NOBLE GAS SYSTEMATICS OF THE 'SOIL-LIKE' APOLLO 16 REGOLITH BRECCIAS. M. Nottingham[1*], N. M. Curran[2,3,4], J. F. Pernet-Fisher[1], R. Burgess[1], J. D. Gilmour[1], I. A. Crawford[5], K. H. Joy[1], [1]Dept. of Earth and Environmental Sciences, University of Manchester, M13 9PL, UK [2]Catholic University of America [3]NASA GSFC, Maryland 20771, USA [4]CRESST2 [5]Dept. of Earth and Planetary Science, Birkbeck College, University of London, WC1E 7HX, UK (*mark.nottingham@manchester.ac.uk).

Introduction: Samples collected at Apollo 16 landing site, situated on the nearside lunar highlands (15"30' E, 8"58' S), include a wide array of regolith breccias [1,2]. These samples were soils that, at some point in the past, were consolidated into breccias. Two common consolidation age groups of regolith breccias have been identified across the Apollo 16 sample collection: the 'ancient' (consolidated into breccias ~3.8 – 3.4 Ga) and the 'young' (consolidated ~2.5 – 1.7 Ga) breccia samples [2,3]. A third group – termed the 'soil-like' breccias are predicted to have formed from the fusion of more recent soils [1]. This group are characterized as being are loosely consolidated, heterogeneous, generally low Mg# (like the soils present at the landing site), and contain components such as volcanic and/or impact glass beads, indicative of a formation in a surficial soil. No consolidation ages for the these 'soil-like' regolith breccia group have so far been determined, but they are thought to have formed within the last 2 Ga [3]. If so, these soil-like breccias may provide insight into impact and regolith processes in the late Eratosthenian and Copernican eras when the impact flux on the Moon is poorly constrained.

In order to better understand how these samples fit into the Apollo 16 regolith evolution history, this work determined their noble gas inventories.

Samples: We measured chips of 10 Apollo 16 soil-like samples for their textures [4], bulk chemistries, and noble gas inventories (this work). Sample textures range from 'brownish soil breccias' (65746, 65747, 65749, 60637 65926 and 65748) to grey/white breccia (60535) and a crystalline impact melt rock which was a coarse fine from soil 61504 [6]. The samples span a range of durations of exposure to space weathering (i.e., maturity), based on reported I_s/FeO indices[1].

Methods: The samples were split in a class 10000 clean room at the University of Manchester. One sub-split was analyzed on an SEM to determine sample texture [4]. The remaining portion was split into two chips, one for light noble gas (He, Ne, Ar) analyses (~0.1 to 0.3 mg), and one for heavy noble gas (Kr, Xe) analyses (~3 mg; both chips were from the same parent sample). The samples were step heated and analyzed for their noble gas isotopic concentrations using a Thermo Fisher Helix Multi-collector Mass Spectrometer running in static mode. Evolved gases were purified using NP-10 and GP-50 getters, were cryogenically trapped down so each element could be analyzed separately. Isotope sensitivities are calibrated against repeat measurements of a known terrestrial air standard, and multi-detectors are cross-calibrated for signal intensity.

Results: All breccia samples analyzed so far within our sample suite show a solar wind dominated isotopic composition (70 to 90% of the total inventory released from each sample), with relatively minor cosmogenic, and radiogenic contributions. Isotopic ratios show that the first 'low temperature' laser power step (0.01 W) is dominated by solar wind composition gas for all samples (accounting for ~70 to 80% of the total released gases), with each subsequent release (laser power 0.03 to 0.6 W) being a lower concentration of gas, and showing progressive depletion of solar wind composition gases (indicative of a shift from surface-correlated implanted solar wind gases, to volume-correlated cosmogenic gases). Most samples show a second significant release at intermediate (~3 W) laser powers (accounting for ~10 to 20% of the total released gas; this release generally also shows a more solar wind rich isotopic composition, variably mixed with additions of cosmogenic composition gases) - after which, the trend of progressively lower concentration, and more cosmogenic composition gas enriched releases continues.

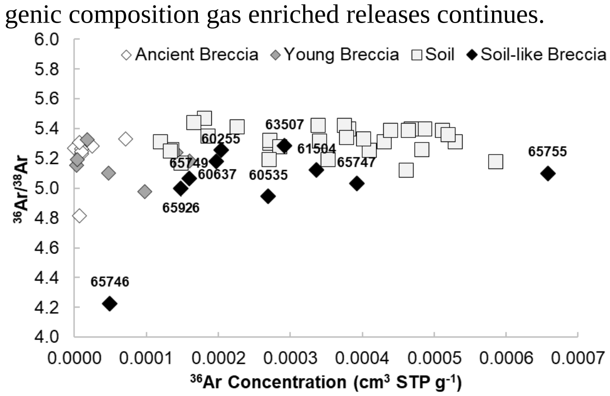

Figure 1. Total inventory Ar isotopic ratios and concentrations for (i.e., summed steps) each soil-like regolith breccia sample compared to literature available data for Apollo 16 regolith breccia and soil samples (compiled by [5]).

Noble gas concentrations: The range of Ar concentrations shown by the soil-like breccias studied here are comparable to the concentrations reported for Apollo 16 soils [2,5] (Fig. 1). Comparisons of major isotope elemental ratios between ^{4}He, ^{20}Ne, and ^{36}Ar suggest there has likely been loss of He isotopes, and possibly

Ne isotopes in several of our samples. We note a low $^{36}Ar/^{38}Ar$ ratio for sample 65746 (Fig. 1), likely due to the partial loss of / or the lower contribution of surface-correlated implanted solar wind gases. This is consistent with our petrographic observations that the allocated sample appears to be an impact melt sample and is not actually a regolith breccia.

Cosmic Ray Exposure ages: Cosmogenic contributions appear to be derived from shallowly shielded exposure (i.e., within the reach of the solar cosmic ray flux: within approximately <10 cm depth of the surface). We calculated cosmic ray exposure ages for the cosmogenic isotope systems of ^{3}He, ^{21}Ne, ^{38}Ar, and ^{126}Xe for a range of shielding depths (between an expected 0 g/cm^2 and an upper limit of 500 g/cm^2), and using the literature bulk sample data [4]. Taking the surface exposure (i.e. 0 g/cm^2 shielding) scenario, the regolith breccia samples show CRE ages of T3 = 2 to 5 Myr, T21 = 2 to 16 Myr, T38 = 30 to 150 Myr, and T126 = 10 to 35 Myr.

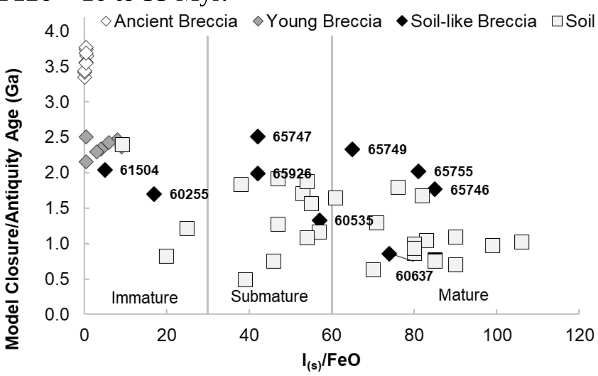

Figure 2 – Calculated ^{40}Ar-^{36}Ar antiquity age (regolith breccias) and closure ages (soils), and reported $I_{(s)}$/FeO maturity indices [1] for our soil-like regolith breccia samples, compared to data available for other Apollo 16 breccias, and soils (compiled by [5]).

^{40}Ar-^{36}Ar antiquity indicator ages: Using the calibration of [3] and reported sample bulk chemistry [4], we estimate the formation age (or antiquity age) of each regolith breccia using the $^{40}Ar_{(parentless)}/^{36}Ar_{(trapped)}$ antiquity system [3,7], as a semi-quantitative model of when these samples were consolidated to form breccias (see [7] for details). These antiquity ages often present large uncertainties in terms of their exact timing, but do establish an estimated timeline between the youngest and oldest breccias formed at the landing site. Samples 65749 and 65747 show higher antiquity ages between 2.33 and 2.51 Ga. Samples 65746, 65755, 61504, and 65926 show ages of 1.76 to 2.04 Ga. Samples 60535 and 60637 show ages of 0.86 to 1.33 Ga.

Summary: Synthesizing the evidence presented in Figures 1 and 2, we see that our soil-like regolith breccia sample set show higher concentrations of implanted solar wind gases, as well as higher I_s/FeO indices. This indicates formation from regolith that had been exposed on the lunar surface for a relatively long time (allowing the concentration of implanted solar wind gases to accumulate, as well as the production of nanophase iron particles across the soil grain surfaces). Therefore, our data support the theory of [1], that these regolith breccias formed from soils that resemble those 'modern' soils found at the Apollo 16 landing site. This is in contrast to the lower gas concentrations and lower maturity indices that have been reported for the young and ancient regolith breccia groups [8-10]. The young and ancient regolith breccias formed from immature soils that tend to be more gas-poor than the modern Apollo 16 soils (caused by shorter pre-consolidation surface residency durations, due to higher rates of regolith re-processing caused by enhanced lunar bombardment at this earlier time). These findings suggest these soil-like regolith breccias likely formed more recently than the young and ancient breccias. Thus, the soil-like breccia group likely represents a period of breccia formation that is distinct from these previously reported groups (i.e., formed during a time of declining bombardment, and higher surface residency durations). This is further supported by the observations of sample petrology and chemistry previously made by [3]. The release of implanted solar wind composition gases in each release precludes the possibility that this accumulation of gases occurred post-breccia formation: i.e. these gases were not accumulated during the time the sample resided on the lunar surface as a regolith breccia hand-specimen sample.

Further study of these samples may aid our understanding of the timing of local impact events (i.e., the impacts that consolidated the regolith into rocks), and better constrain the regolith re-processing chronology in the most recent half of the Moon's history.

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