrains) suggesting the presence of impact melt (Le Corre et al., 2013). Both craters are located in a howarditic terrain enriched in eucrite-like material in the FC color ratio map from McSween et al. (2013b), which is in agreement with the results inferred from VIR data (Ammannito et al., 2013a).

Using color parameters derived from the FC color filters, Thangjam et al. (2014) confirmed the presence of olivine-rich units (>60% olivine) in Bellicia and Arruntia craters ranging in diameter from few hundred meters to few kilometers. Arruntia is located ~430 km and Bellicia is located ~350 km from the rim of the Rheasilvia basin. Even though these olivine sites are far from the Rheasilvia basin's floor and walls, Ammannito et al. (2013a) favored a mantle origin for these olivine-rich units because of the large area of the deposits and the lack of detected diogenite-like rock. This seems in contradiction to the generally accepted notion that diogenite from the lower crust would be excavated along with mantle olivine and the fact that all olivine-rich HEDs contain a significant amount of diogenitic material (i.e. orthopyroxenite). Nathues et al. (2015) conducted a global survey of olivine-rich units using FC color data and identified 15 sites in the northern hemisphere corresponding to impact craters with evidence for olivine-rich material on their walls and sometimes ejecta. Based on the geologic settings of these olivine deposits, they conclude a mantle origin for this olivine is unlikely. Additional work focused on the search of olivine-rich units using the VIR data demonstrated the lack of peridotitic mantle inside the Rheasilvia basin (Clenet et al., 2014; Ruesch et al., 2014). In contrast with previous findings, Poulet et al. (2015) proposed that olivine is in fact ubiquitous on Vesta at an abundance of 10–20% mixed in the howarditic regolith, and presented olivine-bearing howardites containing impact melt as further evidence for this finding.

Understanding the origin of olivine on Vesta has important implications for its formation and evolution. So far several hypotheses have been proposed to explain the lack of significant olivine in the Rheasilvia basin and the detection of olivine in the northern hemisphere. Here we summarize the proposed options:

- If the olivine on Vesta is of endogenic origin, excavated during the formation of the South Pole impact basins, then it is possible to assess the depth of crust/upper mantle boundary using geomorphological characteristics of the impact basins. The lack of olivine-rich lithologies (such as harzburgites) in the Rheasilvia basin would suggest that the mantle has not been breached (Clenet et al., 2014), or if it was breached, it is not detectable using the spectral and spatial resolution of the VIR spectrometer as demonstrated by Beck et al. (2013). Combining a VIR mineralogical map of Rheasilvia and Veneneia impact basins with results from impact modeling, Clenet et al. (2014) proposed that the crust/mantle boundary (so-called Moho) on Vesta was deeper than originally thought, at a depth of at least 80 km. They suggested that this deep Moho was probably not breached by the two catastrophic impacts at the South Pole. If this were true, then it is unlikely that the deposits of olivine-rich material in the northern hemisphere could come from Rheasilvia ejecta.
- An alternative endogenous source suggested in Ammannito et al. (2013a) to explain olivine-rich units in the northern hemisphere are olivine-rich plutons rising through the upper crust that are being exposed by impacts. This is a preferred scenario presented in Clenet et al. (2014) to explain both the lack of olivine in the material excavated by the Rheasilvia impact basin and the presence of olivine patches in the northern hemisphere.

[1] http://planetarynames.wr.usgs.gov/Page/VESTA/target.