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Geochimica et Cosmochimica Acta 141 (2014) 199–227

Geochimica et Cosmochimica Acta

www.elsevier.com/locate/gca

# Northwest Africa 5738: Multistage fluid-driven secondary alteration in an extraordinarily evolved eucrite

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Received 5 January 2014; accepted in revised form 11 June 2014; Available online 22 June 2014

**Abstract**

The Northwest Africa 5738 eucrite contains a record of unprecedented geochemical complexity for a sample from the HED asteroid. It originated with a uniquely evolved (Stannern Trend) primary igneous composition, combining ultra-high bulk incompatible element and $Na_2O$ concentrations with a relatively low *mg*. Its bulk oxygen-isotopic composition ($\Delta'^{17}O = -0.27‰$), as well as its trace element composition (e.g., Ga/Al), confirm other evidence for classification as a eucrite. Pyroxene *mg* equilibration, exsolution and "cloudy" inclusions, all reflect a typical eucritic degree of thermal metamorphism. The rock contains an unprecedented array of microscopic fluid-metasomatic vein deposits. Most common are curvy microveins within pyroxene, which consist dominantly of Ca-plagioclase (typically $An_{95}$, in stark contrast with the rock's $An_{68-78}$ primary-igneous plagioclase), with Fe-olivine ($Fo_{14}$) and Cr-spinel as additional major constituents. Likely related to these microveins are small masses of intergrown Ca-plagioclase (again roughly $An_{95}$) and silica (or high-Si glass). Analyses of the microvein Cr-spinels show stoichiometry implying a significant $Fe^{3+}$ content ($Fe_2O_3$ 0.7–2.3 wt.%), and $fO_2$ up to roughly IW+3; clearly elevated in comparison to the normal HED $fO_2$ of about IW−1. The $fO_2$ results show an anticorrelation with equilibration *T* (and with Mg/Fe), which suggests the parent fluid system became more oxidizing as it cooled. NWA 5738 also contains apparent secondary iron metal. The Fe-metals are very pure, with Ni consistently below an EPMA detection limit of ~0.01 wt.%. The vein-like shapes of roughly 1/3 of the largest Fe-metals suggest origin by deposition from a fluid. The role of pyroxene exsolution as template for a denticular (sawtooth) Fe-metal edge shape, and the survival of $Fo_{14}$ olivine in a rock with abundant silica and a far higher bulk *mg*, suggest that the most intense thermal metamorphism occurred no later than the secondary alteration. Near-complete lack of spatial association suggests that the Fe-metals formed during a distinct time period from the curvy microveins. The immediate cause of Fe-metal deposition was most plausibly (or anyway, least implausibly) an abrupt downshift in the fluid $fO_2$. Considering the extremely evolved bulk composition, the fluid(s) may have been largely deuteric. However, more likely the main source of fluid was a nearby buried mass of volatile-rich impactor matter, such as carbonaceous chondrite, that hit the asteroid at low enough velocity to remain mostly intact. We further speculate that the abrupt drop in fluid $fO_2$ may have been caused by a process of carbon-fueled "smelting" (cf. ureilites), triggered by an impact-effected shift of the carbonaceous material to a changed environment, with higher *T* and/or lower *P*. These and other recent eucrite results point to a need for greater scrutiny regarding the absence of comparable alteration-veining in rocks from the lunar highland crust, a mysterious lack in view of recent evidence for abundant lunar water.


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http://dx.doi.org/10.1016/j.gca.2014.06.008
0016-7037/

## 1. INTRODUCTION

Northwest Africa (NWA) 5738 is a recently found eucrite meteorite with distinctive compositional and mineralogical traits. After being found somewhere near Morocco in 2009 as a single mass of 2.2 kg, the meteorite was acquired by Nicholas Gessler. We have studied NWA 5738 mainly in terms of its minor but intriguingly diverse secondary alteration products. "Every picture tells a story", and our observations of these novel materials are based on scrutiny of thin-section images far too numerous to include in the body of any one paper. Readers are urged not to miss this paper's Electronic Annex.

Eucrites, the most numerous subtype among the HED (howardite–eucrite–diogenite) meteorite group, are crustal, cumulate-gabbroic to (more commonly) basaltic rocks. Eucrites are manifestly from the same parent asteroid as the pyroxenitic diogenites and the howardites (e.g., Warren et al., 2009). Most HED petrologists and asteroid scientists believe that the parent asteroid is known, 4 Vesta (Keil, 2002; Russell et al., 2013), although some residual skepticism persists (Schiller et al., 2011; Wasson, 2013), and a few eucrites have been found to show significant deviations from the main HED oxygen-isotopic mass fractionation line (Scott et al., 2009; Benedix et al., 2013). Meanwhile, observations of Vesta's surface by the Dawn mission have been interpreted as evidence for massive local concentrations of exogenously derived carbonaceous-chondritic matter (Reddy et al., 2012) and even possibly massive "devolatilization of the surface after a collision either brought to or tapped a source of water on Vesta" (Russell et al., 2013).

A significant subset of eucrites show evidence of secondary alteration (Table 1), most commonly in the form of fayalitic olivine veins (filled cracks, fringed with reaction zones of FeO-enriched pyroxene) that crisscross large pyroxenes. These were found initially in isolated clasts in polymict breccias (Takeda et al., 1983; Buchanan et al., 2000), but more recently (Warren, 2002; Schwartz et al., 2002; Herd et al., 2004; Roszjar et al., 2011) within a few individual eucrites. An extensive search for these materials (Barrat et al., 2011) found them to be virtually confined to eucrites that feature uncommonly unequilibrated mineralogy (e.g., show limited pyroxene equilibration, including exsolution). Barrat et al. (2011) also discovered that the fayalitic-olivine veins typically include, or have nearby, secondary plagioclase of extremely Na-poor (e.g., $An_{97}$) composition. In the fayalitic-olivine veins of eucrite NWA 5073, Roszjar et al. (2011) found, along with $An_{98}$ plagioclase, minor secondary Cr-spinel and apatite.

Treiman et al. (2004) inferred a secondary (aqueous fluid) origin for rare veins of nearly pure quartz that they discovered within the cumulate Serra de Magé eucrite. No other secondary minerals were found, and Serra de Magé remains the only previously reported case of secondary silica from eucrites. Another distinctive variety of eucrite secondary alteration, produced by infiltration of sulfur-rich fluid, has been documented in NWA 2339 by Zhang et al. (2013). Palme et al. (1988) similarly attributed the origin of the relatively high Fe-metal content of the Camel Donga eucrite to a thermally activated redox process involving sulfur-rich (but in this case fugitive) fluid.

These secondary alterations remain enigmatic. An early discovery of "linear zones" of FeO-enriched pyroxene (but no accompanying olivine) in an unequilibrated eucritic clast in howardite EET 92014, prompted Mittlefehldt and Lindstrom (1997) to invoke a "late-stage, FeO-rich fluid". Schwartz et al. (2002; an abstract) invoked "an Fe-rich melt/fluid that migrated through fractures" to account for fayalitic veins in Pasamonte. Schwartz and McCallum (2005) suggested that Pasamonte's secondary alteration resulted from "metasomatic transport by a dry Fe-rich vapor", and ascribed "multiphase domains" ($Fo_{19}$ olivines associated with $An_{96}$ plagioclase) within Haraiya's pyroxene to "a melt or vapor phase" and "healing of previously existing fractures". Roszjar et al. (2011) suggested that the secondary-vein matter in NWA 5073 might have formed by crystallization after localized in situ incongruent melting of low-Ca pyroxene, "during a short period of a small temperature excursion in the magma chamber". Barrat et al. (2011) argued for deposition from metasomatic, and probably aqueous, FeO-rich fluids. Sarafian et al. (2013) found that many eucrite apatites are rich in F and/or OH.

As will be shown below, even before NWA 5738 acquired its diverse secondary alteration products, the bulk meteorite was an unusually evolved variety of eucrite. NWA 5738 is also, among eucrites that manifest secondary alteration, unusual in having normally equilibrated silicates. Its wide array of different secondary phases, including spinels with compositions that suggest relatively high oxygen fugacity ($fO_2$), provide new insight into the nature of the parental fluids. Especially enigmatic is the widely scattered presence of coarse, elongate native metal, showing evidence of fluid-related deposition, and no spatial association with most of the other (higher $fO_2$) secondary materials. The unusual characteristics arrayed in NWA 5738 add significant new constraints on the nature and evolution of igneously differentiated asteroids.

## 2. METHODOLOGY

In order to survey the minor but important secondary minerals, we studied a total of eight polished sections, mostly thin sections, derived from six widely separated parent chips of NWA 5738. Backscattered electron (BSE) and secondary-electron images were acquired on a LEO 1430 SEM and a JEOL JXA-8200 electron probe micro analyzer (EPMA). Mineral compositions were determined using the JXA-8200's wavelength-dispersive spectrometry (WDS) detectors. For direct measurement of Fe-oxide oxygen using oxygen's low-energy (0.525 keV) X-ray, JEOL's "LDE1" (layered diffracting elements) type WDS detector was used. Analyses were run at 15 keV and a sample current of usually 15 nA, with a focused beam and count durations of 15–20 s. However, for volatilization-prone phases (feldspars) broader beams and currents as low as 2 nA were employed. A few additional semiquantitative analyses were obtained using an EDAX system on the SEM.

Bulk compositional data were obtained for two separate chips of NWA 5738, employing the methodology of