

PETROLOGY AND GEOCHEMISTRY OF UNBRECCIATED HARZBURGITIC DOGENITE MIL 07001: A WINDOW INTO VESTAN GEOLOGICAL EVOLUTION. D. W. Mittlefehldt¹, Z. X. Peng², S. A. Mertzman³, and K. R. Mertzman², ¹Astromaterials Research Office, NASA/Johnson Space Center, Houston, TX, USA (david.w.mittlefehldt@nasa.gov), ²Science Analysis & Research Development, Engineering and Science Contract Group, Houston, TX, USA, ³Department of Geosciences, Franklin & Marshall College, Lancaster, PA, USA.

Introduction: There is a strong case that asteroid 4 Vesta is the parent of the howardite, eucrite and diogenite (HED) meteorites [1]. Models developed for the geological evolution of Vesta can satisfy the compositions of basaltic eucrites that dominate in the upper crust [2]. The bulk compositional characteristics of diogenites - cumulate harzburgites and orthopyroxenites from the lower crust - do not fit into global magma ocean models that can describe the compositions of basaltic and cumulate eucrites [2, 3]. Recent more detailed formation models do make provision for a more complicated origin for diogenites [4], but this model has yet to be completely vetted. Compositional studies of bulk samples has led to the hypothesis that many diogenites were formed late by interaction of their parent melts with a eucritic crust [5], but those observations may alternatively be explained by subsolidus equilibration of trace elements between orthopyroxene and plagioclase and Ca-phosphate in the rocks [6]. Differences in radiogenic ²⁶Mg content between diogenites and eucrites favors early formation of the former, not later formation [7]. Understanding the origin of diogenites is crucial for understanding the petrologic evolution of Vesta.

We have been doing coordinated studies of a suite of diogenites including petrologic investigations, bulk rock major and trace element studies, and in situ trace element analyses of orthopyroxene. Here we will focus on an especially unusual, and potentially key, diogenite, MIL 07001.

Petrology: MIL 07001 is an unbrecciated harzburgitic diogenite that presents a clear view of its original igneous texture. This is unlike the case for most diogenites, which are brecciated. MIL 07001 has a poikilitic texture in which numerous small olivine grains (<0.4 mm) are enclosed in mm- to cm-sized orthopyroxene. Some multi-grain regions of olivine up to 1.5 mm size are present. The average modal olivine content is 11 vol% [8]. Chromite, troilite and metal grains are typically <0.1 mm in size. They are enclosed in orthopyroxene and are present at grain margins. Larger chromite grains up to ~0.7 mm in size are also present. Mesostasis-rich material is present but appears to be highly localized; no such areas have been found in thick section ,55 and only one such area is present in thick section ,54 (Fig. 1). The texture is moderately heterogeneous; a 2×2 mm region surrounding the mesostasis-rich area is devoid of olivine; otherwise,

olivine is uniformly distributed. The mesostasis is composed mostly of an Al-bearing silica phase, likely tridymite (Fig. 1). Minor phases in the mesostasis are high-Ca pyroxene, chromite, troilite and Ca-phosphate. Importantly, no plagioclase occurs in the mesostasis, nor has plagioclase been reported for MIL 07001 [5, 8].

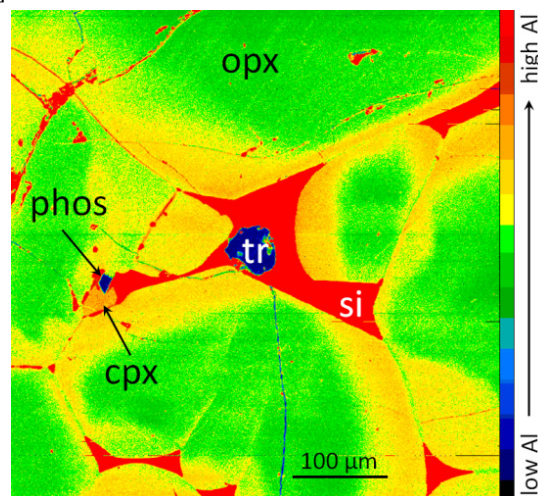


Figure 1. Al x-ray map of mesostasis-rich region of MIL 07001,54. Abbreviations are: opx - orthopyroxene; si - Al-bearing silica phase, likely tridymite; cpx - high-Ca pyroxene; phos - Ca-phosphate; tr - troilite.

Composition: Two roughly 2-gram chips were individually ground and homogenized; splits of the powders were used for X-ray fluorescence spectrometry and inductively coupled plasma mass spectrometry (ICP-MS). The major element compositions recast into CIPW normative mineralogy have ~13 wt% normative olivine, consistent with the average modal data [8]. The whole rock mg# (molar $100 \times (\text{MgO}/(\text{MgO} + \text{FeO}))$) is 75, typical of diogenites. Thus, although MIL 07001 has a higher olivine content, the rock is not more magnesian compared to orthopyroxenitic diogenites.

Incompatible trace element abundances are uniform across different samples of MIL 07001. Rare earth element patterns for two samples from this study and one each from [5, 9] are remarkably similar (Fig. 2a). All samples show very modest depletions in Eu relative to Sm and Gd; MIL 07001 is atypical in this [5]. However, internally, trace element contents of individual orthopyroxene grains determined by laser ablation ICP-MS show substantial variation (Fig. 2b). The majority of analyses from thick sections ,54 and ,55 show

correlated Sm and Yb variations from values slightly less than those of bulk samples to roughly $3\times$ those values in the case of Yb. Two grains located near a large chromite grain show higher Sm contents, while four of six grains located near the mesostasis region shown in Fig. 1 have very high Sm contents (Fig. 2b). Previously we showed that the minor elements Al and Cr show substantial localized variations within orthopyroxene in MIL 07001 [10].

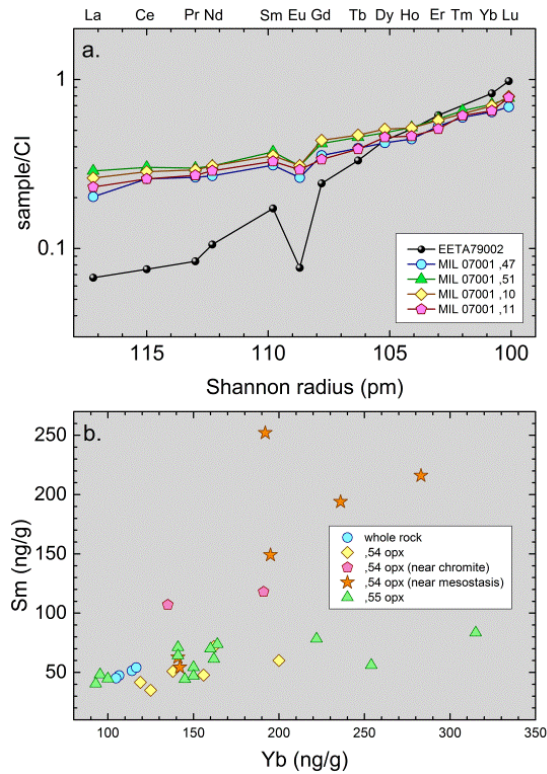


Figure 2. Rare earth element (REE) data for MIL 07001. a. REE patterns compared to genometric diogenite EETA79002. Samples ,47 and ,51 – this study; ,10 and EETA79002 from [5]; ,11 from [9]. b. Sm vs. Yb for bulk samples from panel a compared to LA-ICP-MS analyses of orthopyroxene.

Discussion: The petrology of MIL 07001 presents problems for even the most recent model of vestan petrologic evolution [4]. The occurrence of mesostasis dominated by an Al-bearing silica phase, yet free of plagioclase, implies a parent melt with a very low Al content such that the crystallization sequence was essentially olivine+orthopyroxene, orthopyroxene, orthopyroxene+silica, as in the forsterite-silica phase diagram. This is very different from that inferred for basaltic and cumulate eucrites in which substantial plagioclase crystallizes prior to formation of a silica phase [4].

Compositionally MIL 07001 is unusual. It contains the highest (by a factor of 10) contents of highly sider-

ophile elements measured for a suite of diogenites, with a pattern unfractionated relative to CI chondrites [9]. Because it is an unbrecciated rock, contamination from impactors cannot be the cause. The REE pattern (Fig. 2a) is unusual in that it has only a small depletion in Eu relative to Sm and Gd. Most diogenites show Eu depletions substantially greater than this [5, 6]; only one other diogenite is like MIL 07001 [5]. The Eu content is, in fact, higher than expected for an orthopyroxene+olivine cumulate from magma with chondritic-relative REE ratios. Thus, the bulk rock REE budget, especially for the middle to light REE, is likely affected by a trapped melt component. This is consistent with the presence of mesostasis regions observed in thick section (Fig. 1) and the localized variation in trace element contents (Fig. 2b).

MIL 07001 is finer-grained than typical for diogenites. Most orthopyroxene grains in our thick sections are a few mm across, although a few are ~ 1 cm in size. In contrast, orthopyroxene grain *fragments* in many diogenites can be several cm in size [e.g., 2]. This suggests that the MIL 07001 magma cooled relative fast compared to classic diogenites such as Johnstown. Some diogenites are finer-grained and some of these show modest zoning in Fe/Mg, a characteristic not found in coarse-grained diogenites [11]. These authors suggested that such diogenites might have formed as shallow intrusions or even as extrusive rocks. Only very slight Fe/Mg zonation is found in electron microprobe traverses adjacent to the mesostasis material in MIL 07001; much less than documented by [11] in their “unequilibrated” diogenites. Therefore, MIL 07001 may have formed in an intrusive environment intermediate between that of classic, deep-seat diogenites and those diogenites suggested to have formed in the upper crust. Regardless, the lack of plagioclase in a cumulate containing visible trapped melt component remains an anomaly that is not easily accommodated by petrogenetic models for the evolution of Vesta.

References: [1] McSween H. Y. et al. (2013) *Meteoritics & Planet. Sci.*, 48, 2090-2104. [2] Mittlefehldt D. W. (2014) *Chem. der Erde-Geochem.*, submitted. [3] Shearer C. K. (2010) *Geochim. Cosmochim. Acta* 74, 4865-4880. [4] Mandler B. E. and Elkins-Tanton L. T. (2013) *Meteoritics & Planet. Sci.*, 48, 2333-2349. [5] Barrat J.-A. et al. (2010) *Geochim. Cosmochim. Acta* 74, 6218-6231. [6] Mittlefehldt D. W. et al. (2012) *Meteoritics & Planet. Sci.*, 47, 72-98. [7] Schiller M. et al. (2011) *Ap. J. Lett.*, 740, L22-L27. [8] Beck A. W. (2013) *Meteoritics & Planet. Sci.*, 48, 2155-2165. [9] Day J. M. D. et al. (2012) *Nature Geosci.*, 5, 614-617. [10] Mittlefehldt D. W. and Peng Z. X. (2013) *LPS XLIV*, Abstract #1285. [11] Yamaguchi A. et al. (2011) *J. Geophys. Res. Planets*, 5, 614-617.