IDENTIFYING PARENT ASTEROID OF UNGROUPED ACHONDRITE NORTHWEST AFRICA 6704: LESSONS FROM DAWN AT VESTA.
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Introduction: Northwest Africa (NWA) 6704 is an ungrouped achondrite meteorite that was found in 2010 in Algeria as a fractured stone (42 pieces) with a total mass of 8387g. The stone is lacking a visible fusion crust (probably eroded by the action of wind and sand) but the interior appears unaltered with yellowish/green large crystals and fewer brownish grains (Fig.1). Smaller grains of opaques and metal can also be found [1]. Weathering is limited to coatings of desert dust on the broken surfaces. This stone is paired with NWA 6926 and NWA 6693, which have similar composition and appearance [2].

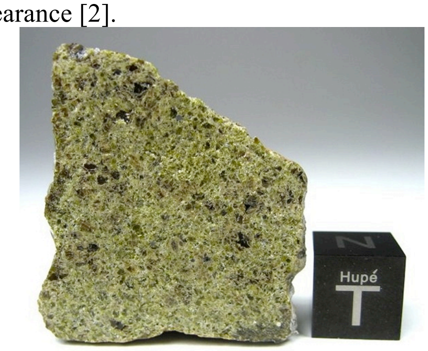

Figure 1: Sample of the NWA 6704 meteorite. Dimensions of this sample are 32 x 28 x 2 mm. Photo Credits: G. Hupé.

This is a unique achondrite containing relatively ferroan mafic silicate minerals with elevated FeO/MnO ratios, anomalous Ni contents in olivine (0.74-0.77 of NiO), interstitial and extremely sodic plagioclase, and very Ni-rich (75 vol.%) metal and sulfides [2, 3]. Its oxygen isotopic composition matches those from the Acapulcoites-Lodranites group but its mineralogy appears different from these meteorites [3]. Also, a chromium isotopic study showed that the precursor material for NWA 6704 is distinct from the acapulcoites-lodranites [4]. Abundances of highly siderophile elements in NWA 6704 are consistent with primitive achondrites (brachinites) [5]. NWA 6704 contains 70 vol.% orthopyroxene with coarse grains (5-11 mm), 16 vol.% olivine with smaller grains (0.5-0.8 mm), 13 vol.% feldspar (albite), 0.6 vol.% Cr-spinel (0.1-0.6 mm), 0.4 vol.% awaruite with grains < 0.1 mm, very low abundances of sulfides and phosphates [2, 3]. Trains of empty bubbles (2-20 µm) are embedded in the orthopyroxene crystals [3]. [2] proposed that the micro-inclusions have been formed by shock, but the loss of fluids form the bubbles suggests the event happened prior to cooling [2]. However, NWA 6704 appears generally unshocked [3] with only some rare instances of shock deformation [2]. [2, 3, 6] have suggested NWA 6704 has an igneous cumulate origin. In addition, the presence of Ni-rich phases indicates formation in a highly oxidizing environment [2].

Its CRE age has been deterimined to be 30 My [7] and its Ar-Ar age is estimated to be 4.52 By [7] in agreement with the U-Pb age retrieved by [7]. It makes NWA 6704 the oldest igneous rock in the solar system [5]. NWA 6704 has undergone more than one thermal event after crystallization [7].

Laboratory Spectral Data: Two different samples were prepared for spectroscopic measurements, one with grain size <150 µm and one with rock surface directly (chip). Reflectance spectra (Fig.2) were acquired with an Analytical Spectral Devices FieldSpec Pro HR spectrometer over the range of 350 to 2500 nm in 1.4 nm steps, with a spectral resolution of 2 to 7 nm.

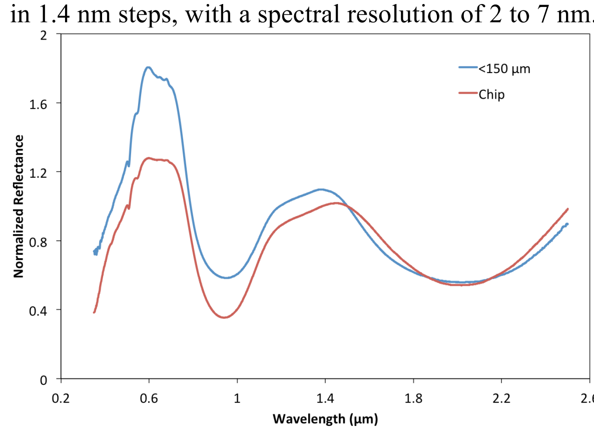

Figure 2: Spectra of NWA 6704 (whole rock surface and grain size <150 µm) normalized at 1.5 µm.

Band Parameters extraction: Band centers are critical for the identification of specific minerals in a surface assemblage. Band center corresponds to the wavelength position of the minimum reflectance in a continuum removed absorption band. The continuum is defined as a straight line across the shorter and longer wavelength shoulders of an absorption band. We also use the Band Area Ratio (BAR), the ratio of the area of 2-µm ferrous iron absorption band in pyroxene to the area of 1-µm absorption band, for characterizing the composition of the samples. Band parameters were extracted from the spectra using a Matlab-based code. For each of the pyroxene absorption bands, band center, band depth, band continuum slope and band area were calculated in addition to BAR and visible slope (0.55–0.65 μm).

Analysis of spectra: Both spectra (Fig.2) exhibit a higher short-wavelength (left) shoulder and lower long-wavelength (right) shoulder for the 1-μm olivine/pyroxene absorption band hence rendering the visible slope negative. This is typically observed with the presence of glass, with the left shoulder becoming more prominent relative to the right one, with increasing amount of glass in a mixture of howardites+glass [8]. Being generally unshocked, NWA contains only a very limited amount of impact melt glass in inclusions and instead is mostly composed of large vitreous grains [2]. Another absorption feature present in both spectra is the 0.625-μm band. The reflectance maximum associated with this absorption is linked to the amount of Ni^{3+} in olivine, and it is expected that the nickel-rich olivine has the reflectance maximum on the short wavelength side of the band [9].

The Band I vs. Band II plot (Fig.3) shows that NWA 6704 falls among the basaltic/cumulate eucrites in agreement with its spectral appearance. Band I center might have been shifted to longer wavelengths due to the negative spectral slope of Band I.

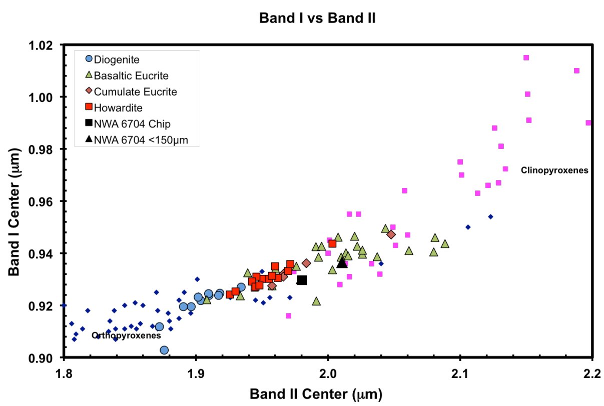

Figure 3: Band I center vs. Band II center of NWA 6704 samples along with HED samples and OPX/CPX.

Mineralogy: We used equations from [10] to derive pyroxene chemistry from Band I and II centers of NWA 6704 spectra. The average Fs and Wo values (mol.%) we obtain for both the chip and <150 μm grain sizes is $Fs_{40.5\pm3}Wo_{9\pm1}$. While these values are consistent with measurements from laboratory analysis (low-Ca PYX: $Fs_{40}Wo_{3}$) [2], the Wo derived from the spectra is higher. This is because the Fs and Wo values we derive from the spectra correspond to mean pyroxene chemistries of both the low-Ca ($Fs_{40}Wo_{3}$) and high-Ca ($Fs_{20}Wo_{40}$) components of NWA 6704.

Fig.4 shows that NWA 6704 falls in the S(VI) zone for the chip sample and in between the S(V) and S(VI) zones for the grain size sample. [11] noted that asteroids falling in the S(VI) zone correspond to OPX-rich silicate-metal assemblage that could match winonaites or partial melt residues [11]. S(V) zone is above the olivine + OPX mixing line due to the presence of clinopyroxene (increases Band I center without an increase in BAR) [11]. [11] proposed that the meteorites sampling the S(V) asteroids are primitive achondrites (lodranites) or metamorphosed H chondrites. This interpretation is consistent with laboratory petrology studies which suggest a primitive achondrite origin for this meteorite.

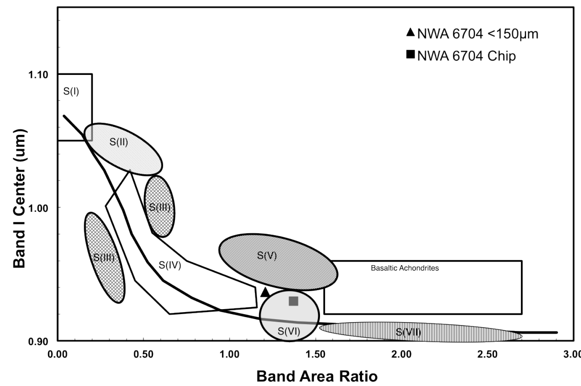

Figure 4: Band I center plotted against BAR for NWA 6704. Regions for different S asteroid sub-types [11] are shown in the plot in grayish ellipses, and basaltic asteroids' region is displayed as a rectangle.

Parent Asteroid: Spectral comparision of NWA 6704 with those of S(V) and S(VI) asteroids from [11] shows little resemblance between the two. The most obvious difference is the higher reflectance at 0.6 μm in the meteorite data compared to the asteroids. The absorption bands in the meteorite are also significantly deeper than any of the S(V) and S(VI) asteroids. Ignoring the 0.6 μm hump, the spectrum of NWA 6704 resembles best those of V-type asteroids including Vesta. A more thorough search for the parent asteroids is ongoing, including searching the Dawn data from asteroid Vesta; results will be presented at the conference.

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References: [1] Meteoritical Bulletin, No. 99, April 2012, *MAPS* 47, E1-E52. [2] Warren P. H. et al. (2013) *GCA*, in press. [3] Irving A. J. et al. (2011) 74th *Metsoc* abstract #5231. [4] Sanborn M. E. et al. (2013) 76th *Metsoc* abstract #5220. [5] Iizuka T. et al. (2013) 44th *LPSC* abstract #1841. [6] Jambon A. et al. (2012) 43rd *LPSC* abstract #2099. [7] Fernandes V. A. et al. (2013) 44th *LPSC* abstract #1956 [8] Buchanan P. C. et al. (2014) 45th *LPSC* abstract. [9] King T. V. V. Phd dissertation (1986), University of Hawaii. [10] Burbine, T.H., and Buchanan, P. C., 2010. 41st *LPSC* abstract #1533. [11] Gaffey M. J. et al. (1993) *Icarus* 106, 573-602.