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Olivine and pyroxene from the mantle of asteroid 4 Vesta

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ABSTRACT

A number of meteorites contain evidence that rocky bodies formed and differentiated early in our solar system's history, and similar bodies likely contributed material to form the planets. These differentiated rocky bodies are expected to have mantles dominated by Mg-rich olivine, but direct evidence for such mantles beyond our own planet has been elusive. Here, we identify olivine fragments (Mg# = 80–92) in howardite meteorites. These Mg-rich olivine fragments do not correspond to an established lithology in the howardite–eucrite–diogenite (HED) meteorites, which are thought to be from the asteroid 4 Vesta; their occurrence in howardite breccias, combined with diagnostic oxygen three-isotope signatures and minor element chemistry, indicates they are vestan. The major element chemistry of these Mg-rich olivines suggests that they formed as mantle residues, in crustal layered intrusions, or in Mg-rich basalts. The trace element chemistry of these Mg-rich olivines supports an origin as mantle samples, but other formation scenarios could be possible. Interpreted as mantle samples, the range of Mg-rich olivine compositions indicates that Vesta's structure differs from that predicted by conventional models: Vesta has a chemically heterogeneous mantle that feeds serial magmatism. The range of olivine major element chemistries is consistent with models of an incompletely melted mantle such as in the model proposed by Wilson and Keil (2013) rather than a whole-mantle magma ocean for Vesta. Trace element chemistries of Mg-rich pyroxenes (Mg# = 85–92) provide support that some of these pyroxenes may represent initial fractional crystallization of mantle partial melts.

1. Introduction

Meteorites can sample separate portions of differentiated asteroidal bodies; for instance, iron meteorites represent cores and basaltic achondrites correspond to crusts. While meteorite collections include samples that originate from up to 150 chemically distinct parent bodies (Burbine et al., 2002), those representing the ultramafic mantles of differentiated asteroids are rare. Most mantle samples should be characterized by Mg-rich olivine, based on redox conditions inferred from crustal meteorite assemblages, and assuming a chondritic bulk composition. The only meteorite examples are pallasites, which may be derived from mantle–core boundaries, and are not tied to any known crustal meteorite groups (Burbine et al., 2002). Mantle lithologies are also rare as collisional fragments in the asteroid belt (Sunshine et al., 2007). The rarity of mantle material, combined with the relative abundance of differentiated samples represented by crustal and core material, has confounded researchers.

One plausible location to search for samples containing mantle material is asteroid 4 Vesta, where the impact that created the Rheasilvia basin excavated to mantle depths of 60–100 km (McSween et al., 2013a; Jutzi et al., 2013). However, olivine has not been detected in this basin, possibly because modest amounts of coarse-grained olivine ($\leq$30%) are easily masked by orthopyroxene in visible/near-infrared spectra (Beck et al., 2013a). Although olivine-rich areas have been identified elsewhere on Vesta, the related olivine chemistry has not been determined and the related geologic context is not consistent with mantle material (Ammannito et al., 2013). The most abundant samples sourced from a differentiated body are the howardite, eucrite, and diogenite (HED) meteorites. HEDs are interpreted to represent samples of the crust of Vesta and possibly its upper mantle, based on numerous observations (McSween et al., 2013b); furthermore, the orbital

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distribution of Vesta-like asteroids in the asteroid belt is consistent with their ejection from Vesta during the impact that produced the Rheasilvia basin. Relatively small Vesta-like asteroids routinely cross Earth's orbital path and become meteorites. The vestan meteorites include a wide range of igneous lithologies, including eucrites (basalts and gabbros), and diogenites (orthopyroxenites, harzburgites). The howardites are brecciated samples of Vesta's regolith and megaregolith (e.g., Cartwright et al., 2014). Howardites incorporate fragments of eucrites, diogenites, impact-derived materials, exogenic chondritic components, and rare lithologies of undetermined provenance (e.g., Barrat et al., 2012). In this study, we investigate the provenance and petrogenesis of a howardite component of unknown origin: olivine and pyroxene fragments that are more Mg-rich than similar phases occurring in eucrite or diogenite meteorites.

2. Materials and methods

2.1. Meteorite samples

The 4 howardites in this study were all found within a ~4 km area in the Grosvenor Mountains field area (GRO) in Antarctica. These howardites—GRO 95534, GRO 95535, GRO 95574, GRO 95581—were proposed as a pairing group in their initial descriptions. Their pairing is also supported by similarities in their bulk geochemistry. Based on solar wind concentrations, these paired howardites formed from regolith that was exposed on an asteroid's surface, rather than from buried megaregolithic material (Cartwright et al., 2014).

The following howardite thin sections were analyzed in this study: GRO 95534,4; GRO 95535,16; GRO 95574,17; and GRO 95581,7. They all contain Mg-rich olivine of unknown provenance, as well as less magnesian olivine grains having compositions typically associated with diogenites (Beck and McSween, 2010). To evaluate the consistency of our methods with previous oxygen isotope analyses on HED meteorites using laser fluorination analytical methods, we also analyzed diogenite-composition olivine in the howardites and two diogenites: GRA 98108,16 and LEW 88008,14, which respectively represent meteorites found in the Graves Nunataks (GRA) and Lewis Cliff (LEW) sites in Antarctica.

2.2. Major element analyses & quantitative modal analyses

Electron microprobe analyses (EMPA) were performed with a Cameca SX-100 EMP at the University of Tennessee using wavelength-dispersive spectrometry (WDS). The mineral spot analyses were conducted with a 1 µm beam at the following conditions: 15 kV and 30 nA for olivine, and 20 kV and 100 nA for pyroxene. Analyses used PAP corrections. Natural and synthetic standards were analyzed daily, and ≥99% consistency with standards was maintained. The 3σ detection limits for 20 kV and 100 nA EMPA on olivine (Table 1) are as follows or lower (in ppm): Si 136, Mn 80, Fe 123, Mg 179, Al 122, Ca 120, Ti 77, Ni 44, Cr 111. The 3σ detection limits for 15 kV and 30 nA EMPA on pyroxene (Table 2) are as follows or lower (in ppm): Si 202, Na 243, Mn 249, Fe 349, Cr 249, Al 154, Ca 213, Ti 212, Mg 211, K 242. We calculated $\text{Mg\#} = \text{Mg}/(\text{Mg} + \text{Fe})$ values from our molar EMPA data.

The 4 howardite thin sections were mapped with WDS for 8 elements: Mg, Si, Fe, Al, Ca, Cr, K (K-lines) and Ni (L-line). EDS (energy-dispersive spectrometry) x-ray maps were collected simultaneously for S and Ti. Using methods similar to those of Beck et al. (2012), we constructed lithologic distribution maps with ENVI 4.2 software to locate olivine and pyroxene grains with Mg-rich compositions. The 10 x-ray maps were assembled into a multispectral image cube for each thin section. Regions of interest (ROIs) were defined based on mineral spot analyses for specific minerals or ranges of mineral chemistries. These ROIs and minimum distance classification were used to map the distribution of each phase (defined by ROIs) in these howardites, including those relevant to this study: Mg-rich olivine, diogenite olivine, and Mg-rich orthopyroxene. Grains of interest identified by our lithologic distribution mapping were analyzed by EMP prior to oxygen isotope and/or trace element analysis.

2.3. Oxygen isotope analyses

In situ oxygen three-isotope analyses were conducted on a Cameca IMS 1280, a large-radius double-focusing secondary ion mass-spectrometer at the WiscSIMS Laboratory, University of Wisconsin, Madison. Analytical conditions and data reduction are similar to those of Kita et al. (2010) and Tenner et al. (2013). The primary Cs^+ beam was focused to a 15 µm diameter spot with an intensity of 3 nA. The oxygen isotope data are reported relative to the standard Vienna Mean Ocean Water (VSMOW) using delta notation: $\delta^{17}O = [(^{17}O/^{16}O)_{\text{sample}}/(^{17}O/^{16}O)_{\text{VSMOW}} - 1] \times 1000$; $\delta^{18}O = [(^{18}O/^{16}O)_{\text{sample}}/(^{18}O/^{16}O)_{\text{VSMOW}} - 1] \times 1000$; and $\Delta^{17}O$ is defined as $\delta^{17}O - 0.52 \times \delta^{18}O$, representing the displacement from the terrestrial fractionation line (TFL).

Matrix effects were evaluated from olivine standards (Fo_{60}, Fo_{89}, and Fo_{100}) and instrumental biases of unknowns were corrected as a function of their Fo contents as determined by EMPA. Four bracket analyses on the San Carlos olivine (Fo_{89}) standard were completed before and after sets of 12 unknown analyses. Typical reproducibility (spot-to-spot or 2σ standard deviation; 2SD) of San Carlos olivine standard was ~0.3‰ for $\delta^{18}O$, $\delta^{17}O$, and $\Delta^{17}O$. A total of 81 unknown spot analyses were collected on 30 separate olivine grains in the howardite and diogenite thin sections: 14 of the grains were diogenite composition olivine ($\text{Mg\#} = 61$–79) and 16 were Mg-rich olivine ($\text{Mg\#} = 80$–92). Between 1 and 6 spots were measured per olivine grain. Available flat fracture-free areas large enough to accommodate the 15 µm spot analysis dictated the number of spots per grain. The oxygen three-isotope contents of diogenite composition olivine fragments in the GRO 95 howardites were measured along with the Mg-rich olivine fragments. Most oxygen isotope analyses of HED meteorites have been on bulk rock samples and, to our knowledge, no *in situ* SIMS analyses of oxygen isotopes in HED minerals have been published. Thus, we analyzed diogenite olivine to independently determine the oxygen three-isotopic composition of slowly cooled HED (vestan) olivine. The average $\Delta^{17}O$ compositions were calculated for Mg-rich olivine ($n = 47$) and diogenite olivine ($n = 34$), respectively. The 2σ standard errors of the means of both unknowns and San Carlos olivine standard ($n = 40$) were propagated into the final uncertainties of the average $\Delta^{17}O$ compositions.

2.4. Trace element analyses

In situ trace element analyses were conducted at Virginia Tech using an Agilent 7500ce inductively coupled plasma mass spectrometer (ICP-MS) combined with an Excimer 193 nm ArF GeoLasPro Laser Ablation (LA) system. Laser spot sizes of 16–60 µm were used to analyze single-phase olivine or pyroxene. We analyzed 13 Mg-rich olivine grains and 4 Mg-rich pyroxene grains in the GRO 95 howardites. Between 1 and 5 spots were measured per mineral grain. Available flat fracture-free areas dictated the size and number of spots on each grain. The external standard used was NIST SRM610 reference glass. Every 2 hr, we measured the NIST standard twice for 60 s to correct for drift. For each of the analyses, approximately 60 s of background signal was collected before the ablation process was initiated. Sample ablation times ranged from 30–50 s using a laser repetition rate of 5 Hz. The