MOON UNITED: MEASURING COSMIC-RAY EXPOSURE AGES OF PRISTINE SAMPLE HORIZONS.

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Introduction: The Moon United team of the Apollo Next Generation Sample Analysis consortium will measure the noble gas budgets of a variety of particles from both shadowed soils and drive tubes to understand the site lithologies and complement volatile and organic compound analyses.

The lunar regolith is the boundary between the surface of the Moon and the dynamic space environment. The regolith preserves a record of the Moon's geologic history, its interaction with the solar wind and cosmic rays, and its modification by asteroid and cometary impacts [1-4]. Unlike the Earth, the Moon has an insufficiently thick exosphere and is thought not to have had a significant magnetic field to protect it from the space environment. As a result, particles from the solar wind, the lunar interior, and the wider environment (e.g., solar cosmic rays (SCRs), galactic cosmic rays (GCRs), micrometeorites) directly interact with the regolith.

Over the last 4.5 billion years, volatile compounds (such as water) and organic compounds have also been exogenically and endogenically added to the lunar surface [5-7]. Volatiles have been implanted in the regolith by the solar wind [8, 9] and trapped as they escape the lunar interior [7, 10, 11]. Both volatiles and organic molecules have been delivered by asteroidal and cometary impacts over time [12-15]. Furthermore, volatiles and organics may be produced during the interaction of the solar wind and cosmic rays with surface exposed material [16-19].

Noble gases are a powerful tool for measuring these potential sources of input and destruction on the Moon. Noble-gas ratios and abundances provide important constraints on the amount and history of the solar wind and cosmic ray exposure record, indigenous degassing, and impact processing of the lunar surface [20]. These parameters help reveal the geologic history of a specific landing site.

Soils, breccias and rock fragments collected from the surface of the Moon have, at least in the last few million years, all been exposed to surface processes, including exposure to cosmic rays (producing a "cosmogenic" component), exposure to the solar wind (direct "solar" component), in-place radiogenic decay from heavy elements, "trapping" of escaped gases from the interior of the Moon (for example, ^{40}Ar that escapes the surface but is entrained in the solar wind and re-implanted), bombardment by asteroids, and by the input of comets and micrometeorites. The noble gas inventory of the regolith helps decipher how long a sample was exposed to the space environment (cosmic ray exposure (CRE) age), how much gardening and overturn was experienced (maturity indices), and the timing of breccia formation or soil appearance (antiquity age). These noble-gas derived quantities give crucial context to the history of volatile and organic compounds in the regolith. In this project, we will use a combination of noble-gas isotopic ratios and abundances to decipher the importance of each input source and help answer the following geologic questions.

What does the petrology and noble gas inventory tell us about the geologic history of the Apollo landing sites? In the absence of exogeneous input, and if there were no fractionation of the noble gases (i.e., separation of isotopes from the same element) or disruption by secondary thermal heating processes (i.e., loss of the lighter elements/isotopes) during the trapping of noble gas isotopes, lunar rocks lie on a mixing line between the cosmogenic and solar end-members. Of the available data for soils and regolith breccias, the reported CRE ages range from ~1 to 1100 Myr for soils, 1.3 to 575 Myr for crystalline (basaltic and anorthositic) lunar samples, and 0.6 to 365 Myr for impact-melt rocks. However, the majority of lunar soils have an exposure age of <400 Myr. The Apollo 16 and 17 sample collections host some of the oldest soils and regolith breccias collected during the Apollo missions (Fig. 4), where a dichotomy between ancient (>3.5 Ga) and young (<2.5 Ga) samples can clearly be identified [21].

We will investigate the noble-gas parameters of exposure age, maturity, antiquity, and abundance on different rock types, originating from different depths, to acquire a range of information from different periods of lunar history. These parameters will enable us to describe the geologic history of the two landing sites and address what properties govern the volatiles and organics budgets at these sites, including lithologic types, geologic setting, and regolith processes such as landslides and impacts.

What are the relative contributions to the noble-gas inventory from solar wind and micrometeorite bombardment in shadowed soils? Permanently shadowed regions (PSRs) at the lunar poles are key sites for the retention of volatiles. They are incredibly cold (<110K), enabling them to sequester exogenously-added components from volatile-rich asteroids and/or comets, as well as endogenic noble gases [13, 22-27]. However, their geometry shields them from the solar wind. Soil samples 72320 and 76240 provide a useful opportunity to isolate the effect of shielding from the solar wind on the input budgets of noble gases and other volatiles. These "permanently"/partially shadowed soils record the most recent history (last few tens of millions of years) at the Apollo 17 landing site.

Measuring the noble gas contents of these soils using modern techniques will shed light on these apparent discrepancies and give a fuller picture to the processes taking place in these small shadowed regions. To minimize potential ambiguity in the results when comparing shadowed soils from our lab with noble gas analyses of non-shadowed soils in other labs, we will also request and measure the same quantities from nearby, unshadowed soils. Soil sample 76260 (I_s/FeO = 58, agglutinates 45% agglutinates), has a very similar petrology and maturity to 76240 (I_s/FeO = 56, agglutinates 48% agglutinates) [28, 29] and sample 72501 is very similar to 72320. We will examine both crystalline fragments and bulk soil from shadowed and unshadowed samples to determine their exposure and maturity histories, as well as the total inventory as a proxy for micrometeorite input, to understand how shadowing has affected the relative inputs of volatiles to these soils.

What is the variation in exposure ages and maturity with depth? As lunar soil matures at the surface by micrometeorite comminution and agglutination, it can be overturned or buried by larger processes of movement and turnover collectively known as gardening. The movement of material by large impacts is the dominant mode, but slumping and landslides can also be locally important. The formation of layers can aid preservation of molecules by removing them from direct surface interaction, but organic molecules may continue to degrade as cosmogenic effects are still felt meters into the regolith.

We have completed a mineralogic and petrographic survey of materials from these horizons [30, 31] showing the different lithologies includes varying abundances of agglutinates (correlated with maturity), a variety of impact-melt breccias, highland material (anorthosites, granulites) and regolith breccias (note that we have been able to complete mineralogical, bulk composition, and petrology of these samples). Each rock type has a different origin, transport history, and bulk chemistry which allows us to not only build a picture of the compositional variation with depth but place temporal constraints on the local geology and volatile inventory with depth.

We will also be able to compare the Apollo 17 drive tube to the surface soils measured and the Apollo 16 drive tube, thereby enhancing our ability to interpret the history of both sites. Determining the exposure age, antiquity, maturity, and abundance of noble gases in these horizons will allow us to address how long organic molecules have been exposed to potentially damaging cosmic rays, and when volatiles and organics were gardened back into the soil column and protected from escape.

Summary: The Moon United team will use noble-gas ratios to constrain the exposure and gardening history of the lunar regolith and thereby provide crucial context to the exposure history experienced by volatile and organic compounds in these samples. We will use shadowed samples to assess the input budgets from solar wind and exogeneous sources, while the drive tubes offer an opportunity to systematically study exposure horizons with depth and under-stand how the local region has evolved over time. Together, these measurements will provide significant value to the ANGSA consortium efforts to understand the complete geologic history of these samples, their sites, and lunar processes.

References: [1] Hörz, F., et al., in *Lunar Sourcebook*, G.H. Heiken, et al., Editors. 1991, Cambridge University Press: Cambridge. p. 61-120. [2] Lucey, P., et al. (2006) *Rev Min Geochem* **60**, 83-219. [3] McKay, D.S., et al., in *Lunar Sourcebook*, G.H. Heiken, et al., Editors. 1991, Cambridge University Press: Cambridge. p. 285-356. [4] Taylor, L.A. and T.T. Meek (2005) *J Aerospace Eng* **18**, 188-196. [5] Anand, M., et al. (2012) *Planet Space Sci* **74**, 42-48. [6] Colaprete, A., et al. (2010) *Science* **330**, DOI: 10.1126/science.1186986. [7] McCubbin, F.M., et al. (2015) *Am. Min.* **100**, 1668-1707. [8] Wieler, R. (1998) *Space Sci. Rev.* **85**, 303-314. [9] Wieler, R. (2016) *Chemie der Erde* **76**, 463-480. [10] Joy, K.H., et al. (2011) *Geochim. Cosmochim. Acta* **75**, 7208-7225. [11] Killen, R.M. (2010) *Met Planet Sci* **37**, 1223-1231. [12] Barnes, J.J., et al. (2016) *Nature Communications* **7**, 11684. [13] Füri, E., et al. (2012) *Icarus* **218**, 220-229. [14] Greenwood, J.P., et al. (2011) *Nature Geoscience* **4**, 79. [15] Marty, B., et al. (2016) *Earth Planet. Sci. Lett.* **441**, 91-102. [16] Crites, S., et al. (2011) *AGUFM. P13D1730C*. [17] Dartnell, L.R. (2011) *Astrobiology* **11**, 551-582. [18] Liu, Y., et al. (2012) *Nature Geoscience* **5**, 779. [19] Walker, R.M. (1975) *Ann Rev Earth Planet Sci* **3**, 99-128. [20] Eugster, O. (2003) *Chemie der Erde* **63**, 3-30. [21] McKay, D.S., et al. (1986) *J. Geophys. Res.* **91**, D277-D303. [22] Gladstone, G.R., et al. (2012) *J. Geophys. Res. Planets* **117**, E00H04. [23] Hodges Jr, R.R. (Year) *LPSC Proceedings*, 2463-2477. [24] Hodges, R.R. (2002) *J. Geophys. Res.* **107**, 5011--7. [25] Miller, R.S., et al. (2014) *Icarus* **233**, 229-232. [26] Sanin, A.B., et al. (2012) *J. Geophys. Res. Planets* **117**. [27] Wacker, J.F. and E. Anders (1984) *Geochim. Cosmochim. Acta* **48**, 2373-2380. [28] Heiken, G. and D.S. McKay (Year) *LPSC Proceedings*, 843-860. [29] Morris, R.V. (1978) *Proc. Lunar Planet. Sci. Conf.* **9**, 2287-2297. [30] Curran, N.M., et al. (2017) *LEAG Anual Meeting*, #2041. [31] Curran, N.M., et al. (2018) *LPSC,* # 2732.