GEOCHEMICAL VARIATIONS AMONG A TRIO OF HOWARDITES: DO THE PIECES FIT TOGETHER?

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Introduction: Howardite, eucrite, and diogenite (HED) meteorites are a unique suite of achondrites, thought to originate from asteroid 4 Vesta [1]. Howardites, impact-generated polymict breccias of eucrite and diogenite clasts, e.g. [2-3], provide a window into the geologic history of Vesta. In this study, analyses of three howardite meteorites, Pecora Escarpment (PCA) 02009, 02013, and 02015 reveal internal igneous processes and impact-induced alteration on the surface of Vesta. Found within 1 km of each other, these three howardites were tentatively paired [4]. Geochemical and petrographic analyses illuminate compositional and textural variations, allowing critical testing of their initial pairing. Evidence suggests sample PCA 02015 may not be paired with the others.

Methodology: Polished thin-sections of the three howardites were subjected to detailed petrographic examination and electron microprobe chemical analyses, including Energy-Dispersive Spectroscopy (EDS) and Wave-Dispersive Spectroscopy (WDS). Detailed digital mapping permitted direct comparisons of their textures.

Results: Meteorites PCA 02009, 02013, and 02015 contain pyroxene, olivine, plagioclase, and FeNi metal in proportions and with compositions similar to those of other known howardites, e.g. [2, 5, 6]. Differences in olivine, FeNi metal, and pyroxene chemistry provide suggestive evidence these three meteorites are not paired.

These howardites contain three types of ***pyroxene***: Mg-rich orthopyroxene (diogenites) and Fe-rich pigeonite and augite (eucrites). Large orthopyroxene crystals (up to 2mm) and cumulate orthopyroxenites make up ~95% of the diogenite clasts, with minor amounts of olivine and accessory troilite, chromite, and FeNi metal. Diogenite compositions in these three meteorites are typical for the HED suite, averaging ~$Wo_{3\pm2}En_{73\pm4}Fs_{24\pm3}$ (Fig. 1) [7]. Clinopyroxenes range in composition and texture within eucritic components. PCA 02015 contains a porphyritic, fine-grain (~3-20μm) eucritic matrix compared to the larger porphyritic, coarse-grain size (~3-50μm) of matrix in both PCA 02013 and 02009. All three samples display exsolution of augite in pigeonite. However, the meteorites have different clinopyroxene compositions, indicated by a separation in pigeonite and augite along a compositional line, as displayed in Fig. 1. PCA 02015 contains clinopyroxenes depleted in Fe, compared to those in PCA 02013. Pigeonite and augite compositions in PCA 02009 fall on both sides of the dashed line in Fig. 1 in roughly equal proportions, as compared to the other two meteorites. A separation of pyroxene compositions also exists in Ti & Al. PCA 02015 has a distinct lower ratio than PCA 02013 and 02009 (Fig. 2).

Fig. 1

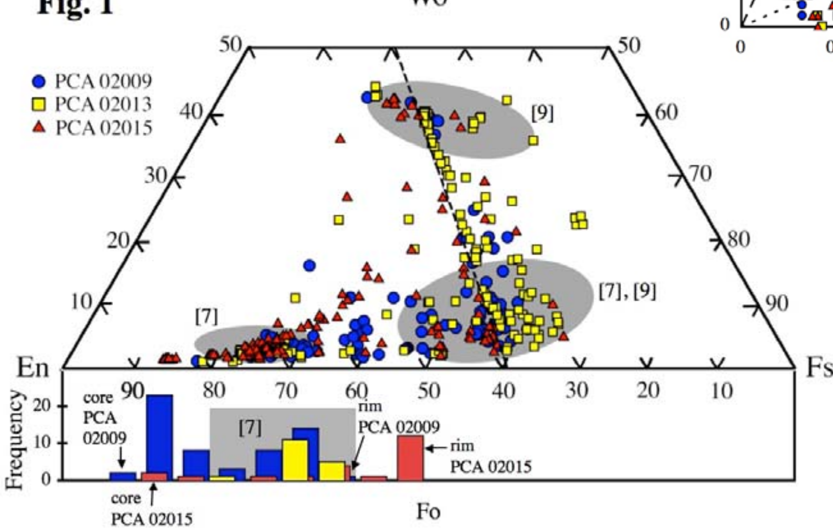
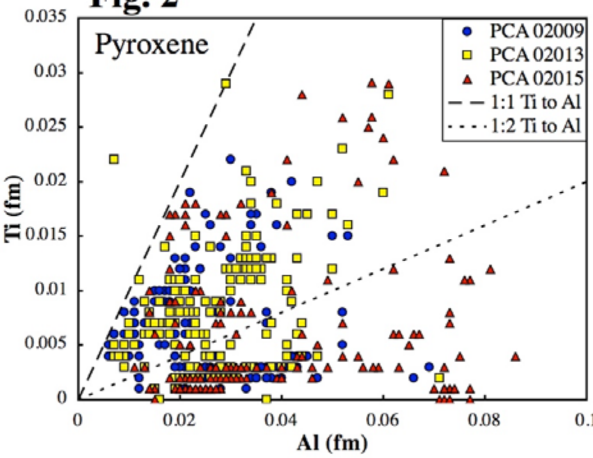


Fig. 2

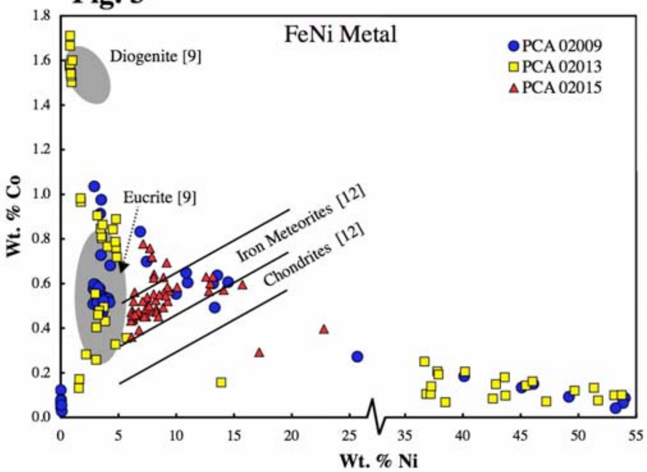


Plagioclases, mostly occurring as anhedral, 10-100 μm grains in a wide range of textures, have only minor differences in AN content among the three meteorites. Grains of plagioclase range in composition from An_{96-68} in meteorite PCA 02013, from An_{95-63} in PCA 02015, and ~An_{86} in PCA 02009, which corresponds to that of typical HEDs [8]; however, plagioclase grains in PCA 02013 tend to be slightly more Ca rich than the majority of grains in PCA 02015. Minor subophitic, lathe-shaped textures can be seen in plagioclase of sample PCA 02015.

PCA 02015 and 02009 have zoned ***olivine*** grains, which range from Fo_{50-87} (PCA 02015) and Fo_{62-92} (PCA 02009). In comparison, PCA 02013 has homogeneous olivines from Fo_{62-76} (Fig. 1), mostly compositionally different from those in the other two meteorites.

Like olivine and pyroxene compositions, ***FeNi metal*** compositions vary among the three meteorites (Fig. 3). Over 90% of FeNi metals in PCA 02015 have Ni and Co compositions typical of iron meteorites and chondrites, as defined by [12]. The remaining analyses in PCA 02015 do not fall within any of the HED zones. In contrast, PCA 02013 FeNi metal compositions are typical of those found in HEDs with the exception of some grains with unusually high (53 wt. %) Ni [9-10]. PCA 02009 has a combination of the FeNi metal compositions previously listed for the other two meteorites, as well as a unique grain of almost pure Fe (Fig. 3).

Fig. 3



Discussion: Compositional variations in pyroxenes, plagioclases, olivines, and FeNi metals suggest that two of these meteorites are not paired. However, evidence does indicate that the three achondrites are linked in origin to the HED parent body, but most likely originated at different locations in the regolith.

Two compositionally distinct eucrites are components of the meteorites analyzed. PCA 02013, with Fe-rich pigeonite and Ca-rich plagioclase, has sampled a different type of eucrite than that represented by the Mg-rich pigeonite and Na-rich feldspar in PCA 02015, e.g. [6, 9]. The third meteorite, PCA 02009, has a mixture of both of these eucrite compositions (Fig. 1). Comparisons of Al:Ti ratios of pyroxenes in the meteorites also divide the group. PCA 02015, the Na- and Mg-rich sample, contains proportions of Al and Ti that suggest its eucrite component is more primitive than the more-evolved eucrite component of the other two meteorites, assuming they evolved from the same source, e.g. [6, 9]. However, it is also possible that these two types of eucrites did not evolve from the same parent magma [11]. In either case, compositional variations of this degree suggest that two different areas on the surface of Vesta [11], or two different depths in the strata of Vesta [9], were sampled in the formation of these meteorites. This hypothesis is supported by the presence of different olivine compositions. PCA 02013 contains olivines with no zoning and homogeneous compositions, versus extensive zonations in PCA 02015 and 02009. It would appear that PCA 02013 cooled significantly slower than the other two meteorites.

FeNi metal compositions provide the most compelling evidence for different sample locations of these three howardites on Vesta. The high proportions of iron meteorite and chondrite-like FeNi metal grains in PCA 02015 indicate possible contamination of the sample by a foreign source. While there are minor amounts of FeNi metal with this composition in PCA 02009, it is absent in PCA 02013. This contrast in FeNi metal suggests that the meteorites did not originate from the same location on the regolith of Vesta. PCA 02013 and 02009 have similar metal compositions, both containing some high Ni values (>52%). These tetrataenite compositions are evidence for similar origins, or a possible pairing.

Conclusion: **Compositional variations among these three howardites contradict the idea that they are paired samples of the same meteorite**. Differences in FeNi metal, pyroxene, olivine, and plagioclase compositions suggest that PCA 02013 and 02015 originated at two distinct localities on Vesta. Although preliminary results indicate a possible pairing between PCA 02009 and 02013, conclusive evidence has not been observed. These three samples demonstrate the wide range of varying lithologies found in Vesta's regolith and the effects of impact brecciation on texture and composition.

References: **[1]** McCord et al., 1970, *Science 168*, 1445-1447; **[2]** Wahl, 1952, *GCA 2*, 91-117; **[3]** Gaffey, 1997, *Icarus 127*, 130-157; **[4]** Russell et al., 2004, *MaPS, 8*, A215-A272; **[5]** Mason, 1962, *Meteorites: The Achondrites*, 104-119; **[6]** Stolper, 1977, *GCA 4*, 587-611; **[7]** Mittlefehldt et al., 1998, *Planet. Mat., RIMS 38*, 102-131; **[8]** Delaney et al., 1984, *LPSC XV*, C251-C288; **[9]** Ikeda & Takeda, 1985, *LPSC XVI*, C649-C663; **[10]** Gooley & Moore, 1976, *Amer. Mineral. 61*, 373-378; **[11]** Hewins & Newsom, 1988, *Meteor. & Early Solar System*, 73-101; **[12]** Moore et al., 1969, *Meteor. Res.,* 738-748.