IN SEARCH OF A GROUP FOR THE UNGROUPED ACHONDRITES NWA 7680 AND NWA 6962

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Introduction: Northwest Africa (NWA) 7680 and NWA 6962 (NWA 7680/6962) are ungrouped achondrites with comparable major element olivine compositions [1]. Their oxygen isotope values places them near the carbonaceous chondrite anhydrous mineral (CCAM) line and within the ureilite field. This composition also falls near the acapulcoite-lodranite trend line, but at higher $\delta^{18}O$ [1]. We further compare these meteorites to grouped and ungrouped materials to better understand their formation environment and history.

Methods: Polished sections of NWA 7680/6962 were analyzed using a JEOL JXA-8230 electron microprobe to determine major and minor element compositions of phases. A Horiba LabRAM Aramis micro-Raman spectrometer was used to analyze unknown phases for comparison with RRUFF database spectra [2]. An Agilent 7500cs (quadrupole) ICP-MS system with a New-Wave UP213 (213 nm) solid-state Nd:YAG laser was used to determine mineral rare earth element (REE) compositions *in situ*.

Petrography: NWA 7680 is metal-rich with a silicate portion composed of roughly mm-scale olivine grains bordered predominantly by feldspar. The olivine is homogeneous ($Fa_{44.8}$, Fig.1-2), while the feldspar shows a variable composition ($An_{2.1\text{-}51.1}Or_{1.1\text{-}83.8}$, Fig.3). The K-rich feldspar is rare and generally found along grain boundaries. Clinopyroxene is present as a minor phase. Most grains have minimal zonation; however, some have zones of varying composition ($Fs_{11.0\text{-}22.8}Wo_{46.6\text{-}48.6}$, Fig.1). Clinopyroxene is often found along grain boundaries associated with sulfide and a Na-rich silicate. The Na-rich silicate is a minor component found throughout the section. Raman spectra are consistent with a nepheline-tridymite-like phase (Fig.4), although its exact structure and composition are still being determined. Chromite is also found throughout the section along with minor merrillite and fluorapatite.

NWA 6962 has olivine comparable to NWA 7680, in both size and composition ($Fa_{47.2}$, Fig.1-2). However, in this case the grains are mainly associated with a mixture of feldspar ($An_{4.1\text{-}33.9}Or_{0.2\text{-}3.3}$, Fig.3), clinopyroxene ($Fs_{11.9\text{-}23.4}Wo_{42.3\text{-}48.7}$, Fig.1) and merrillite. The clinopyroxene is more ubiquitous in NWA 6962 and exhibits complex zonation. Chromite, sulfide, metal and minor fluorapatite and Na-rich silicate (Fig.4) are also found in the section.

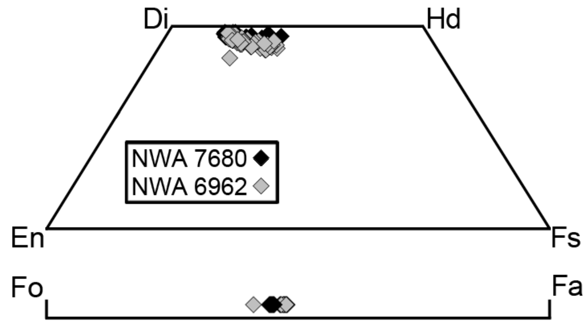

Figure 1. Clinopyroxene and olivine compositions for NWA 7680/6962.

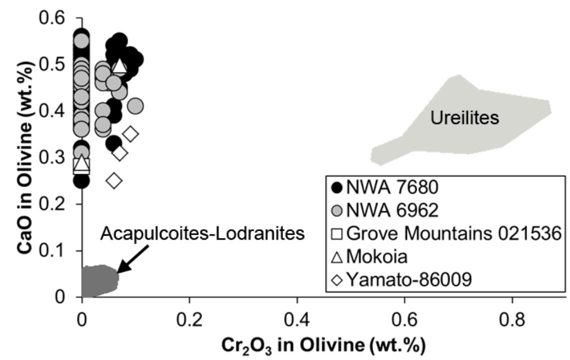

Figure 2. CaO and Cr_2O_3 content of olivine in NWA 7680/6962 for comparison with acapulcoites-lodranites and ureilites [3], a Grove Mountains 021536 clast [4] and clasts in Mokoia and Yamato-86009 [5].

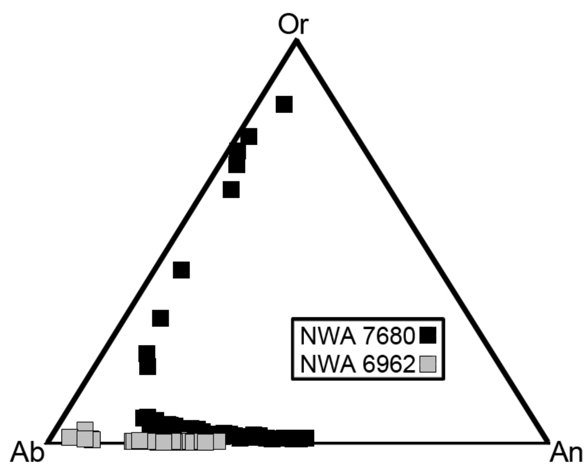

Figure 3. Feldspar compositions for NWA 7680/6962.

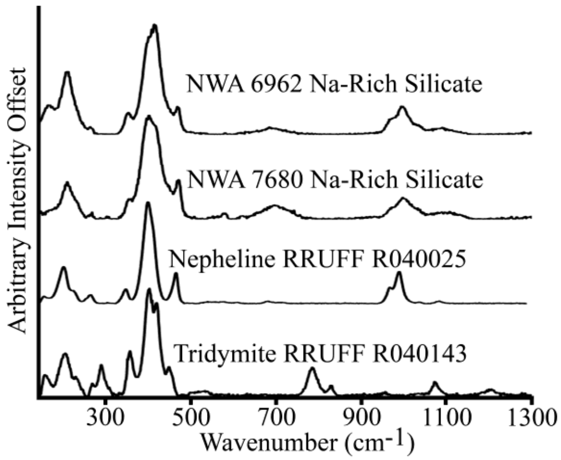

Figure 4. Raman spectra of the Na-rich silicate, nepheline (RRUFF) and tridymite (RRUFF).

Trace Element Compositions: The mafic mineral REE compositions for NWA 7680/6962 overlap for the most part; however, the more homogeneous NWA 7680 clinopyroxene exhibits a flatter pattern, whereas in NWA 6962 the zoned clinopyroxene pattern is convex, with concentrations increasing from La to Sm, and has a negative Eu anomaly (Fig.5).

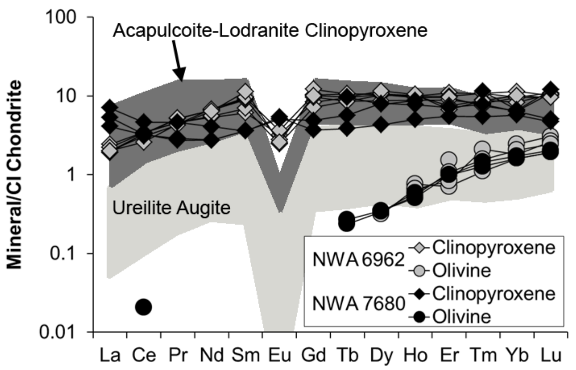

Figure 5. Pyroxene and olivine chondrite normalized REE compositions for NWA 7680/6962. Acapulcoite-lodranite data from [6] and ureilite data from [7,8].

Discussion: The mineralogical and geochemical similarities, along with past work [1], suggest that NWA 7680/6962 are from the same parent body.

Major element composition in NWA 7680/6962 olivine and pyroxene (Fig.1) along with oxygen isotope compositions [1] suggest no direct relationship to reported primitive achondrites [e.g.9]. NWA 7680/6962 are more FeO-rich than the ureilites and acapulcoites-lodranites. Minor element composition in olivine (Fig.2) also does not suggest a direct relation to either the ureilites or acapulcoites-lodranites.

Instead, the minor element compositions overlap with clasts from CM [4] and CV [5] chondrites. These clasts are olivine-rich, most contain plagioclase and pyroxene and some contain nepheline and/or merrillite and others [4,5]. However, the olivine grains in these clasts are smaller and have lower FeO content (Fa_{34-39}) than those in NWA 7680/6962. All of these clasts have oxygen isotope compositions that place them near the CCAM line. These clasts may have originated from the interior of the CV parent body [4,5]. Another potentially related material is the "FELINE" clast found in the Parnallee LL 3.6 chondrite [10]. This clast is nepheline-rich (12 modal%) and has an oxygen isotope composition that also falls near the CCAM line [10].

The clinopyroxene REE compositions here are somewhat similar to those of acapulcoites-lodranites; however, the NWA 6962 grains exhibit smaller Eu anomalies and the NWA 7680 grains have a flatter REE pattern (Fig.5). The NWA 6962 compositions actually overlap with compositions from augite in carbonaceous chondrites [e.g.11]. These compositions suggest a primitive parent body for NWA 7680/6962. Concentrations of REE are above those expected for ureilite clinopyroxene (Fig.5) and olivine [7,8].

Recently feldspar-rich crustal material from the ureilite parent body was found in Almahata Sitta [12] with oxygen isotope compositions similar to NWA 7680/6962. Other geochemical signatures and mineralogy suggest a ureilite parentage is unlikely for NWA 7680/6962; however, intrusion of a feldspar-rich crustal melt into an olivine-rich mantle is a conceivable scenario for forming NWA 7680/6962-like material.

Conclusions: We suggest that NWA 7680/6962 are not directly linked to any currently established achondrite group. Perhaps they originate from deep within a carbonaceous chondrite(-like) parent body. Alternatively, they could be from a unique FeO-rich achondrite parent body. Impact melting/mixing and parent body heterogeneity will be further considered before completely ruling out links to currently grouped achondrites. The cause of melt generation (i.e., differentiation vs. impact melting) is unknown, but may be resolved by thermochronology work in progress.

References: [1] Hyde B. C. et al. (2013) *MAPS*, 76, A5207. [2] Lafuente B. et al. (2015) *Highlights in Mineralogical Crystallography*, pp. 1-30. [3] Goodrich C. A. and Righter, K. (2000) *MAPS*, 35, 521-535. [4] Zhang A. et al. (2010) *MAPS*, 45, 238-245. [5] Jogo K. et. al. (2013) *MAPS*, 47, 2251-2268. [6] Floss C. (2000) *MAPS*, 35, 1073-1085. [7] Guan Y. and Crozaz G. (2000) *MAPS*, 35, 131-144. [8] Guan Y. and Crozaz G. (2001) *MAPS*, 36, 1039-1056. [9] Day J. M. D. et al. (2015) *MAPS*, 50, 1750-1766. [10] Bridges J. C. et al. (1995) *Proc. NIPR Symp. Antarct. Meteorites*, 8, 195-203. [11] Jacquet E. et al. (2012) *MAPS*, 47, 1695-1714. [12] Bischoff A. et al. (2014) *PNAS*, 111(35), 12689–12692.