THE PETROLOGY AND GEOCHEMISTRY OF FELDSPATHIC GRANULITIC BRECCIA NWA 3163: IMPLICATIONS FOR THE LUNAR CRUST C. L. McLeod[1], A. D. Brandon[1], T. J. Lapen[1], J. T. Shafer[1], A. H. Peslier[2,3], A. J. Irving[4]. [1]Department of Earth and Atmospheric Sciences, University of Houston, Science and Research Building 1, Houston, TX 77204, USA [2]Jacobs Technology, ESCG, Mail Code JE23, Houston TX, 77058, USA, [3]ARES, NASA-Johnson Space Center, Houston. TX 77058, USA, [4]University of Washington, Department of Earth & Space Sciences, Seattle WA, 98195, USA.

Introduction: Lunar meteorites are crucial to understand the Moon's geological history because, being samples of the lunar crust that have been ejected by random impact events, they potentially originate from areas outside the small regions of the lunar surface sampled by the Apollo and Luna missions. The Apollo and Luna sample sites are contained within the Procellarum KREEP Terrain (PKT, Jolliff et al., 2000)[1], where KREEP refers to potassium, rare earth element, and phosphorus-rich lithologies. The KREEP-rich rocks in the PKT are thought to be derived from late-stage residual liquids after ~95-99% crystallization of a lunar magma ocean (LMO). These are understood to represent late-stage liquids which were enriched in incompatible trace elements (ITE) relative to older rocks (Snyder et al., 1992)[2]. As a consequence, the PKT is a significant reservoir for Th and KREEP. However, the majority of the lunar surface is likely to be significantly more depleted in ITE (84%, Jolliff et al., 2000). Lunar meteorites that are low in KREEP and Th may thus sample regions distinct from the PKT and are therefore a valuable source of information regarding the composition of KREEP-poor lunar crust.

Northwest Africa (NWA) 3163 is a thermally metamorphosed ferroan, feldspathic, granultic breccia composed of igneous clasts which exhibit a bulk anorthositic, noritic bulk composition. It is relatively mafic (~5.8 wt.% FeO; ~5 wt.% MgO) and has some of the lowest concentrations of ITEs (17ppm Ba) compared to the feldspathic lunar meteorite (FLM) and Apollo sample suites (Hudgins et al., 2011)[3]. Localized plagioclase melting and incipient melting of mafic minerals require localized peak shock pressures in excess of 45 GPa (Chen and El Goresy, 2000; Hiesinger and Head, 2006)[4, 5]. NWA 3163, and paired samples NWA 4481 and 4883, have previously been interpreted to represent an annealed microbreccia which was produced by burial metamorphism at depth in the ancient lunar crust (Fernandes et al., 2009)[6]. This is in contrast to the interpretation of Hudgins et al. (2009)[7] where NWA 3163 was interpreted to have formed through contact metamorphism. To further constrain its origin, we examine the petrogenesis of NWA 3163 with a particular emphasis on *in-situ* measurement of trace elements within constituent minerals, Sm-Nd and Rb-Sr isotopic systematics on separated mineral fractions and petrogenetic modeling.

Considerations from *in-situ* geochemical information on mineral separates (determined by laser-ablation inductively coupled plama mass spectrometry: LA-ICP-MS) from NWA 3163 imply an origin that is inconsistent with a LREE-depleted source which would be expected if the protolith was primordial lunar crust which formed during crystallistaion of the LMO. Instead, NWA 3163 may represent the product of metasomatism of impact-related partial melting of KREEP-poor crustal rocks and is therefore, potentially, one of the best examples of lunar lower crust in the lunar meteorite collection.

Methods: Major and trace element concentrations of maskelynite, pyoxene, olivine, and Ti-oxides in a polished slab were measured *in-situ* by electron probe microanalysis (EPMA) at NASA-JSC and LA-ICP-MS at University of Houston, respectively. During analysis for major elements, sodium was measured first in each sequence of crystal switching to minimize loss by volatilization. For each analyzed laser spot, a 10-15 second gas blank was collected prior to ~30 seconds of sample ablation. Laser ablation spots were chosen to be coincident with previous EMP analyses. However, due to the generally homogeneous composition of the major mineral phases, especially maskelynite, several laser ablation spots were in areas not previously analyzed by EMPA.

About 60 mg of coarsely crushed NWA3163 minerals were separated into dark, intermediate and light fractions. Each fraction will be analysed for Sm-Nd and Rb-Sr geochronology.

Results: There is little variation in the anorthite content of maskelynite throughout our section of NWA 3163. Overall, the mean An% (percent anorthite content) is 96.9 ± 1.6 (2σ, all further errors 2σ unless specified). Therefore, plagioclase in NWA 3163 was either initially homogeneous or homogenized during thermal metamorphism and/or maskelynization. Olivine is relatively ferroan and exhibits very little variation in forsterite content (Fo%) with mean Fo% of 57.7 ± 2.0 (2σ). The majority of pyroxene is low-Ca pigeonite (En% 57.2 ± 3.4, Fs% 32.5 ± 3.6, Wo% 10.3 ± 3.1). Augite (En% 45.7 ± 5.6, Fs% 21.7 ± 4.8, Wo% 32.6 ± 10) is less common, comprising approximately 10% of analyzed pyroxene. Orthopyroxene is commonly found as extremely thin lamellae within discrete augite crystals. No resolvable difference in major element composition ws observed in individual pyroxene crystals from core to rim. Spinel crystals exhibit a 53% chromite composition along the chromite-ulvöspinel solid solution series Fe_2TiO_4 - $FeCr_2O_4$.

Chondrite-normalized incompatible trace element (ITE) compositions are shown in Fig. 1. The ITE concentrations of olivine are characteristically low with LREE depleted chondrite-normalized profiles (La/Yb_{CI} ~ 0.14). Profiles for pyroxene have negative Eu anomalies (Eu/Eu* < 0.1,) and are LREE depleted (La/Yb_{CI} = 0.08) relative to chondrites (Fig. 1). Plagioclase exhibits the characteristic positive Eu anomaly (Eu/Eu* ~4) typical of lunar plagioclase and is HREE depleted (La/Yb_{CI} = 12.5).

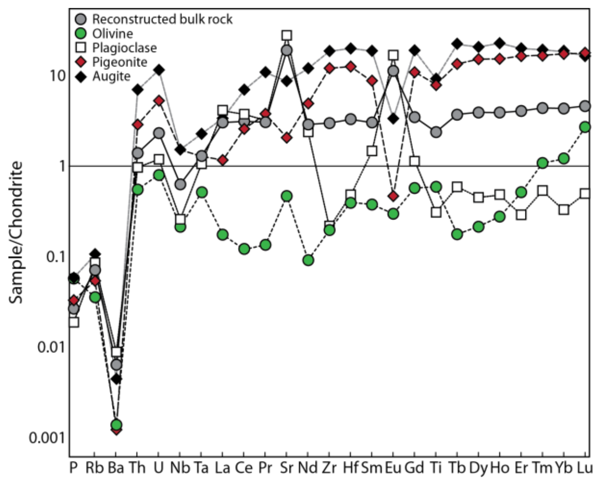

Fig. 1: Chondrite normalized ITE patterns for NWA 3163 minerals

Discussion: The concept of the lunar magma ocean (LMO) has advanced due to multiple lines of evidence indicating that the ferroan anorthosite crust and mafic mantle source lithologies for mare basalts can be explained by a planetary scale melting event (Smith et al., 1970)[8]. Ferroan anorthosites, like the NWA 3163 protolith, have been interpreted to represent direct LMO crystallization products. If this is the case, trace element concentrations in NWA 3163 primary mineral phases should be in equilibrium with residual LMO liquids present during crystallization of those phases. Our initial petrogenetic modeling suggests that the NWA 3163 protolith could not have been formed from crystallization of an initially LREE depleted LMO as suggested by[9, 10], but rather required an initially chondritic LMO with substantial early garnet crystallization or a LREE enriched LMO.

Hudgins et al.[3] report an Ar-Ar age of 3327±29 Ma for NWA 3163, which they consider to be the age of the thermal metamorphism that resulted in the granulitic texture. Paired sample NWA 4881 indicates a young age of 1335±32 Ma (Fernandes et al., 2009)[6]. These ages are younger than the purported time of the late heavy bombardment (LHB~3.8 – 4.0 Ga). If a giant impact did provide the latent heat for the thermal metamorphism of NWA protoliths, it occurred outside of the LHB. Alternatively, Ar is largely hosted in plagioclase and the resetting event at ~3.3 Ga may have been the age of the impact event that caused melting of plagioclase and formation of maskelynite. Maskelynite is not found in the Apollo granulitic breccias and these samples all have Ar-Ar ages that are within the LHB period, which suggests that the younger age of NWA 3163 and paired sample NWA 4881 may be related to the maskelynization after the granulitic metamorphic event. It is hoped that our Rb-Sr, Sm-Nd chronology study will provide additional constraints to the evolution of NWA 3163.

References: [1]Jolliff et al. (2000) *JGR*, *105*, 4197–4216. [2]Snyder et al. (1992) *GCA*, *56*, 3809-3823. [3]Hudgins et al. (2011) *GCA*, *75*, 2865-2881. [4]Chen and El Gorsey. (2000) *EPSL*, *179*, 489-502. [5]Hiesinger and Head. (2006) *Rev. Min Geo* 60. [6]Fernandes et al. (2009) *LPS XL*. Abstract #2009. [7]Hudgins et al. (2009) *72nd AMSM*. Abstract #5157. [8]Smith et al. (1970) *Proceedings of the Apollo 11 LSC*, pp. 897-926. [9]Boyet and Carlson. (2007) *EPSL*, *262*, 505-516. [10]Brandon et al. (2009) *GCA*, *73*, 6421-6445.