PETROLOGY, BULK COMPOSITION, AND PROVENANCE OF METEORITE NORTHWEST AFRICA 5000 (NWA5000) A. B. Nagurney[1,2], A. H. Treiman[2], P. D. Spudis[2], [1]Department of Geology and Environmental Geosciences, Lafayette College, Easton, PA 18042 (nagurnea@lafayette.edu) [2]Lunar and Planetary Institute, Houston, TX 77058

Introduction: Lunar meteorites provide information about the composition of regions of the Moon that cannot be inferred from Apollo samples or remote sensing data. Northwest Africa 5000 (NWA5000) was discovered in 2007 in Morocco (Fig. 1a) and at 11.5 kg is the second largest known lunar meteorite [1]. Previous work has examined the petrology, metal compositions, and Ar-Ar age [1-3], but this is the first general study of the meteorite.

NWA5000 is a polymict leucogabbronorite breccia, with light-toned rock fragments set in a dark fragmental matrix. It is noteworthy compared to other lunar rocks and meteorites because both the matrix and clasts contain relatively high concentrations of metal, ~2% by volume [2]. Many lunar samples contain small proportions of metal [4], mostly of meteoritic origin, but at much lower abundances than in NWA5000. This suggests that NWA5000 may have an unusual parent material or be a product of unusual processes.

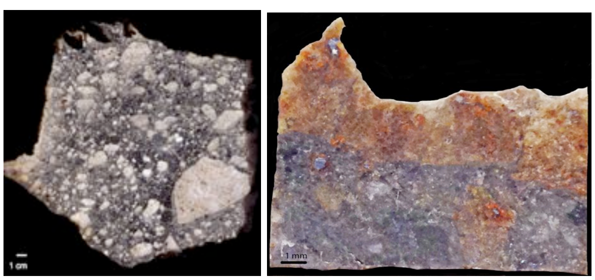

Figure 1. Slabs of NWA 5000. *a) Cut surface across whole meteorite. Note scale (c/o The Hupe Collection) b) The slab studied here. Upper 1/3 of slab, light-colored and stained orange, is typical of the large leuconorite clasts that dominate the meteorite. Lower 2/3 of slab is fragmental matrix material.*

Sample and Methods: We examined a 0.74 gram slab of NWA5000, which exposes nearly equal parts of clast and matrix material (Fig. 1b). We analyzed the chemical compositions of silicate minerals in the clast and matrix, using normal methods (15kV, 10 nA beam) with the CAMECA SX100 electron microprobe at ARES, Johnson Space Center. We also analyzed nine metal grains at 15kV, 60nA.

To determine the mineral proportions in the clast, we used element X-ray maps taken with the JEOL 7600F SEM at JSC, and classified all the map points using the software package MultiSpec©. Mineral proportions and compositions (and literature data on densities) were used to calculate the bulk composition of the clast.

Results: Mineral proportions of the clast are: 66.6% anorthite, 18.8% augite, 6.8% pigeonite, 5.6% olivine, 1.9% kamacite, and 0.3% merrillite. The high abundance of plagioclase and similar proportions of both pyroxenes indicate that the sample is a leucogabbronorite. Its texture suggests that it is an impact melt; larger plagioclase grains (> 200µm) are set in a sub-ophitic matrix of pyroxenes surrounding plagioclase and olivine (Fig. 2).

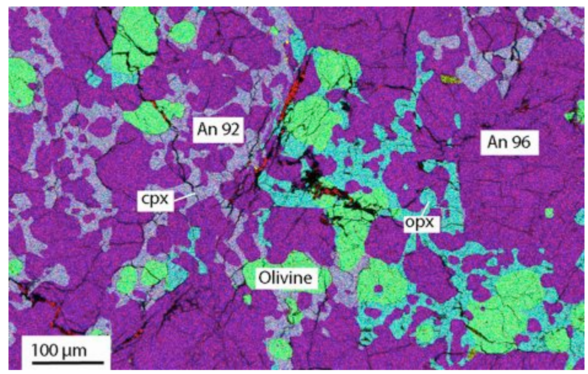

Figure 2. *False color X-ray map of clast texture. Red=Ca, Green=Mg, Blue=Si. Note large plagioclase grains (An96) are more calcic that plagioclase intergrown with pyroxenes (An92).*

Olivine occurs as equant rounded to subhedral grains (Fig. 2), which are commonly rimmed by pigeonite. Mg# in the olivine averages 68.5, and its molar Fe/Mn = 88. Pyroxenes (augite and pigeonite) occur as rims on olivine and as wormy grains intergrown with plagioclase (Fig. 2). Pyroxene compositions are fairly homogeneous (Fig. 3), and are consistent with equilibration at 700-800°C [5].

Plagioclase is the most abundant mineral in the clast. Larger grains are more calcic, An_{95-97}, consistent with typical ferroan anorthosite [6]. Smaller plagioclase grains among the wormy pyroxene grains are more sodic, ~An_{92-94} (K_2O~0.08%).

The clast contains six large (0.5-1.0 mm) metal grains, $Fe_{92}Ni_6Co_{0.5}$, which is consistent with that of

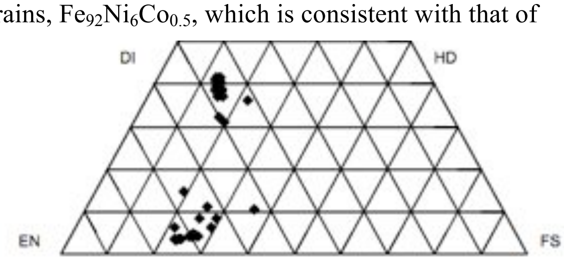

Fig 3. *Ortho- and clinopyroxene compositions in the leucogabbronorite clast.*

Table 1. Composition of clast by modal recombination.

Oxide	Wt %
SiO_2	44.9
TiO_2	0.4
Al_2O_3	23.0
Cr_2O_3	0.2
FeO	5.2
MnO	0.1
MgO	7.8
CaO	15.5
Na_2O	0.4
K_2O	~0.04
Fe	1.7
Ni	0.1
Co	0.01

meteoritic kamacite [7]. Merrillite was identified by EDS spectra, but not analyzed yet.

The matrix around the clast consists of fragments of minerals from the clasts, mineral fragments not related to the clasts, and a variety of fine-grained lithic and vitreous fragments.

Bulk Composition: Because minerals in the clast are chemically homogeneous, we can calculate the bulk composition of the clast by adding their compositions, weighted by their modal abundances and corrected for density. Table 1 shows the estimated bulk chemical composition of the clast.

Discussion: *Lunar Origin:* Despite its unusual abundance of metal, we believe that NWA5000 is of lunar origin as shown by its: O isotope ratios [1]; Fe/Mn ratio and Mg# of olivine [6,8]; plagioclase composition [8]; and low K abundance.

Clast Petrology: The clast textures are consistent with those of an impact melt breccia: larger mineral grains, presumably fragmental relics of the protolith (plagioclase of ~An_{96}), set in a matrix with an igneous sub-ophitic texture (Fig. 2). The metal in the clast must be ascribed to the impactor because its composition is chondritic and such large proportions of metal are not characteristic of known lunar rock types. After formation, this impact melt breccia remained hot for a long time, as shown by the chemical homogeneity of its olivine and pyroxene, and evidence for gallium diffusion from the metal into its plagioclase [2].

Impact Mixing: The leucogabbronorite is an impact mixture, containing a plagioclase-rich lunar protolith mixed with meteoritic metal. Because the leucogabbronorite is richer in augite than nearly all other lunar rocks, it is difficult to identify a lunar protolith. However, the meteoritic component can be constrained. The O isotopic composition of NWA 5000 is consistent with those of other lunar rocks [1], implying that it must contain relatively little (< 10%) chondritic material; E chondrites are excluded from this restriction as their O isotopes are not distinguishable from those of the Moon.

With so little meteoritic silicate fraction, the proportion of metal in NWA 5000 seems to rule out most possible chondritic impactors – unless the metal is concentrated during impact melt sheet differentiation [9]. Of non-E chondrites, only H and CH/CB types contain enough metal so that a ~10% admixture could yield the ~2% metal seen in NWA 5000. Abundances of siderophile trace elements in the metal do not match those of metals in any known meteorites [2], but abundances of some elements (Ge, Ga) may have been modified by chemical exchange with the silicate minerals [2]. Thus, the impactor that produced NWA 5000 must have been metal-rich, possibly of an unknown meteorite type.

Provenance: Because NWA 5000 contains a distinctive chemical composition and mineralogy, we can suggest a relatively limited number of possible sources areas on the Moon. First, NWA 5000 is clearly a highlands sample, far from mare basalt (no mare clasts were found), so that we consider areas in the lunar highlands with relatively high FeO content (Table 1), based on lunar surface chemistry from the Clementine orbiter [10]. Such areas include the floor of the Lomonosov-Fleming and South Pole-Aitken basins, the near side of the southern highlands, and the general vicinity of King crater [10].

Second, NWA 5000 contains more augite (~19%) than nearly all known lunar samples and meteorites [11]. Thus, we screened the mafic highlands areas for those regions with more augite than pigeonite, using the NIR reflectance spectra from the Kaguya spacecraft [12]. Finally, considering the relatively young age Ar-Ar of NWA 5000 of ~600 my [3], we identified impact craters of Copernican age (i.e., fresh craters). From these criteria, one of the following craters could be the source of NWA5000: Bürg, Faraday C, Glushko, King, Necho, Robertson, Rutherford, Thebit A, or Tycho. We plan to continue study of the remote sensing data in order to better constrain the source area of this unusual lunar rock.

References: [1] Irving A.J. et al. (2008) *LPSC* XXXIX, 2168. [2] Humayun M. and Irving A.J. (2008) *Goldschmidt Conference Abstr.* A402. [3] Fernandes V.A. (2009) *Goldschmidt Conference Abstr., GCA* 73, A365. [4] Warren P.H. et al. (1987) *JGR* 92, E303. [5] Lindsley D.H. (1982) *American Mineralogist* 68, 484. [6] Jolliff B.L. et al. (2006) *New Views of the Moon,* 95, 103. [7] Wittman A. and Korotev R.L. (2013) *LPSC* XLIV, 3035. [8] Papike J.J. et al. (2003) *Amer. Mineralogist* 88, 469. [9] Grieve R.A.F. et al. (1992) *JGR* **92**, 14113. [10] Spudis, P.D., *et al.* (2002) *LPSC* XXXIII, 1104. [11] Korotev R.L. (2005) *Chemie der Erde* **65**, 297. [12] Yamamoto S. *et al*. (2015) *JGR* **120**, 831.