COSMIC-RAY EXPOSURE HISTORIES OF TH-RICH LUNAR REGOLITH BRECCIAS. J. F. Pernet-Fisher[1*], M. Nottingham[1], N. M. Curran[2], and K. H. Joy[1], [1]Department of Earth and Environmental Sciences, University of Manchester, M13 9PL, UK. [2]NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, Maryland 20771, USA (*john.pernet-fisher@manchester.ac.uk).

Introduction: Some of the oldest basalt fragments recovered from the Moon are present as clasts within lunar meteorites [e.g., 1, 2]. One such clast has recently been reported within regolith breccia MIL 13317 [2]; apatite grains within these clasts yield crystallization ages of ~4.34 Ga [2, 3], similar to the oldest group of Apollo 14 mare basalts and ancient VLT meteorite Kalahari 009. Meteorite MIL 13317 forms part of a loosely defined group of Th-rich (> 3 ppm) regolith breccias that contain low-Ti to very low-Ti basaltic clasts (Fig. 1); [4]. Trace-elements in the MIL 13317 fusion crust have very similar abundances to two other Th-rich regolith breccias; Lynch 002 and Calcalong Creek [5, 6; Fig. 1]. This leads to speculation that these meteorites are grouped [2]. Establishing whether these samples are grouped is important for understanding the origins of ancient Ti-poor volcanism on the Moon, and enabling fundamental questions to be addressed, such as are they sourced from the same geographical location on the Moon? To assess the potential that these samples are grouped, we report natural noble gas isotope systematics (Ne-Ar-Kr-Xe) for these three meteorites in order to calculate cosmic-ray exposure (CRE) ages (including two splits from different portions of MIL 13317, split 10 represents a regolith portion, split 11 represent a fragmental breccia portion). This will enable the residence times on the lunar surface/within the regolith of these breccias to be estimated and provide critical insights into the regolith history of this group of meteorites.

Methods and Results: A ~ 1 mg chip was used to analyze Ne-Ar isotopes, and a ~40 mg split was used to analyze Kr-Xe isotopes. Chips were heated using a Photon Machine Fusion diode laser (λ = 900 nm). In total 4 heating steps were undertaken per sample. Two steps were conducted at low power (15, 25 W, < ~600 to ~1000ºC), a third at about the melting point of the sample (35 W, ~1200°C+), and a fourth final high temperature (45 W) to ensure the liberation of all gas from the samples. The extracted gases were cleaned using charcoal getters (one hot and one cold) for 15 mins before introduction into the Uni. Of Manchester Thermo Helix MC Mass Spectrometer. Neon and Ar were measured using multicollection mode. This allows for the interference of $^{40}Ar^{++}$ on ^{20}Ne to be completely resolved. Krypton and Xe isotopes were measured using peak jumping mode. Noble gas isotope systematics reflect mixtures of implanted solar wind (SW) and cosmogenic spallation products (Fig. 2). In general, the low temperature steps yield the greatest contribution from implanted solar wind gases. At higher temperatures, more gas is released allowing these steps to yield at greater contribution from cosmogenic spallation gases.

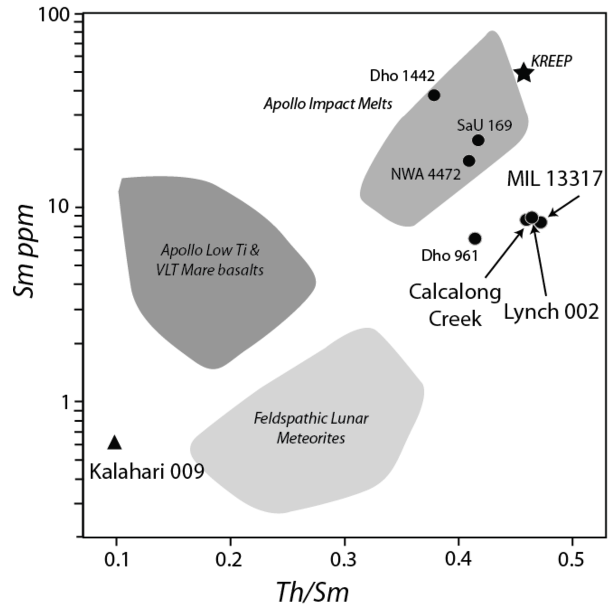

Figure 1: Bulk Sm vs. Th/Sm for main lunar lithologies. Black circles represent Th-rich regolith breccias.

Cosmic Ray Exposure Ages: Literature major- and trace-elements (Ba and La) abundances for the fusion crust were used to calculate the cosmogenic production rates (values for MIL 13317 from [2]; Lynch 002 from [5]; Calcalong Creek from; [6]). The depth-sensitive shielding indicator $^{131}Xe/^{126}Xe_C$ indicates a regolith shielding depth of ~100 g/cm^2. Assuming an average regolith density of 1.5 g/cm^3, this corresponds to burial depths of > 1 m within the lunar regolith. This depth was used to calculate the cosmogenic production rates of ^{21}Ne, ^{38}Ar, ^{126}Xe. Exposure ages for neon (t21) are between 210 and 595 Ma. Argon (t38) exposure ages for Calcalong Creek and MIL 13317,11 (fragmental portion) are 595 and 529 Ma respectively, whereas Lynch 002 and MIL 13317,10 (regolith portion) yield anomalous ages of ~1500 Ma. These old exposure ages are likely a result of these chips being saturated with implanted parentless ^{40}Ar and solar wind implanted ^{36}Ar. This cannot be corrected for when calculating the cosmogenic ^{38}Ar abundance, thus these ages a likely meaningless. Xenon (t126) exposure ages are between 861 and 981 Ma for all meteorites. The exposure ages presented here for MIL 13317,10 are similar to the ages reported by [2] and the t38 ages for Calcalong Creek presented here is similar to the age reported by [7].

Exposure ages longer than reported ejection ages (e.g., [8]) indicate that these meteorites record a complex lunar surface exposure history. We take the cosmic ray exposure ages calculated using $^{126}Xe_c$ to reflect the residence time of these breccias on the lunar surface. Neon and Ar can be lost during thermal heating and/or impact events affecting the t21 and t38 CRE ages. This is reflected in the younger CRE ages relative to t126 ages. This is commonly observed in studies that report combined Ne-Ar-Xe CRE ages [2, 9].

Discussion: *Pairing relationship:* Without the use of radioactive cosmogenic nuclides such as ^{10}Be and ^{26}Al, we cannot categorically establish if the three meteorites investigated here are launch pairs (i.e. samples ejected from the lunar surface by the same impact event). However, all three meteorites have similar residence ages within the lunar crust and display similar extents of diffusive gas loss reflected by their t21 and t38 exposure ages. Furthermore, the similar fusion crust major- and trace-element compositions (see Fig. 1), suggest a similar geological provenance. On this basis, we suggest that these meteorites are likely launch paired, or at the very least, sample the same geographical region of the Moon.

Source region of Ancient volcanism: The high bulk Th abundances of these meteorites precludes an origin of these breccias reflecting a simple mare basalt-feldspathic mixture [4]. Rather, the occurrence of KREEP-rich clasts within Lynch 002 and Calcalong Creek suggest that this pair of meteorites were sourced from within the Procellarum KREEP Terrane (PKT). Indeed, when bulk values are compared with the Lunar Prospector gamma ray spectrometer remote sensing data set, these three meteorites all share the eastern region around Mare Frigoris as a potential source location [2, 10]. Whereas Mare Frigoris is a good candidate for a source of Ti-poor basaltic volcanism [11], these lava flows are thought to be much younger than the Ti-poor basaltic clast within MIL 13317 (based on crater counting [12] estimated an emplacement age of ~3.6 Ga for lavas in eastern Frigoris). The basaltic clasts sampled by MIL 13317 may represent related older volcanism that does not outcrop significantly at the lunar surface in this area.

Meteorite Kalahari 009 also contains low-Ti basaltic clasts that yield similar crystallization ages as reported for MIL 13317 [1], however bulk chemical data for this meteorite suggests that originated from outside the PKT, possible in cryptomare regions close to the

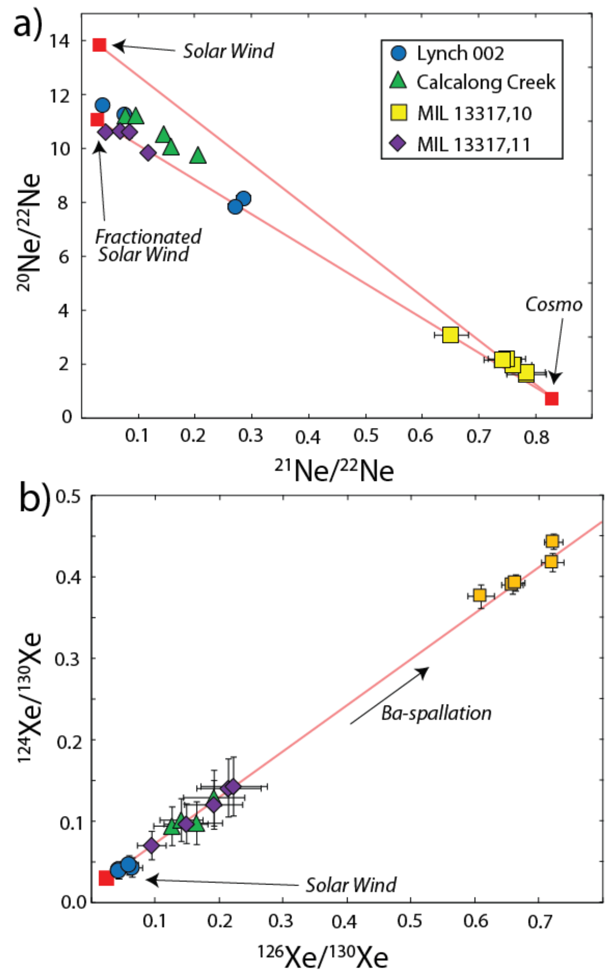

Figure 2: a) Ne three isotope plot b) Xe three isotope plot. Red squares represent solar wind, fractionated solar wind and cosmogenic endmembers.

Mendel-Rydberg basin [10]. This indicates that ancient Ti-poor lunar basaltic volcanism at ~4.3 Ga was not restricted to a single location on the lunar surface, potential representing a phase of widespread volcanism early in the Moon's history.

References: [1] Terada et al. (2007) Nature, 450, 849. [2] Curran et al. (2019) MaPS, 7, 54. [3] Shaulis et al. (2016) LPSC 47, #2027. [4] Korotev et al. (2009) MaPS, 44, 1287. [5] Robinson et al. (2016) LPSC 47 #1470. [6] Hill & Boynton, (2003). MaPS, 38, 595. [7] Swindle et al. (1995). MaPS. 30, 100. [8] Lorenzetti et al (2005) MaPS, 40, 315. [9] Mészáros et al. (2017) MaPS, 52, 2040. [10] Calzada-Diaz et al. (2015) MaPS, 50, 214. [11] Kramer et al. (2015) JGR, 120, 1646. [12] Hiesinger et al. (2010) JGR, 115, (E3).