DETERMINING AGES OF ROCKS ACCESSIBLE WITHIN THE ARTEMIS EXPLORATION ZONE.

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Introduction: NASA's Artemis program is initially designed to explore impact-cratered terrain within 6° latitude of the lunar south pole [1]. Samples collected from these potential landing sites can address fundamental questions related to the formation, differentiation, thermal history, and impact processing of the Moon (e.g., [2-7]). These questions require high-precision chronology and/or thermochronology, in concert with petrologic and geochemical data, to be sufficiently addressed. This study combines published spectral data, updated crater counting models, and legacy maps to provide a framework from which to develop chronological efforts on samples likely collected from potential landing sites.

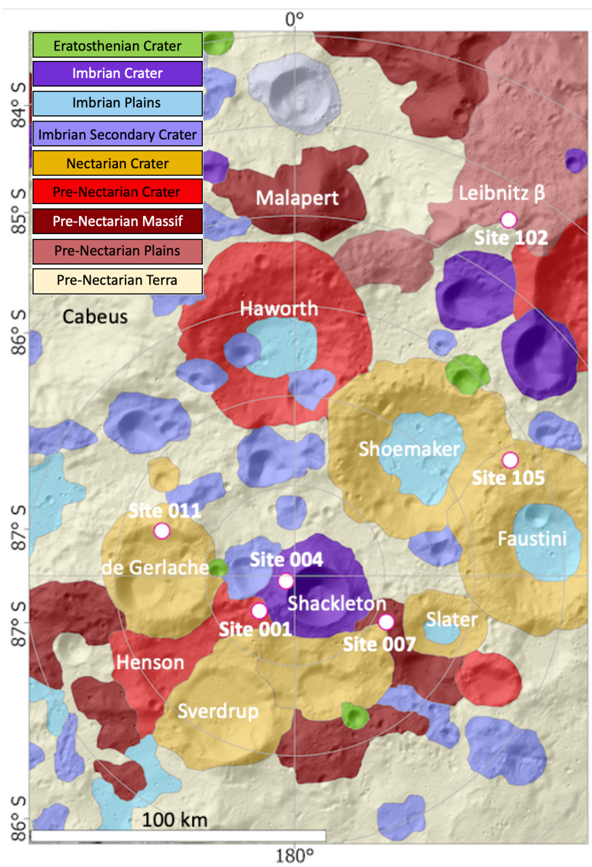

Figure 1. Shaded relief geological map of the lunar south polar region with the locations of several potential Artemis landing sites (001, 004, 007, 011, 102, and 105). Base map by [8] in the LPI Lunar South Pole Atlas using geology of [5, 9, 10] and Lunar Orbiter Laser Altimeter data.

Methods: Ages of geologic units (Fig. 1) were updated from [10] with new crater counting ages determined from orbit [5, 9], suggesting sampled materials may range in age from 3.5 to 4.5 Ga. Mapping was performed in ArcGIS Pro.

The Kaguya Spectral Profiler (SP) is a visible to near infrared spectrometer with a ~500 m footprint that acquired data via three spectral bands (one visible, two near infrared) between 500 and 2600 nm [11]. We used the polar gridded maps from [12] (1 km/pixel) to extract the average abundance of olivine, low-calcium pyroxene (LCP), high-calcium pyroxene (HCP), and plagioclase in the six potential Artemis exploration zones (Fig. 2) [13, 14].

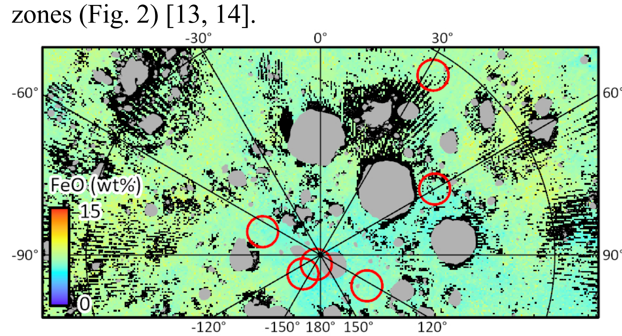

Figure 2. Artemis exploration zone FeO content (0 to 15 wt. %). Potential landing sites = red circles (10 km radius), PSRs = gray, No data = black.

Results: Potential landing sites are scattered across a feldspathic terrain reworked by impact cratering processes dominated by average compositions of noritic/gabbroic/troctolitic anorthosite and anorthositic norite/gabbro/troctolite lithologies [15]. Although a wider variety of lithologies may exist at each of the sites, particularly in clastic materials, the spectral study is limited to the 500 m/pixel detection of the Kaguya SP.

Chronology considerations:

Anorthositic lithologies (Includes: purest anorthosite (PAN), anorthosite, noritic/gabbroic/troctolitic anorthosite). Anorthosites are cumulate plutonic rocks containing >90% plagioclase and <10% mafic minerals (olivine and pyroxene) by volume; some of the cumulates may be related to lunar magma ocean processes [16]. Anorthositic lithologies have likely been subjected to prolonged impact processing which can obscure primary textures and compositions. Despite this, successful dating of the protoliths has been accomplished with Sm-Nd analyses of separated feldspar and mafic phases (e.g., [17]) and U-Pb in mafic phases (e.g., [18]). In PAN lithologies, Rb-Sr model ages may be a viable approach for pristine specimens. The timing of metamorphism can be constrained by Ar-Ar (e.g., [17]), but those data are often limited to the last Ar degassing event (typically between 3.3 to 4.0 Ga).

Mafic lithologies (anorthositic norite/gabbro/ troctolite, gabbro/norite, olivine norite/gabbro/ troctolite). Gabbro and other mafic lunar lithologies can be used to define magmatic periods and chemical characteristics of mantle components contributing to the sources of the magmas [19]. Some gabbroic/noritic cumulates have and others may not have participated in the gravitational overturn during the time of SPA formation [6] and return samples of this type would reveal critical information about magmatic differentiation events in early lunar history.

The chronologic options for mafic rocks are expected to be much greater than those for anorthositic lithologies. Uranium-rich trace phases (e.g., zircon, baddeleyite, phosphate, zirconolite, tranquillityite) have the potential for some of the most precise chronology of any approach, but those phases may not occur in all mafic lithologies. Other options that can provide age and source composition data include Sm-Nd, Lu-Hf, U-Pb, and Rb-Sr internal isochron approaches. It is important to note that each isotope system has its advantages and disadvantages regarding element mobility related to secondary processes (REE and HFSE systems have the potential to more robustly retain their primary isotopic characteristics than isotope systems based on mono- and bi-valent cations).

Ultramafic lithologies (pyroxenite, peridotite, dunite). Ultramafic rocks are representative of mantle or cumulate materials and exist mostly at depth except for clasts brought to the surface by impact processes. The chronologic options for these materials are limited; approaches including Re-Os, Lu-Hf, and Sm-Nd have the potential for mineral isochron dating and model age characterization.

Basaltic materials. These materials may represent some of the earliest volcanism on the Moon (e.g., [20, 21]). Mare fragments in the polar regions have likely been buried by the later emplacement of crater ejecta material and basin-forming events [22]. Clasts of mare in breccias have the potential to host U-rich accessory phases (e.g., MIL 13317; [21]) that can be readily dated. KREEP-rich (K- potassium, REE- rare earth elements, P-phosphorous) and, thus U-rich, materials do not appear to be abundant based on orbital data. Mare specimens that do not contain U-rich accessory minerals and are too small or fine-grained for mineral isochron dating can be dated by Ar-Ar, but the system is prone to metamorphic degassing. Thus, fine-grained mare specimens pose a special challenge to dating and may require specialized *in situ* approaches including U-Pb and/or Rb-Sr of pyroxene and plagioclase.

Impact melts and breccias. Many impact melt rocks contain lithic and mineral clasts from the target [23, 24] with a range of shock and thermal effects [25]. Repeated impact processing on the lunar surface can make interpretations complex. Ages of the impact metamorphic/melting events often rely on the Ar-Ar and U-Pb systems (e.g., [26).

Return Sample Collection Strategy: Apollo astronauts were instructed to collect lunar samples with the largest grain sizes to allow for easier mineral separation during lab analyses [27]. Due to technological advancements, Artemis astronauts may not be bound by the same constraints. Crews can focus on collecting the widest geochemical variety of materials, regardless of grain size. For example: impact melts (glassy) may be used to reliably and precisely date impact events, while norites (cumulates) can provide detailed information about the petrochemical evolution of the early Moon system. Brecciated samples may contain heterogenous mixtures of lithologies and fragments of rare mantle materials excavated from depth.

References: [1] NASA (2020) *Artemis III SDT*. [2] Borg L. E. et al. (2022) *Proc. Natl. Acad. Sci. U.S.A.,* 119. [3] Kraettli G. et al. (2022) *Icarus,* 371, 114699. [4] Kring D. A. et al. (2021) *Adv. in Space Res.,* 68, 4691–4701. [5] Tye A. R. et al. (2015) *Icarus,* 255, 70–77. [6] Hurwitz D. M. and Kring D. A. (2014) *J. Geophys. Res. Planets,* 119, 1110–1133. [7] Elkins-Tanton L. T. et al. (2011) *Earth and Planet. Sci. Lett.,* 304, 326–336. [8] Allender E. J. et al. (2019) *Adv. in Space Res.,* 63, 692–727. [9] Deutsch A. N. et al. (2020) *Icarus*, 336, 113455. [10] Spudis P. D. et al. (2008) *Geophys. Res. Lett.* 35, L14201. [11] Haruyama J. et al. (2008) *Earth, Planets and Space,* 60, 243–255. [12] Lemelin M. et al (2022) *Planet. Sci. J.*, 3, 63. [13] Lemelin M. et al. (2019) *Planet. and Space Sci.,* 165, 230–243. [14] Lemelin M. et al. (2015) *J. Geophys. Res. Planets,* 120, 869–887. [15] Stöffler D. et al. (1980) *Proc. Conf. Lunar Highlands Crust*, 51-70. [16] Wood J. A. (1970) *Apollo 11 Lunar Sci. Conf.*, 1, 965-988. [17] Norman M. D. et al. (2003) *Meteoritics and Planet. Sci.*, 38, 645-661. [18] Borg L. E. et al. (2011) *Nature*, 477, 70-72. [19] Papike J. et al. (2006) *Planet. Materials,* pp. 5–103 to 5–161. [20] Shaulis B. J. et al. (2013) *LPS XLIV*, Abstract 1781. [21] Snape J. F. et al. (2018) *Earth and Planet. Sci. Lett*., 502, 84-95. [22] Kring D.A. (2019) *NASA Expl. Sci. Forum*. [23] Stähle V. (1972) *Earth and Planet. Sci. Lett.,* 17, 275–293. [24] Dressler B. O. and Reimold W. U. (2001) *Earth-Sci. Rev.,* 56, 205–284. [25] Bischoff A. and Stöffler D. (1984) *J. Geophys. Res.,* 89, B645. [26] Beard S. P. et al. (2022) *Meteoritics and Planet. Sci*., 57, 2276-2288. [27] Phinney W. (2015) *NASA SP-2015-626.*