Dating Key Lunar Events With Artemis. B. A. Cohen[1] N. M. Curran[1], C. I. Fassett[2], B. L. Jolliff[3], J. D. Kendall[1], D. P. Moriarty[1], N. E. Petro[1], T. D. Swindle[4], S. N. Valencia[1], R. A. Yingst[5], K. E. Young[1], and N. E. B. Zellner[6], [1]NASA Goddard Space Flight Center (Barbara.A.Cohen@nasa.gov), [2]NASA Marshall Space Flight Center; [3]Washington University; [4]University of Arizona; [5]Planetary Science Institute; [6]Albion College.

Introduction: Geochronology, or determination of absolute ages for geologic events, underpins many inquiries into the formation and evolution of planets and our Solar System. The bombardment chronology inferred from lunar samples plays a crucial role in the development of models of early Solar System and extrasolar planet dynamics, as well as the timing of volatile, organic, and siderophile element delivery. Absolute ages of ancient and recent magmatic products provide strong constraints on the dynamics of magma oceans and crustal formation, and the longevity and evolution of interior heat engines and distinct mantle/crustal source regions. Absolute dating also relates habitability markers on other planets to the timescale of evolution of life on Earth. Major advances in planetary science can thus be driven by absolute geochronology of additional lunar samples, calibrating lunar-specific chronology and creating a framework for understanding Solar System formation, the effects of impact bombardment on life, and the evolution of planets and interiors.

Artemis activities at the lunar South Pole will create a unique opportunity to accomplish multiple important goals in lunar geochronology. A South Pole site offers chances of dating the South Pole-Aitken (SPA) and Schrödinger basins, respectively the oldest and one of the youngest lunar basins. Many locations under consideration could also contain material from Shackleton crater for dating, which would help unravel the geologic history of polar volatile deposits in permanently shadowed regions (PSRs). Collecting and examining these important samples could be accomplished by astronaut sampling and return, by crew emplacement of robotic assets, or by robotic activities enabled by the Artemis architecture.

Bracketing the Basins: The leading, but contentious, model for lunar impact history includes a pronounced increase in large impact events around 3.9 Ga, and possibly extending back in time to at least 4.2 Ga. This cataclysm would have extended throughout the inner Solar System, a result of the gas-dust dynamics of forming disks and giant planet migration in our Solar System that now may be invoked to understand systems of exoplanets around other stars [2]. As we seek to better link what we know about these other systems, we ask a fundamental question: Is our Solar System typical or anomalous? One of the best ways to address this question is to determine what processes occurred and their timing and duration in the early Solar System and then compare to planetary systems currently forming around other stars. A key test of these dynamical models is whether the terrestrial planets and asteroid belt experienced a relative “lull” in impacts between formation and later bombardment. One way to address this objective is by establishing the formation time of large planetary basins by dating their impact-melt sheets.

Apollo-era studies attempted this dating by sampling terrains thought to be formed by ejecta from large basins, including Imbrium, Serenitatis, and Nectaris. However, recent work has increased the possibility that lunar samples were influenced by repeated (albeit unintentional) sampling of Imbrium ejecta at the various Apollo landing sites [3, 4]. The locations envisioned for Artemis are geographically far from the Imbrium basin and fortuitously occur at the overlap between ejecta from the oldest and one of the youngest lunar basins, SPA and Schrodinger [5-9]. Identification of ejecta materials is challenging, as our Apollo experience shows, but fortunately the SPA basin impact melt sheet has a distinctive geochemical signature to tie it to the basin [10]. Further field mapping to establish geomorphologic indicators of Schrodinger ejecta would also help guide specific sample locations.

Probing the PSRs: We do not yet fully understand the relationships between lunar PSRs, cold traps, volatile content, water ice content, and surface vs. subsurface reservoirs spatially or temporally, which inhibits the utility of PSRs as resources. It will be impossible to test the soil and subsurface at every location to determine where water exists or does not. A geologic understanding of the origin and evolutions of these deposits is therefore imperative.

We know that the deep water stores are not found at every current PSR, meaning they are unlikely to be products of a current equilibrium trapping process [11, 12]. Instead, comparison with Mercury’s cold traps [13] and current orientation of lunar deep ice deposits [14] strongly implies that the deep water stores could have been emplaced by a singular event such as volcanic outgassing or cometary impact, filling all available niches at the time of the event [15-17]. That map would have then been modified by 2 Ga or more of geologic activity by impact events degassing some areas and mobilizing molecules to other areas [18, 19]. Dating Shackleton (or indeed any other polar crater) would put a strong constraint on the likelihood of this (or any other) geologic history of the deep ice deposits. This measurement, made in conjunction with stable-isotopic analysis of the deep ice deposits themselves to constrain their origin, would represent an enormous advance in understanding the resource potential of these deposits. Comparing the absolute age of Shackleton to the crater statistics on its ejecta blanket would also constitute an additional point in calibrating the crater chronology function [19].

Instrumentation and Implementation: Sample return and analyses in Earth-based laboratories remains the gold standard of geochronology, enabling multiple state-of-the-art laboratories to work on each individual sample to extract complementary information [20]. Astronauts bring the benefit of field contextualization and could carry handheld instruments to match samples to criteria such as chemistry to return samples for specific uses [21, 22]. However, a comparison between astronaut collected samples and rake fines, as may be collected by robots, shows that the entire range of compositions is likely to be collected (Fig. 1), enabling correlations to be accomplished in terrestrial laboratories (of course static robotic landers reduce the field context to what is directly observable by onboard instruments).

In the 2003 and 2013 Planetary Science Decadal Surveys, sample return was the only viable method considered for geochronology. In the last two decades, however, through the PICASSO, MatISSE, and DALI programs, NASA has invested in the development of *in situ* dating techniques. The 2015 NASA Technology Roadmap calls out *in situ* dating to improve these measurements and extend their range of applicability to investigations across the Solar System, recommending a minimum precision better than ±5% for rocks 4.5 Ga, or approximately ±200 Myr, and a desired precision of ±1% for 4.5 Ga rocks (or about ±50 Myr).

Multiple *in situ* chronometric techniques developed for planetary surfaces like Mars also have immediate applicability to the Moon [23, 24], including radiometric isotope dating (e.g., K-Ar, Rb-Sr, and U-Th-Pb systems), cosmogenic nuclide dating, dosimetry-based methods (i.e., luminescence), and exploitation of processes such as flux of extraterrestrial material. Multiple groups have made substantial progress in bringing some of these techniques to flight implementation. The technology readiness levels of instruments using complementary radiogenic isotopic systems (K-Ar and Rb-Sr) will be at TRL 6 (ready to be infused into a flight opportunity) well before the Artemis-3 mission.

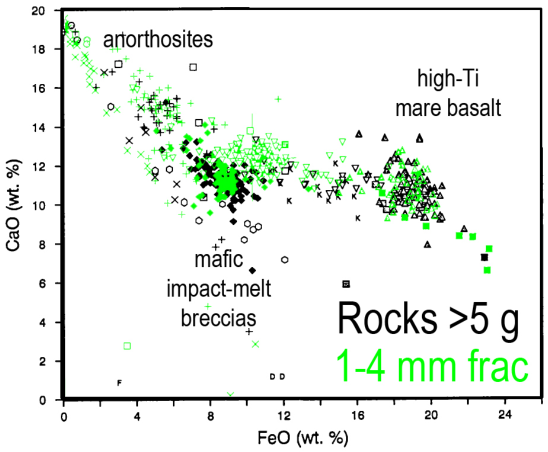

Figure 1. The range of compositional variability of the Apollo 17 site is similarly represented by hand-selected samples (black) as by smaller rake samples (green), which would be analogous to robotically collected samples [1].

Alongside these instruments, sample collection and handling systems have been matured and evolving operational scenarios examined. *In situ* dating instruments on small robotic platforms could be emplaced by astronauts as ALSEP-style platforms in key locations, or mounted aboard helper rovers, and left to collect data after crew departure. Alternatively, opportunities to deploy robotic missions either directly from Earth or from the Gateway, could access both the South Pole as well as other key locations, including the South Pole-Aitken Basin interior [25].

Summary: A human and robotic exploration program to the lunar South Pole would enable significant scientific advancements in lunar crater chronology and volatile emplacement. Implementation options include astronaut sample collection and return, by Artemis-enabled emplacement of robotic assets, or by synergistic robotic activities.

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