NORTHWEST AFRICA 5415: A HOWARDITIC IMPACT-MELT BRECCIA WITH ZONED RELICT ORTHOPYROXENES AND AUGITES, AND CORRODED, COMPLEXLY MANTLED FO-59 OLIVINES

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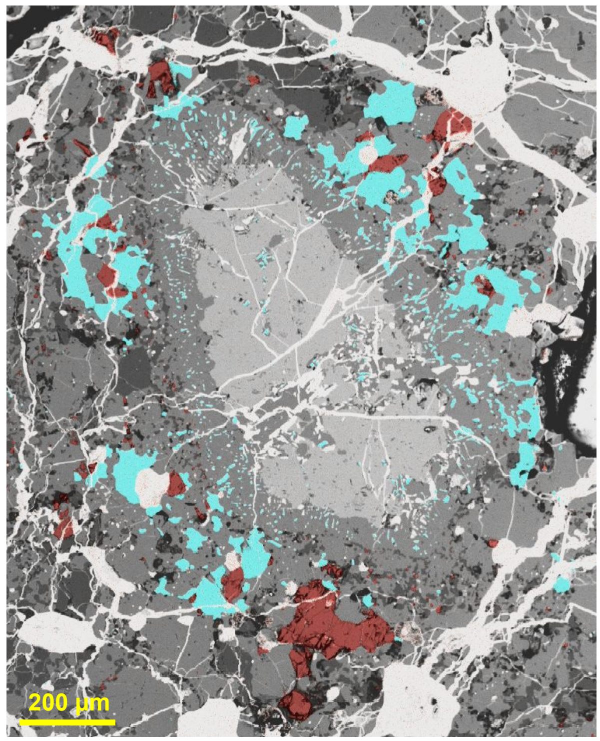
Introduction: The Northwest Africa (NWA) 5415 meteorite is unusual among HED meteorites for its clear manifestation of origin by pervasive, large-scale impact melting. A thin section from a relatively unweathered portion includes five relict olivines, all of which display similar reaction textures (pyroxene coronas) formed as a consequence of immersion of these grains in a melt on the Si-rich side of the olivine-pyroxene liquidus boundary.

Most HED meteorites are breccias, so impact cratering was obviously important on the parent asteroid (Vesta?). However, the role of impact melting in the origin of polymict HED meteorites is generally difficult to assess, because most polymict HEDs consist largely of comminuted noncumulate eucrites, and the basaltic (typically subophitic) textures of noncumulate eucrites have much in common with typical mafic impact-melt textures. As one indication of the scarcity of manifest impact-melt breccias among the polymict HEDs, the entire class of howardites is commonly defined as the "regolith breccia" form of HED — implicitly denying the existence of any impact-melted polymict HEDs containing major proportions of both eucrite and diogenite. (As noted by Warren et al. [1], on closer study it appears that only a relatively small and compositionally distinctive subset of the howardites are in fact regolith breccias, in the sense that the term is used in the context of lunar impactites.)

Weathering and oxygen isotopes: NWA5415 shows its impact melt pedigree despite generally severe weathering. Effects of terrestrial alteration include veins of FeO-rich crud that pervasively criss-cross the sample. The widest such veins include substantial components of Saharan desert detrital matter, in the form of clustered, distinctively ovoid and size-sorted grains of silica, along with minor feldspar. These ovoid vein-filling grains show distinctively terrestrial compositions: extremely Al-poor (i.e., plutonic quartz, originally) silica and K-feldspar. This major and inextricable terrestrial component complicates application of oxygen isotopes to aid in classification of the meteorite. Our bulk analyses yielded two similar compositions that average $\delta^{17}O = 1.89$ and $\delta^{18}O = 3.84‰$. The implied $\Delta^{17}O$ of $-0.14\pm0.02‰$ is high, by HED standards [2,3], but might be significantly lower if the terrestrial contamination could be eliminated (we tried acid treatments, but they only served to enhance the terrestrial-silica component).

Complex mineralogy and texture: The most spectacularly mantled olivine is shown in Fig. 1, which is a back-scattered electron image over which we have superimposed x-ray mapping results for Cr-spinel (blue) and merrillite (red). Other phases are the broken and corroded relict olivine (light grey), pyroxene (medium grey) and plagioclase (dark grey). The white patches and veins are FeO-rich alteration materials, except for the black-rimmed region near the central right edge, which is a sectioning artifact.

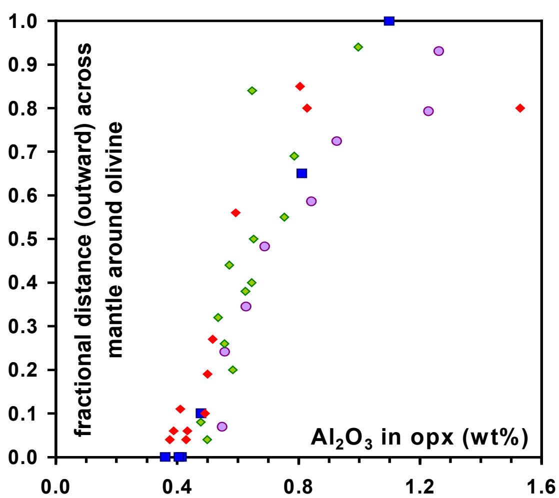


All of the olivines feature the same texture of a corroded rim enclosed by a fine-grained pyroxene dominated mantle roughly 100-200 µm in breadth; and with tiny Cr-spinels scattered within that mantle and tending, when elongate, to have long axes aligned radially in relation to the olivine. The abundance of large Cr-spinels and merrillite at about 200-400 µm from the olivine is particularly high here, perhaps because this was the smallest (highest surface-area-to-volume ratio, i.e., fastest-corroding) of the 5 olivines sectioned. It is also the most ferroan, at Fo57.7. The others range from Fo58.6-59.4 (averages of 9 or more analyses per grain;

no zoning was detected in any of the olivines). Fo59 is a typical composition for diogenitic olivine [e.g., 4,5].

The rock as a whole consists predominantly of low-Ca pyroxene, compositionally clustered near En63-65Wo3. The pyroxenes in the mantles rimming the olivines are almost entirely of this compositional type (although the inner mantles curiously include a few scattered grains of augite, some in direct contact with olivine). However, 5 exceptionally large relict orthopyroxenes are normally zoned, from cores as magnesian as En78.4Wo1.5, toward rims similar in composition to the groundmass pyroxenes. Minor element contents in these grain cores are consistent with literature data for diogenitic pyroxenes [4,5,6]. Supporting the other indications of HED affinity, FeO/MnO wt. ratios are consistently close to 27, in both the relict diogenitic orthopyroxenes and other forms of low-Ca pyroxene.

Although the pyroxene coronas around olivine are fairly uniform in major-element composition, they do feature zoning in minor elements, e.g., Al (Fig. 2; col-



ors represent four different mantled olivines). Ti and Cr show similar increases (larger, in relative terms) going from the inner to outer rims of the mantles.

Away from the olivines several large grains of augitic pyroxene were found, each with (very unusually, for NWA5415) abundant exsolution lamellae (low-Ca px, up to ~0.5 µm in width, spaced roughly 3 µm apart). These grains feature corroded rims and are reversely zoned in *mg*. Evidently the same impact melt that was too evolved for the olivines was too primitive for these augites. The augites are enigmatic, because even their cores are too magnesian to derive from ordinary non-cumulate eucrites, and yet primary augite is extremely rare (unknown?) from more magnesian HEDs such as diogenites and cumulate eucrites.

Plagioclase is compositionally unexceptional, by HED standards. It averages An91.6, with a range of An81.9-96.7 (based on 109 analyses). In general, it appears that the initial impact melt had a highly mafic (far undersaturated in plagioclase) composition, as might be expected if the impact target was howarditic. Slow diffusion in the augites possibly "froze" their equilibration with magnesian early-stage melts, but the unzoned olivines (and their uniform-*mg* coronas) equilibrated with late-stage melts that were very ferroan, by the standards of bulk eucrites.

Silica is also a significant phase in the groundmass. It contains 0.09-0.46 wt% Al_2O_3 and 0.29-0.78 wt% FeO, and is up to 400 µm in apparent pre-brecciation breadth. It is commonly associated with relatively coarse plagioclase, but in no case is it closer than 150 µm from olivine (the few small black patches in Fig. 1 are voids). Despite the severe weathering, several 100-µm grains of metallic FeNi survive in the thin section, mostly kamacite (with 4.7-6.3 wt% Ni and 0.43-0.55 wt% Co) but also including at least one grain of taenite (51.6 wt% Ni, 0.08 wt% Co).

Cr-spinel forming a corona around olivine is the inverse of a texture previously known from a few olivine diogenites [7,8]. Despite its great diversity in terms of size and setting in relation to relict olivines, the Cr-spinel of NWA5415 is fairly uniform in composition. The range in Cr/(Cr+Al) (atomic, based on 49 analyses) of 0.72 to 0.82 is typical of chromite in olivine diogenites [4,7]. The lower end of the NWA5415 range corresponds to the minute chromites (see Fig. 1) that grew from pockets of melt trapped within olivine, or as part of the innermost reaction rim around olivine. Merrillite composition is also fairly uniform. The average (18 analyses, in wt%) has 0.99 Na_2O, 3.7 MgO, 45.0 P_2O_5, 48.0 CaO, 1.27 FeO, roughly 0.06 Y_2O_3, and undetectable F, Cl, La and Ce.

Conclusions: Further study, and more samples, will be required before a comprehensive picture can be obtained of the overall role of impact melting on the HED parent asteroid. Obvious dissolution textures, while not unprecedented [9], are still rare. But that may be in part because phases prone to grow reaction rims are rare near the surface of Vesta. NWA5415 shows that impact melting was at least locally important, and should finally lay to rest the over-simplistic notion that all howardites, as a class, are regolith breccias.

References: [1] Warren P. H. et al. (2009) *MAPS*, submitted. [2] Ziegler K. and Young E. D. (2007) *LPS* abstr. 1338. [3] Greenwood R. C. et al. (2005) *Nature 435*, 916. [4] Mittlefehldt et al. (1998) in *Rev. Mineral. 36*. [5] Bunch T. E. et al. (2007) *MAPS 42*, 5133. [6] Shearer C. K. et al. (2008) *LPS* abstr. 1835. [7] Irving A. J. et al. (2005) *LPS* abstr. 2188. [8] Irving A. J. et al. (2003) *LPS* abstr. 1502. [9] Warren P. H. (2003) *MAPS 38*, A153.