# SCIENCE PRIORITIES FOR SAMPLE RETURN FOR ARTEMIS MISSIONS TO THE LUNAR SOUTH POLE.

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**Introduction:** Geologic samples collected by Apollo are literally 'gifts that keep on giving' and one of the great legacies of the Apollo missions. Over the years, over 3000 sample requests have resulted in ~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 superbly curated Apollo samples continue to provide answers to questions of solar system history, planetary differentiation and evolution, and the specific conditions of formation of the Moon and its relationship to Earth.

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. 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 white paper, we address the key science priorities for which samples are needed.

**Science Priorities.** Science issues to be addressed at the South-Circumpolar Region [1] include (1) local and regional geology, comparison to the "Apollo zone," and comparison to the lunar meteorites and global remote sensing, (2) lunar and impact crater chronology, (3) polar volatiles including organics, and (4) regolith in the unique environment of the lunar poles.

Local and Regional Geology. We need to understand the geologic setting of the Artemis landing site and surrounding region. Much information is available from remote sensing, but we must document the geology on the ground with astronaut observations, photographs, samples, and experiments (i.e., field geology) to understand the geologic context of the collected samples from these regions. We need to know the physical properties of the regolith, especially if they differ in some way from regolith characteristics known from Apollo sites (see also [2]). Physical properties such as grain size distribution, density, compaction and compressibility, dielectric properties, maturity, and other geotechnical properties specific to the poles could be determined from a combination of in-situ experiments and regolith samples collected for return to Earth.

We need to know the composition, mineralogy, and lithology of the regolith deposits at the landing site and in the surrounding regions. Are the deposits composed mainly of materials of the feldspathic highlands (largely anorthositic), or is there a significant amount of impact ejecta from surrounding craters and basins? Collection and return of samples is crucial in order to provide ground truth for remote sensing, as many of the key characteristics of the materials affect remote sensing spectra and thus require detailed chemical, mineralogical, and petrographic analysis in labs on Earth. The likely south-circumpolar regions 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 previously sampled during Apollo. These materials will provide new insights to the Moon's crust and mantle, nearside-farside differences/dichotomy, and geologic history.

Materials from the Artemis landing site will also be compared to the growing collection of meteorites from the Moon, and the global remote sensing context. The lunar meteorites now number >200 stones and represent >50 (and perhaps many more) unknown sampling locations on the Moon. Statistically, many of these must be from the farside highlands (and possibly even from the polar highlands). Having additional highlands samples far from Apollo will allow better interpretation of the provenance of the lunar meteorites, especially the feldspathic regolith breccias.

Impact Melt and Chronology. One of the great legacies of the Apollo samples is the temporal record of events contained in the rocks returned from each landing site. Basaltic rocks record the age of nearby basaltic surfaces and are used to calibrate the lunar chronology by determining the corresponding crater size-frequency distribution (CSFD) of the underlying basaltic surface. Impact breccias can be related to a specific impact crater or basin using radiometric age dating methods and contribute to the lunar chronology. Geologic relationships at the landing site and determined from remote sensing are critical in providing the context for such interpretations. South-polar locations likely to be selected for Artemis are far from any basaltic surfaces, thus impact-melt rocks and breccias will be most useful for determining chronologic relationships and crater ages. Impact breccias are complex mixtures of rocks assembled by impact forming processes and are best understood by studies of large, hand-sample-sized rocks; in contrast, studies of many small rocks provide information about the diversity and representativeness of the rock components at the landing sites (see also [1]). Large regolith samples (kg to multi-kg size) provide literally thousands of small rock samples that complement the much smaller number of collected hand-sample-sized (hundreds of g to several kg) rocks.

Tycho. An example of the use of samples and geologic relationships to determine the age of major impact events that define key lunar time-stratigraphic horizons is the age of Tycho crater, inferred from exposure ages of Apollo 17 materials disturbed by secondary impacts and a landslide deposit. The indicated age is ~110 Myr. At the south pole, a ray from Tycho crosses the ridge between de Gerlache and Shackleton craters [3] and it is possible, if not likely, that samples in this area will also reflect the age of Tycho via sample exposure ages.

South Pole-Aitken Basin. Among the most important age dates on the Moon is the age of its largest and oldest preserved impact basin, South Pole-Aitken (SPA). This 2500 km basin stretches from the south pole on its south rim to Aitken crater on its north rim. The basin likely formed sometime in the interval of 4.35 to 4.2 Ga ago, judging by the large-crater size-frequency distribution. The impact that formed this basin likely excavated mantle material of the Moon, and some of those materials may exist as clasts in impact breccias. Some of the large massifs such as Malapert are remnants of the southern rim of SPA basin. Many large impact craters and several smaller basins formed within the SPA basin, and these would have ejected materials of the basin to rim locations such as the south pole. Unlike the Apollo landing sites, which are all relatively close to the large and younger Imbrium basin, the Artemis landing site will be dominated by materials of the feldspathic highlands mixed with impact breccias derived from the SPA basin. Ejecta from other local large craters and nearby Schrödinger basin are also likely to occur in the regolith at the Artemis landing site and will be present among the rocks and rock fragments. Samples of these materials will provide a rich scientific payoff which has been called out in the past two decadal surveys as of high priority because they can address key events in early solar system history But these breccias must first be returned to Earth for careful analysis of their components and their record of the SPA basin chronology.

PSR Volatiles, Ice Deposits, and Organics. The primary reason for a south-pole landing site for Artemis is the ice deposits associated with permanently shaded regions (PSRs), especially to recover and use water, and possibly hydrogen and oxygen, separately, as rocket fuel. Remote sensing with neutron spectrometers indicates abundant $H_2O$ ice in the shallow subsurface associated with the PSRs and other polar latitude locations, and the LCROSS mission directly revealed the volatile-rich character. Much remains unknown about these deposits, however, and these will be key targets of polar exploration by precursor missions as well as Artemis III. We need to know how variable the ices are in composition and distribution, what are the impurities, and what reactions may have taken place owing to transient heating events such as meteor impacts or heating of deposits at the edge of PSRs.

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 delivered by comets or wet asteroids. Determining the origins requires careful isotopic analysis of the volatile elements such as D/H, oxygen, nitrogen, carbon, and others. Because of the difficulty of sampling and maintaining the integrity of ice deposits, it is likely that sophisticated instruments will be used to analyze these materials in-situ, in addition to collecting samples for return to Earth. Initially, samples should be collected that can be sealed for isotopic and chemical analysis even if the volatile compounds change phase or undergo reactions during the time between collection and return to Earth. 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 a high priority.

Organic compounds in regolith or associated with ice deposits are also a priority for sampling. Samples from a variety of environments are needed, including mature and immature regolith, shadowed vs. non-shadowed regolith for comparison, near the lander vs. far from the lander, and surface vs. subsurface (e.g., core materials). For organics, contamination is a very significant issue; recent, sensitive analyses indicate terrestrial contamination as one source of organics in the Apollo samples [4]. Organics from exogenous sources (i.e., meteorites, asteroids, comets) may be better preserved in the cold, polar regolith and ice deposits.

Polar Regolith and Surface / Dust. Artemis represents the beginning of a sustained human presence on the Moon. One of the key technical hurdles that must be overcome is associated with lunar dust. The ultrafine grains sizes, the sharp and "sticky" character of the grains, including glassy agglutinates and tiny, broken shards of glass, the special environment of the lunar surface all contribute to problems of dust buildup and impairment of suits and other mechanisms. The ultrafine grains include those of respirable size, <10 micrometers to sub-μm sizes that can become embedded in human lungs and even get into the bloodstream and be 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. All of these things are known from the characteristics of Apollo regolith samples. What is unknown is if polar regolith differs in important ways from the lower latitude Apollo and Luna regolith (see [2]). Is it finer-grained? Does it have the same high proportions of agglutinates, and nanophase Fe-metal components? The dust must be well characterized, and surface samples, including the uppermost few mm and cm, need to 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.

Careful analysis of science objectives may dictate the relative proportions of different sample types for return to Earth, but clearly, sample return mass should be maximized for Artemis III and subsequent missions.

**References:** [1] Head, J. et al. (2020) White Paper: How Artemis can accomplish major lunar exploration scientific goals and objectives: a sampling strategy and the "Artemis rake." [2] Denevi et al. (2020) White Paper: Science Strategy for Understanding Regolith Development and Space Weathering with Artemis III. [3] Denevi, B., and Robinson, M. (2020) Lunar Surface Science Workshop 2020, #5122. [4] Elsila et al. (2016) *GCA 172*, 357-369.