A TRACE-ELEMENT INVESTIGATION OF LUNAR METEORITE NORTHEAST AFRICA 001.

J. F. Snape[1], K. H. Joy[1,2,3] and I. A. Crawford[1]. [1]The Joint UCL / Birkbeck Dept. of Earth Sciences, UK. [2]IARC, Dept. of Mineralogy, The Natural History Museum, London, UK. [3]STFC, Rutherford Appleton Laboratory, UK. (Email j.snape@ucl.ac.uk)

Introduction: Lunar meteorite Northeast Africa 001 (NEA 001) is a feldspathic polymict regolith breccia [1,2,3]. The sub-section studied for this investigation was subject to a detailed petrologic study outlined in [4], which included the acquisition of major element mineral and clast composition data. This study aims to build on these results by providing trace element data on several lithic fragments within the sub-section.

Methods: Trace element concentrations of the sub-section were measured using an Agilent laser ablation inductively coupled mass spectrometer (LA-ICP-MS) at UCL/Birkbeck. NIST 612 (a synthetic doped glass) was used as an external standard [5], and Ca wt.% data from our previous study [4] was used as the internal standard.

Clast trace element concentrations were measured by ablating several tracks (typically 3 – 5 analyses per clast) with dimensions of 200 × 80 µm, and averaging the results. Errors shown in Figure 1 and Figure 2 reflect the standard deviation variation between the tracks measured in each clast. These errors, therefore, represent the heterogeneity of each clast analyzed (i.e. large errors indicate more heterogeneous clasts), rather than analytical uncertainty on a single measurement.

Results: Average clast trace element concentrations were obtained for four impact melt breccia clasts and four basaltic clasts in the sub-section. These results are discussed below:

Impact melt breccias: All of the impact melt clasts analyzed (IM1, IM2, IM4 and IM6) are of feldspathic composition (>25 Al$_2$O$_3$ wt.%) and comparison with other lunar samples shows the impact melt clasts to have similar concentrations of trace elements to typical ferroan anorthosite (FAN) lithologies (Fig. 1).

REE concentrations are at ×7 to ×20 chondritic abundances [6] and are moderately LREE-rich with flatter HREE patterns (1.1-1.7 La/Lu$_{cn}$, where $_{cn}$ implies chondrite normalized). Positive Eu-anomalies (1.6-2.7 Eu/Eu*: calculated as $Eu_{cn}/\sqrt{(Sm_{cn} \times Gd_{cn})}$) are identified for all four impact melt clasts (Fig. 2a).

Basaltic clasts: We previously reported [4] that basaltic samples in NEA 001 have low-Ti (1-6 TiO$_2$ wt.%) to VLT (<1 TiO$_2$ wt.%) compositions. Three of the VLT basalt clasts (labeled B1a, B1b and B7 in Fig. 1) have unusually low concentrations of incompatible trace elements (ITEs) compared with other basaltic lunar samples (Fig. 1). The NEA 001 VLT clasts (Fig. 2) have REE concentrations at ×2 to ×10 chondritic abundances [6] (Apollo low-Ti basalts typically have ranges of ×20 to ×50, and VLT basalts typically have ×5 to ×15 chondritic abundances [7]). All three clasts are LREE poor and HREE rich (0.2-0.5 La/Lu$_{cn}$) and have positive Eu anomalies (1.6-3.0 Eu/Eu*: Fig. 2).

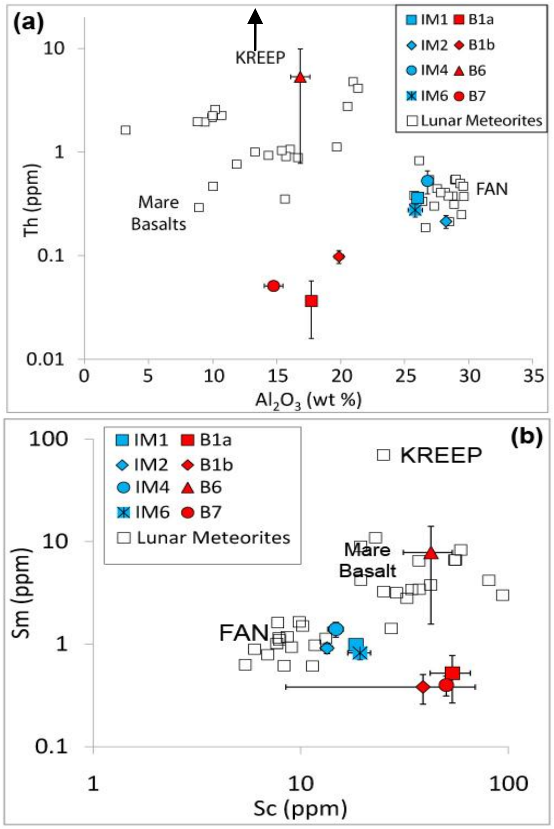

Figure 1. Bi-element compositional plots of clasts in NEA 001: (a) Al$_2$O$_3$ wt.% vs. Th (ppm). Al$_2$O$_3$ values taken from data presented in [4]. (b) Sc (ppm) vs. Sm (ppm). NEA 001 data are compared with bulk compositions of lunar meteorites taken from [7].

A fourth VLT basaltic clast (B6) has much greater ITE abundances (Fig. 1) and a REE profile (Fig. 2) similar to those seen in KREEPy mare basalt material [7]. This is the only example of KREEP-rich material in our NEA 001 section.

Discussion: The sub-section studied exhibits a far more heterogeneous nature than is noted in previous studies of NEA 001 [1,2].

Impact melt breccias: The impact melt clasts in NEA 001 exhibit REE patterns, typical of plagioclase dominated materials. They exhibit similar elemental

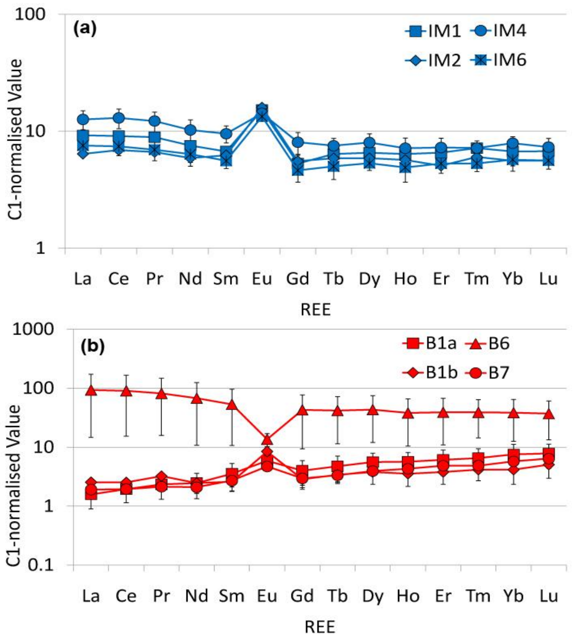

Figure 2. Chondrite normalized [6] average clast concentrations of (a) REE in impact melt clasts and (b) basalt clasts.

abundances to FAN lunar meteorites (Fig. 1b) and are as ITE-poor as the Group-4 Apollo 16 [8] feldspathic impact melts (although the NEA 001 melts are comparatively Sc-richer) indicating that the target bedrock was KREEP-poor and feldspathic in nature.

Basaltic clasts: The REE profile and ITE concentrations of B6 suggest the clast may have been derived from a distal KREEP-rich source.

The REE pattern exhibited in the remaining three VLT basalt clasts, and their low concentrations of incompatible elements, have implications with regard to their petrogenetic origin.

Positive Eu-anomalies are highly unusual for mare basalt material, but small, or essentially flat positive Eu-anomalies have been reported for rare Luna 24 ferrobasalt samples [9] and in VLT lunar meteorite MIL 05035 [10]. [9] invoke several possible explanations for the occurrence of both small positive and negative Eu-anomalies in Luna 24 samples, which should also be considered in the case of the VLT clasts in NEA 001. These include: (1) the presence of Eu-rich phosphates; (2) higher feldspar concentration due to processes such as accumulation, assimilation or remelting; (3) varying degrees of partial melting or variation in the source composition.

Our investigations revealed no evidence of any phosphate phases (apatites or merrillite) within the basalt clasts.

The second explanation provides a plausible way of modifying the REE concentrations of the clasts studied. The work of [11] provides a detailed investigation into the processes of anorthosite dissolution and crustal assimilation processes in lunar picritic magmas, in which it is concluded that anorthosite dissolution may be important in producing some of the compositional variability of mare basalts. The low concentrations (<×10 chondritic) of REE recorded in several of the clasts in NEA 001 (Fig. 2) implies that slight changes in mineralogy, can greatly affect any apparent anomalies in Eu concentration [9]. Therefore, even relatively small amounts of crustal assimilation could potentially derive the observed positive Eu-anomalies.

It is also possible that VLT basalts such as those observed in NEA 001 and in many of the Luna 24 samples originated from a region of the lunar interior compositionally distinct from other basaltic materials. Low La/Lu$_{cn}$ values (Fig. 2b), and their Sc-rich nature (Fig. 1b), indicates that the basalts have originated from a pyroxene-rich source region. One possibility is that the VLT source was formed from mantle cumulates (dominantly olivine and pyroxene) that formed early in lunar differentiation, prior to significant removal of anorthosite from the lunar magma ocean [10].

The nature of the REE patterns and possible causes for the positive-Eu anomalies will be the subject of further investigation involving trace element modeling and geochemical studies.

Meteorite source region: The FAN-rich, KREEP-poor nature of the impact melt clasts, coupled with the presence of basaltic material [4] suggest that the meteorite originated from a highland source region in close proximity to outcrops of ITE-poor VLT mare basalt. If this were the case, then the VLT basaltic clasts within NEA 001 could be representative of basaltic material more common to the outer Feldspathic Highlands Terrane [12], potentially on the farside of the Moon, which have been observed to be Ti-poorer and Th-poorer than basalts outcropping on the near side [13-15].

References: [1] Korotev and Irving (2005) LPSC *XXXVI,* Abstract #1220. [2] Haloda et al. (2005) LPSC *XXXVI,* Abstract #1487. [3] Korotev (2008) *GCA,* Vol. 72, pp. A492. [4] Snape et al. (2008) LPSC *XXXIX,* Abstract #1316. [5] Pearce et al. (1997) *Geostan. & Geoanal. Res.* Vol. 21, pp. 115-144. [6] Anders and Grevesse (1989) *GCA,* Vol. 53, pp. 197-214. [7] Jolliff et al. (2006) *Rev. Mineral.,* Vol. 60, pp. 721. [8] Korotev (1994) *GCA,* Vol. 58, pp. 3931-3969. [9] Laul, J.C. et al. (1978) *GCA,* Vol. 9, p. 537-568. [10] Joy et al. (2008) *GCA,* Vol. 72, pp. 3822-3844. [11] Morgan et al. (2006) *GCA,* Vol. 70. pp. 3477-3491. [12] Jolliff et al. (2000) *JGR – Planets, Vol. 105 (E2), pp. 4197-4216.* [13] Lucey et al. (2000) *JGR – Planets,* Vol. 105 (E8), pp. 20297-20305. [14] Spudis et al. (2000) LPSC *XXXI,* Abstract #1414. [15] Spudis et al. (2002) LPSC *XXXIII,* Abstract #1104.