The Northwest Africa 10416 Olivine-phyric Martian Basalt: Product of Magma Mixing, Assimilation and Alteration. C. D. K. Herd[1], E. L. Walton[1,2], K. Ziegler[3], Z. Vaci[3], C. B. Agee[3], N. Muttik[3], J. Wimpenny[4], W. S. Cassata[4] and L. E. Borg[4], [1]Department of Earth and Atmospheric Sciences, 1-26 Earth Sciences Building, University of Alberta, Edmonton, Canada, T6G 2E3, herd@ualberta.ca, [2]Department of Physical Sciences, MacEwan University, Edmonton, Canada, [3]Institute of Meteoritics, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM. [4]Lawrence Livermore National Laboratory, 7000 East Ave., Livermore, CA.

Introduction: The Northwest Africa (NWA) 10416 olivine-phyric basalt is distinct from other Martian basalts in several ways, including in the record of pre-terrestrial alteration preserved within it. Here we report the details of the mineralogy, petrology and geochemistry of this intriguing specimen, which suggest that the history of the rock includes assimilation of previously altered igneous phases.

History and physical characteristics: NWA 10416 was purchased by Darryl Pitt from a meteorite dealer in April 2015. The specimen consists of a single, 964 g stone with an irregular, desert-varnished exterior lacking fusion crust. Saw cutting reveals green-orange olivine phenocrysts set in a groundmass of white plagioclase and light-green pyroxene, cross-cut by fine, dark shock-melt veins (Fig 1).

Figure 1. Photograph of cut surface of NWA 10416 showing red-brown olivine cores throughout, orange alteration minerals concentrated near exterior surface and along fractures, and shock melt veins. Sample is approximately 2.5 cm wide.

Methods: Thin sections were analyzed using a JEOL 8200 electron microprobe (EMP) at the University of New Mexico (UNM) or the JEOL 8900 EMP at the University of Alberta (UAlberta) using well-known standards. Oxygen isotopes of several mg-sized acid-washed (for removal of terrestrial alteration) subsamples were analyzed using a CO_2 laser-assisted fluorination extraction line coupled to a MAT 252 dual inlet mass spectrometer at UNM. Major, minor and trace elements were analyzed using the Thermo Element XR ICP-MS at Lawrence Livermore National Laboratory.

Bulk composition: NWA 10416 has a bulk trace element composition consistent with that of (LREE) depleted shergottites having CI-normalized La/Yb ~ 0.1; REE patterns (not shown) are most similar to e.g., Dar al Gani 476, Yamato 980459 and Tissint.

Igneous petrology: NWA 10416 is an olivine basalt comprised of ~10 vol% olivine phenocrysts up to ~1 mm diameter, intergranular pyroxene (~50 vol%) and plagioclase (~30 vol%). Minor phases include ilmenite, chromite, Ti-bearing chromite, titanomagnetite and Fe-sulfide. Pyroxene and olivine compositions show significant chemical variation consistent with igneous zoning (Fig. 2).

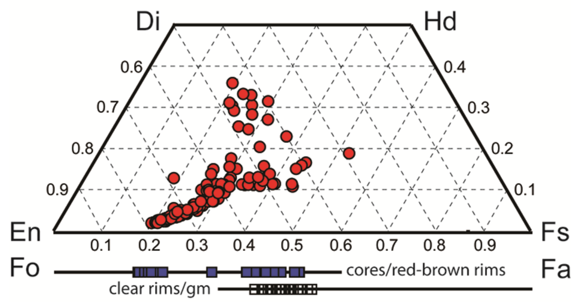

Figure 2. NWA 10416 pyroxene and olivine compositions.

Oxide compositions include spinel which ranges in composition from near endmember, Ti-poor chromite ($Chr_{0.83}Mt_{0.01}Sp_{0.14}Usp_{0.02}$) to Cr-poor titanomagnetite ($Chr_{0.01}Mt_{0.18}Sp_{0.05}Usp_{0.76}$), and ilmenite with variable ferric iron ($Ilm_{0.77-0.90}Hem_{0.02-0.11}$). Few, if any, oxides were found within the red-brown olivine cores; most are associated with (clear) ferroan rims and groundmass olivine. Preliminary estimates of oxygen fugacity (fO_2) based on chromite, enclosing olivine (Fo_{53}) and equilibrium low-Ca pyroxene (~$En_{51}Fs_{38}Wo_{11}$) yield ~QFM-3, consistent with 'magmatic' estimates for other depleted shergottites. Fe-Ti oxide (titanomagnetite and ilmenite) based estimates yield ~QFM-1.3±0.6, suggestive of an fO_2 increase during crystallization.

Most of the plagioclase in NWA 10416 is crystalline and labradoritic ($An_{63\pm4}Ab_{36\pm4}Or_{0.5\pm0.1}$). Approximately 10% has been transformed to maskelynite, primarily in contact with, or adjacent to shock veins. In this way, NWA 10416 shares similarities to NWA 8159 [1]. Thin veins of shock melt cut across all igneous phases and contain high pressure minerals [1].

Secondary alteration: Products of low-temperature aqueous alteration include light orange staining visible in hand specimen, on exterior surfaces (e.g., bottom of Fig. 1) or along fractures. However, light-orange staining is distinct – and overprints – darker orange coloration of olivine cores (Fig. 1), discussed below. In addition, maskelynite has been preferentially replaced along grain margins and in association with shock melt veins, and within shock melt pockets [1] by glassy/amorphous material that is enriched in Al, and depleted in Ca, Na and Si relative to plagioclase, and which is often associated with void spaces, indicating a reduction in volume during alteration via dissolution. Recalculation of EMP data assuming a smectite-type structure gives a formula consistent with beidellite, $(Ca_{0.36}K_{0.05})_{\Sigma=0.4}(Al_{1.99}Mg_{0.05}Fe_{0.05})_{\Sigma=2.1}$ $(Si_{3.0}Al_{1.0})_{\Sigma=4}O_{10}(OH)_2(H_2O)_4$, a Ca-rich dioctahedral aluminosilicate smectite associated with hydrothermal alteration; a Martian origin for this material is possible.

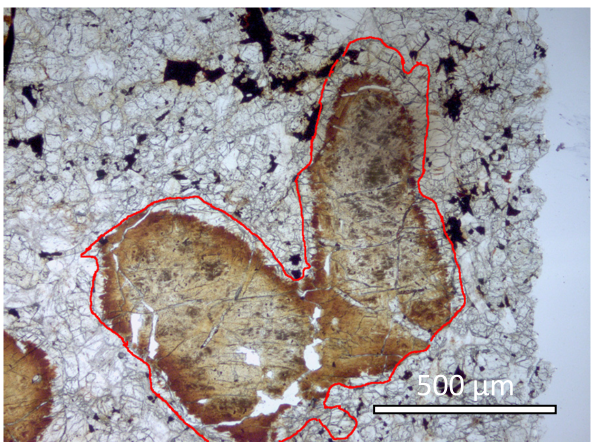

Figure 3. Plane polarized light photomicrograph showing iddingsite-altered margins of olivine cores. Clear rims are delineated in red.

Olivine cores: Olivine grains in NWA 10416 show a unique texture (Fig. 3) – a red-brown coloration that is strongest near the margins. The color is similar to that of iddingsite, known from the nakhlites [2]; analyses are consistent with olivine stoichiometry of composition Fo_{49-60} but with low EMP totals, indicating incipient formation of iddingsite [3]. Notably, clear and colorless olivine rims surround red-brown margins (Fig. 3; see also [3]). The boundary between the red-brown margins and the clear rims is serrated. Pyroxene inclusions ($\sim En_{60-63}Fs_{26-27}Wo_{10-14}$) are poikilitically enclosed by red-brown margins; these pyroxenes are in igneous equilibrium with olivine cores ($\sim Fo_{67}$), not rims. Clear olivine rim compositions are Fo_{52-58}, overlapping with that of red-brown margins (Fig. 2). Additionally, clear olivine of composition Fo_{46-53} is present in the groundmass as distinct phenocrysts.

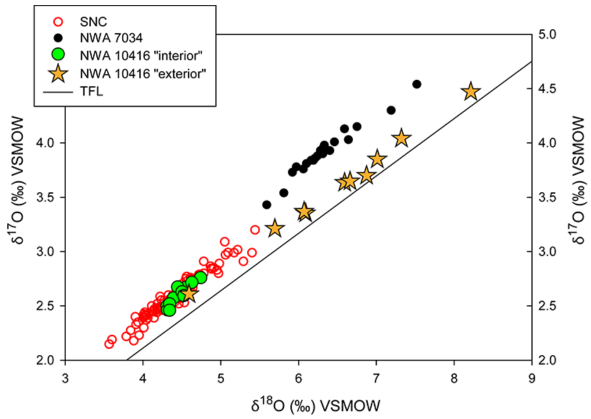

Figure 4. Oxygen isotopic compositions of NWA 10416 samples; data from other SNCs and NWA 7034 [4 and references therein] are shown for comparison.

Oxygen isotopes: The bulk rock oxygen isotopic composition is consistent with a Martian origin, with $\Delta^{17}O$ values of 0.168 to 0.327 (±0.02) ‰ and $\delta^{18}O$ of 4.310 to 4.740 (±0.02) ‰ based on subsamples from the interior of the meteorite (Fig. 4). Material from close to the exterior surface of the meteorite – which tends to show orange staining – shows a wider range of $\delta^{18}O$ (4.592 to 8.214 ‰), and a smaller $\Delta^{17}O$ value (0.071 to 0.205 ‰; Fig. 4). Whether this trend is due to Martian alteration, terrestrial alteration, or a combination of both is not known at this time. Further work on interior, iddingsite-rich olivines is in progress.

Discussion: The overlap in composition between clear olivine rims/groundmass grains and red-brown (iddingsite) margins and the serrated nature of the boundary (Figs. 2, 3), strongly suggest that the alteration affecting the olivine cores is pre-terrestrial, and indeed predates the crystallization of the groundmass. If this is the case, olivine cores must have been liberated from their cognate basaltic matrix, altered at or near the Martian surface, and subsequently incorporated into the basalt now represented by the clear olivine rims and the groundmass of NWA 10416. If beidellite glass and other hydrothermal phases (e.g., Mg-laihunite, [3]) are also preterrestrial, then the petrogenesis of NWA 10416 includes magma mixing and at least two secondary alteration events.

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References: [1] Walton E. L. et al. (2016) *LPS XLVII (this meeting)*. [2] Treiman A. H. (2005) *Chem. Erde-Geochem., 65,* 203-270. [3] Vaci Z. et al. (2016) *LPS XLVII (this meeting)*. [4] Agee C. B. et al. (2013) *Science,* 339, 780-785.