Lunar Surface Science Workshop: Sampling and Sample Curation Session, July 30, 2020

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1.0 Introduction

During Artemis missions, astronauts will collect samples from the lunar surface and return them to Earth for analysis. Samples are needed to address scientific as well as engineering knowledge gaps. Samples collected during the Apollo missions have been studied for five decades and continue to be investigated vigorously; Artemis provide a unique opportunity to build on and complement the success of Apollo science. Because of the lasting importance of the samples and to ensure that samples returned to Earth maintain their integrity, curation of the samples is also a crucial activity. In this session, our goal was to address issues associated with collection of samples on the Moon and curation needs for samples collected by Artemis astronauts. Specific questions included:

- What are the key science questions that samples can help to answer?
- What are the high-priority samples and how should we collect them?
- Are there “special” samples that need to be collected?
- What are the best strategies to minimize contamination of samples?
- How should the samples be curated and will samples require non-standard curation?

- **Aim**: capture a wide breadth of the science community input and encourage community participation.

2.0. Science Questions

The lunar crust is a museum of Solar System history and the samples are the “fossils” that provide a record of that history. Science issues that should be addressed at a south circum-polar site include: (1) local and regional geology, and comparison to the equatorial/mid-latitude “Apollo zone,” with implications for broad planetary science issues; (2) lunar impact crater chronology with implications for the impact flux through solar system history; (3) the distribution and origin of polar volatiles including organics; and (4) the unique environment of the lunar poles, including space weathering.

2.1. Local and Regional Geology, Planetary Processes, and Fundamental Lunar Science

At any lunar landing site, it is important to understand the geologic setting and surroundings of the site. Much information will already be available from remote sensing, but it is important to document the geology on the ground with astronaut observations, photographs, samples and experiments. We will need to know the physical properties of the regolith, especially if they are found to differ in some way from regolith characteristics known from Apollo landing sites. Physical properties such as grain size distribution, density, compaction and compressibility, dielectric properties, maturity, and other geotechnical properties will be determined from a combination of in-situ experiments and regolith samples collected for return to Earth.

The composition, mineralogy, and lithology (rock types) of the regolith deposits at the landing site and in the surrounding regions will need to be characterized as well. Are the deposits composed mainly of materials of the feldspathic highlands (largely anorthositic), or will there be a significant amount of impact ejecta from surrounding craters and basins? Although some preliminary chemical information may be available through the use of handheld or portable instruments such as X-ray fluorescence (XRF) and laser-induced breakdown spectroscopy (LIBS), many of the key characteristics of the materials that relate to remote sensing require detailed chemical, mineralogical, and petrographic analysis, which can only be accomplished via returned samples. Therefore, the collection and return of samples will be crucial to provide ground truth for remote sensing, and to establish geologic context. The likely south-polar landing sites for Artemis are far from the Procellarum KREEP Terrane (PKT) and as such, the rocks and regolith offer access to parts of the Moon, including the farside, that were not sampled in the Apollo zone. Likewise, any volcanic materials occurring in the sampled regolith will provide key new information about the lunar mantle. These materials will provide new insights to the nature and origin of the Moon's crust and mantle, the nearside-farside dichotomy, and the geologic history of the Moon.

2.2. Impact Melt and Chronology

One of the great legacies of the Apollo samples is the chronology or temporal record of events that is contained in the rocks returned from each landing site. In some cases, such as basaltic rocks, the age of a nearby volcanic surface can be determined directly from the radiometric age of the basalt samples; that has, in turn, been used to calibrate lunar and Solar System chronology by determining the corresponding crater size-frequency distribution (CSFD) of the basaltic surface. Other samples that can be related to a specific impact crater or basin using radiometric age dating methods also contribute to the lunar chronology because the cratering event either resets one or more isotopic chronometers or, in the case of impact melt, may completely reset the chronometers.

Geologic relationships at the landing site and determined from remote sensing are critical in providing the context for scientific interpretations. Because the south polar locations likely to be selected for Artemis missions are far from any basaltic surfaces, it is more likely that impact-melt rocks and breccias will be most useful for determining chronologic relationships and crater ages that serve to define key lunar time-stratigraphic horizons. Such rocks, which are commonly breccias, i.e., complex mixtures of rocks assembled by the process of impact-crater formation, are best understood by consortium studies of large, hand-sample-sized rocks. However, studies of many small rocks also provide information about the diversity and representativeness of the rock components at the landing sites; this was the case for all of the Apollo landing sites. Large regolith samples (kilogram to multi-kilogram size) provide literally thousands of small rock samples that complement the much lower number of collected hand-sample-sized (hundreds of g to several kg) rocks.

Two examples of the use of samples and geologic relationships to determine the age of major impact events are the Apollo 12 samples, used to determine the age of Copernicus crater, and the Apollo 17 samples used to determine the age of Tycho crater. In both cases, crater rays (concentrations of ejected materials) were deposited at the Apollo 12 and Apollo 17 sites. At the Apollo 12 site, specific samples can be related by their disturbance ages to ejected material from the Copernicus impact; samples indicate an age of about 800 Myr. At the Apollo 17 site, the ejected materials remain cryptic, but the disturbance of the surface by secondary craters can be dated using exposure ages. The indicated age is ~110 Myr. At the south pole, a prominent ray from Tycho crosses the south pole along the ridge between de Gerlache and Shackleton craters (see talk by B. Denevi) and it is possible, if not likely, that south polar samples will also reflect the age of Tycho as determined by the Apollo 17 sample exposure ages. Confirmation of that age and identification of the ejected material would represent a significant science result, confirming the age of Tycho, and possibly revealing the materials that were ejected from Tycho.

2.2.1. Samples from South Pole-Aitken Basin

Among the most important age dates on the Moon is the ancient age of its largest and oldest preserved impact basin, South Pole-Aitken (SPA). This basin is 2200 x 2500 km across and stretches from the south pole on the south rim to Aitken crater on the north rim. It is likely that the impact that formed this basin excavated well into the mantle of the Moon, and some of those materials may exist as clasts in impact breccias. Some of the large massifs such as Malapert massif are remnants of the southern rim of the SPA basin. The basin likely formed 4.2 to 4.35 billion years ago, judging by the large crater size-frequency distribution. Many large impact craters and several smaller basins formed within the SPA basin, and these would have ejected materials of the basin out to rim locations such as the south pole. Unlike the Apollo landing sites, which are all relatively close to the large and late-formed Imbrium basin, the Artemis landing site will be dominated by materials of the feldspathic highlands mixed with impact breccias derived from the SPA basin. Samples of these materials will provide a rich scientific payoff, but these breccias must be returned to Earth for careful analysis of their components and their record of the SPA basin chronology. The science associated with these samples has been emphasized in the past two decadal surveys as high priority because they may address key events in early Solar System history.

2.2.2. Samples from Schrödinger basin

Another high priority impact basin for exploration is Schrödinger, which is the second youngest impact basin on the Moon. Accordingly, its age is also key to the lunar chronology. Centered at 75º south latitude, it lies within one basin diameter of the south pole, or only about 300 km from its southeastern rim. It is thus likely that impact-melted materials from Schrödinger basin will also occur in deposits at the south pole. Determining the age of this basin, along with SPA, would define the period of late, heavy impact bombardment of the Moon and contribute to our understanding of the timing and intensity of that bombardment and models of early Solar System planetary dynamics that may have caused large projectiles to impact all the terrestrial planets.

2.3. PSR Volatiles, Ice Deposits, and Organics

The primary science rationale for a south polar landing site for Artemis is to study permanently shadowed regions (PSRs), especially to investigate, recover, and use water (and possibly hydrogen and oxygen, separately) as a resource. Remote sensing with neutron spectrometers (Lunar Prospector and LRO) indicate abundant water ice in the shallow subsurface associated with the PSRs and other high-latitude locations, and the volatile-rich character was directly revealed by the LCROSS mission. The uncertainties of current measurements are high, and much remains unknown about these deposits. We need to know how variable the volatiles are in composition and distribution, what are their compositional variations, what reactions may have taken place owing to transient heating events such as meteor impacts or heating of deposits at the edge of PSRs, and how the distribution of volatiles varies over short and long timescales. Therefore, PSRs will be key targets of polar exploration by precursor missions as well as Artemis.

The origin of the volatiles is also unknown. They could be indigenous to the Moon, solar-wind implanted and concentrated in the polar cold traps, or perhaps delivered by comets or volatile-bearing asteroids and sequestered in the cold traps. Determining the origins will require careful isotopic analysis of volatiles such as D/H, oxygen, nitrogen, carbon, and so forth. Organic compounds may also be sequestered with the ices. Owing to the difficulty of sampling and maintaining the integrity of the PSR samples, sophisticated instrumentation will likely be needed to analyze these materials in-situ, while also collecting samples for return to Earth. It is unlikely that cryogenic sampling will be attempted for the first Artemis mission; however, samples can be collected and sealed such that they will still be useful for isotopic and chemical analysis even if they change phase or undergo reactions during the time between collection and return to Earth and analysis. These volatile materials are of enormous scientific value, so it is likely that they will be the focus of early Artemis sample science. To avoid surface contamination by rocket exhaust or astronaut activity, cores should be collected and carefully sealed for return to Earth. Preservation of regolith subsurface stratigraphy is also a high priority.

Organic compounds in regolith or associated with ice deposits should also be a high priority for sampling. Samples from a variety of environments are desired, including mature and immature regolith, shadowed and non-shadowed regolith for comparison, near the lander and far from the lander, and surface and subsurface (e.g., core materials). For organics, contamination is a very significant issue because a small amount of organic contamination would likely be enough to mask lunar organic signatures. For example, amino acids are key for life on Earth and have been found in carbonaceous meteorites. They were detected in Apollo samples but there was no consensus on origin during Apollo-era analyses. Recently, more sensitive analyses have become possible, and terrestrial contamination was implicated as a source of the amino acids in the Apollo samples. Nevertheless, there are likely sources for low levels of organics in lunar regolith, including exogenous sources (meteorites, asteroids, comets), and these materials may be better preserved and accumulated in cold, polar regolith and ice deposits.

2.4. Polar Regolith and Surface Materials, Dust, and Space Weathering

Finally, Artemis represents the beginning of a sustained human presence on the Moon. One of the key technical hurdles that must be overcome are the problems associated with lunar dust. Dust buildup and impairment of suits and other mechanisms can occur due to: the ultrafine grain sizes; the sharp and electrostatic (“sticky”) character of the grains – including glassy agglutinates and tiny, broken shards of glass; and the special environment of the lunar surface, consisting of a hard vacuum and existing in a constant plasma of charged particles. The ultrafine grains include those of respirable size, <10 micrometers to sub-micrometer sizes that can become embedded in human lungs, move into the bloodstream, and become distributed into various organs. Components such as nanophase Fe metal, ubiquitous in lunar regolith grain rims and agglutinates, may pose special problems with long exposure. These reactions to sample grains were determined based on prior exposure to Apollo regolith samples and their measured physical characteristics.

What is unknown is if polar regolith differs in important ways from the lower-latitude Apollo and Luna regolith. Is space weathering fundamentally different at the circum-polar latitudes? Is regolith finer-grained? Does it have the same high proportions of agglutinates and nanophase Fe-metal components? The dust will have to be well characterized, and surface samples, including the uppermost few mm and cm will be collected for study, including the possible effects on astronaut health during long-duration stays. As with ice deposits, efforts should be made to investigate the dust physical characteristics, components, and chemistry on the lunar surface in the space environment, in addition to samples returned to Earth for careful study on Earth.

Samples will be needed for further study related to engineering priorities, including physical properties, as indicated above, in-situ resource utilization (ISRU), construction, infrastructure, additive manufacturing, etc. We need to determine before the mission what total mass of collected and returned samples should be for ISRU. Lunar regolith simulants are rarely suitable for the evaluation of processes that need fidelity in terms of the special components of regolith such as agglutinates, nanophase Fe metal, impact glass content, and specific chemistry. Because regolith, especially the finer grain-size fractions, will be of interest for ISRU, rock fragments separated from bulk regolith samples can be set aside for science objectives. If subsequent Artemis missions return to the same landing site, it may be necessary to construct landing pads or structures, for example, to prevent issues associated with plumes of ejecta. How will we work towards a sustained human presence that will allow more samples in the future to be collected and returned?

A contingency sample should be collected as was done on Apollo missions. Planners should consider a drive tube for science and a large bulk regolith sample for science *and* engineering. Bulk regolith samples from different locations are also important and are complemented by cores, drive tubes, trench, and surface skim samples. Samples from different depths also provide ground truth for remote sensing methods that sense to different depths, e.g., optical, X-ray, gamma-ray, and neutron detection.

Finally, we may also consider that sample priorities will shift with subsequent Artemis missions, once we learn what the materials are like in the south circum-polar regions and, specifically, at the site selected for the Artemis landings. It may be desirable to phase sampling and sample-return priorities for subsequent missions based on what we learn from Artemis III samples.

3.0 Mobility for Sampling

A key lesson for sampling the geologic diversity of landing sites came in the form of the Apollo "J" missions, which introduced the lunar roving vehicle or LRV. This mobility enhancement allowed the Apollo 15, 16, and 17 astronauts to greatly expand their exploration regions around the landing sites and to explore and sample specific targets indicated beforehand using remote sensing, as well as astronaut geologic intuition. The LRV enabled the astronauts to increase manyfold their sampling efficiency. Many of the high priority science objectives will only be accessible through the use of mobility enhancement equal to or better than the Apollo LRVs.

4.0 Tools for Sampling

Tools for sampling on the lunar surface for Artemis will include new and improved versions of similar tools as were used on Apollo missions, including the rock hammer, rake, scoop, tongs, extension handles, drive tubes, contingency sample containers, and sample bags. The rake tool proved highly valuable during Apollo for the collection of rock fragments in the regolith; a rake tool with adjustable tines would be highly desirable. The new spacesuit (xEMU) is much more capable and should make use of some of the tools easier than during Apollo, and testing and design modifications are ongoing in this regard. The dexterity of the gloves is especially important for various sampling activities. The polar environment may necessitate modifications in materials used for some tools to ensure they will function under very cold conditions. A concern raised numerous times during the workshop is the need for an automated and much improved coring device for the polar environment and for coring ice-bearing regolith. The collection of cores and drive tubes was a very time- and energy-consuming task for Apollo astronauts, and at the poles, cores will be especially important for volatiles sequestered in the regolith and ice-bearing deposits. Concerns also exist for the potential alteration of the ultra-cold ice deposits by the sampling devices used for collection and storing.

To make sampling more effective and efficient, new handheld analytical tools will be available such as a hand-lens camera for in-situ observation and characterization, and a handheld x-ray fluorescence (XRF) spectrometer and laser-induced-breakdown spectrometer (LIBS) for sample composition. Such devices need not be carried everywhere, but should be available to astronauts during EVA, for example, mounted on a lunar roving vehicle. Results from such instrumentation should be readily and immediately available via heads-up display (HUD), with voice activation for display, and procedures that avoid astronaut sensory overload. Data should also be available in real time to scientists in the "back room" for evaluation.

Tools may also be optimized for mass, and may be prepositioned by precursor missions prior to Artemis III. In addition to geologic and geotechnical tools, tool carriers, sockets, wrenches, cutters, portable lighting and others will be needed. Because of the very different lighting conditions at the poles (low sun, long shadows), artificial lighting will also be needed for sampling.

5.0 Curation of Returned Samples

Sample preservation is necessary to facilitate the numerous scientific investigations afforded by returned lunar samples. Sample preservation includes pre-flight, in-flight, and post-flight considerations, including contamination, materials selection, and sample handling and storage protocols. In addition, knowing the analyses that the scientific community wants to make is critical for quantifying engineering requirements for flight and curatorial hardware and mission operations planning. By designing and implementing quantified contamination limits for species of interest, the ability to accomplish the science goals of Artemis sample return will be maximized.

5.1 Contamination

Contamination can take the form of particulates, metal fragments, organics, and volatiles. The effects of contamination on sample science can be mitigated in two ways. The first is via contamination control (CC), which limits the physical contamination of the sample; the second is contamination knowledge (CK), which monitors existing contamination on samples or hardware. CC is largely determined by the sensitivity of the scientific measurements that need to be made on the samples: the amount of contamination of a certain species should not mask the signature that will be measured. By understanding the measurement sensitivities of various instruments, contamination requirements cane be implemented that maximize the signal from the sample, and not from foreign materials.

Because contamination cannot be completely eliminated, CK is critical to understanding the contamination that is introduced to the sample. This is accomplished either via witness materials or coupons to better understand possible disturbances or contamination that occur during sample collection. Since Artemis surface and sample collection operations will be highly complex, there will be a need for multiple witness coupons, including: within sample containers, inside the cabin with astronauts, and with every tool.

To characterize contamination, a high amount of contaminants should be collected (where “high” is relative to the analytical technique used to quantify the contaminant levels). Witness plates and coupons should be able to collect as much contamination as possible, and to ensure that the shelf life of the witness materials is sufficient for mission science purposes. Previous sample return missions have used witness materials and their lessons learned should be used to feed forward to Artemis. Multiple witness materials should be considered since not all materials capture contamination equally. A rapid analysis of sensitive (easily altered) materials should occur after sample return, if needed. Witness plates should also be used to monitor contamination on the sample tools and containers, both for monitoring the tools themselves and the environments in which they are taken.

Contamination can be sourced from the sampling tools and containers, particularly in regards to trace elements. Highly siderophile elements (HSE) are used as key tracers for accretion and differentiation processes of planetary bodies. Thus, the trace-element compositions of the tools and sample containers must be very well constrained for both pre-and-post flight operations.

Organic contamination can also be introduced from numerous sources. Tracing organic contamination can be improved by collecting materials that are near, or in contact with the suits worn by astronauts. The composition of spacesuit materials should be provided to the science community to evaluate as a potential source of sample contamination.

5.2 Materials Selection

Flight spares will be necessary for measuring any trace element or other contamination introduced to the samples from sample tools and containers. Due to their success in preserving Apollo samples, prior flown materials such as Teflon, 6061 aluminum, and stainless steel should be used for Artemis as well.

Because Artemis has strict weight limitations, alternative materials to those used for Apollo are being considered for weight-saving purposes. Titanium has been proposed by engineers as an alternative material for tools because of its light weight and strength. However, the presence of titanium in lunar samples is well known and has been used for the classification of lunar materials (e.g., high/low titanium basalts). Hence, any sample contamination resulting from interaction with titanium-based tools and/or sample containers may result in spurious interpretations of sample geochemistry. The possibility of titanium internal components, which are shielded by aluminum or stainless steel casings, is a possible alternative, though further investigations need to be done to ensure a lack of titanium contamination in the final product.

An additional consideration for materials selection and curation is the ability to work with the materials in the laboratory. Most Apollo-era materials have a long history of ease of use and should be considered for continued use for Artemis samples. However, some materials used previously have been a source of contamination, including lubricants and seals such as molybdenum, xylene, and indium seals.

5.2 Curation of Volatile-Bearing Samples

PSR samples are important for a variety of reasons. They will allow for the first time the direct sampling of lunar volatiles for their return to Earth for scientific study. The contents of PSR samples will be critical for understanding the source and evolution of planetary organics, which has significant implications for understanding pre-biotic chemistry and interplanetary evolution. Numerous samples in the 1-10 g range will be required for volatile and organics studies, not just for direct measurement of lunar volatiles, but for a robust characterization of any contamination that may have been introduced during surface operations. Comparing such samples to analogous non-shadowed/sunlit samples will illustrate key differences between the PSR and non-PSR environments. Regardless of the sample size and number, the overwhelming consensus is that *some sample should be collected at the earliest possible opportunity, and that any PSR sample – regardless of how it is stored and transported – is better than no sample.*

The degree of contamination that has been – and will be – added to the PSR environment by astronaut or spacecraft activity is currently unknown and will need to be well characterized during the Artemis missions. This characterization involves several steps. First, any terrestrial water or volatiles (e.g., propellants) should be well characterized, both compositionally and isotopically, on the ground prior to the start of the mission. Second, witness plates and coupons will need to be strategically deployed to understand the contamination from the cabin environment, sampling tools and containers, space suit(s), and the landing vehicle. Third, numerous and geographically distributed subsurface samples should be collected to allow for an assessment of surface contamination relative to subsurface uncontaminated materials; this can be accomplished via well-sealed drive tubes and drill cores down to at least one meter depth to correlate to remote sensing data (e.g., that of LRO). Fourth, in-situ measurements should be collected if possible to assess surface chemical composition on the Moon for later comparison to measurements on Earth. Fifth, any tools and containers should be cleaned to the greatest extent possible in regards to particulates, volatiles, and organics. Tools should be baked out to remove organics and volatiles prior to packaging for flight.

Sample return from PSRs poses specific challenges for sample collection, storage, transport, and curation, especially regarding the preservation of volatiles. The tools, containers, and other equipment such as spacesuits will need to withstand the thermal extremes of the PSR environment. The materials that will be used in PSR hardware need to be constrained, along with the need for and types of special coatings. If titanium, gold, or platinum are used in any sample-intimate hardware, they will preclude a number of key geochemical analysis, specifically in regards to highly siderophile elements (HSEs) and high-field-strength elements (HFSEs). Therefore, a prioritization between PSR volatiles samples and HSE/HFSE analyses will need to be made since those samples may be mutually exclusive (for a single sample) owing to engineering constraints; multiple samples may be needed to fully meet mission requirements. Additionally, the requirements for vacuum seals should be evaluated for both science and safety reasons, especially in regards to toxic compounds like H_2S that may be present in the samples. Adsorbents are a possible solution to leakage and could be used to capture gases. Regardless of what materials are used, the behavior of equipment in the PSR environment will need to be known and characterized to the greatest extent possible ahead of time.

Given that Artemis III will likely not have a cold/cryogenic stowage capability, PSR samples will likely experience some alteration after collection and during the return journey to Earth. Cryogenic, or at a minimum, near-cryogenic (-80°C) sample stowage should be implemented as soon as possible after Artemis III to maximize sample preservation and safety in flight. Regardless of how they are stored in flight, PSR samples should be cryogenically stored as soon as possible upon return to Earth. Because humans cannot process samples at cryogenic temperatures, a sample processing facility at -20°C will also be needed, although it should only be used for sample processing and not for long-term storage. The Artemis curation facility should also be capable of extracting and handling both condensed and gas-phase volatiles while maintaining materials compatibility and cleanliness constraints. Multiple negative-pressure gloveboxes will be needed to prevent the release of hazardous compounds to the curatorial environment and to provide redundancy in the event that a single glovebox fails. All samples should be stored in a curatorial facility to prevent particulate, organic, and volatile contamination from compromising sample science. The Apollo Next-Generation Sample Analysis (ANGSA) Program should provide key data for assessing the efficacy of the current Apollo Curation Laboratory in preserving lunar samples for particulates, organics, and volatiles.

New technology (since Apollo): XCT (X-ray Computed Tomography) can be used to scan rocks and cores, and can identify clasts (materials with contrasting mean atomic number) without breaking the original samples open. Unopened samples (e.g., core tubes) should be scanned, providing better fidelity and detail than the Apollo X-ray scans. This technique can identify new lithologies, textures, stratigraphy in cores, etc., facilitating optimized sample processing procedures when the containers are opened.

Summary statement on the importance of samples returned to Earth and well curated. The geologic samples collected by Apollo and returned to Earth are literally gifts that keep on giving and one of the great legacies of the Apollo missions. Over the years, there have been over 3000 sample requests and about 50,000 samples allocated for investigations. Some 10,000 samples are currently on loan to over 145 investigators in 16 countries. As new analytical techniques and strategies are devised, and new questions asked, the well-curated Apollo samples continue to provide answers to key questions of solar system history, planetary differentiation and evolution, and the specific conditions of formation of the Moon and its relationship to Earth. Rocks from the Moon represent its primary crust, the products of early planetary differentiation, its secondary crust, formed by partial melting in the interior, intrusion of magmas into the crust and extrusion of lavas onto the surface, and possibly even tertiary crust formed by heating of crustal materials, accompanied by melting and further differentiation to form silicic volcanics and intrusives. Samples from the Moon provide critical ground truth for remote sensing and a temporal and geospatial context for interpretation of the lunar meteorites found on Earth.