



Analytical Capabilities In Situ Versus Mass of Returned Lunar Samples

Introduction

The emerging capabilities of NASA and its commercial and international partners to land significant payloads on the surface of the Moon will provide opportunities to land large and diverse suites of science instruments. It will also provide opportunities to return samples to Earth for scientific analyses in Earth-based laboratories.

During the Apollo Program, the return of samples to Earth was the only viable way to obtain accurate and precise mineralogical and geochemical analyses of lunar samples; technology was simply not available or mature enough to enable these detailed scientific investigations in situ. As mission capabilities improve, architecture is refined, and analytical technologies improve with NASA's return to the Moon with the Artemis missions, a question arises:

Can modern payloads to the Moon provide sufficient analytical capabilities to replace the need for return of samples to Earth?

This paper provides a brief overview of the science enabled both by conducting analyses in situ on the lunar surface and by returning lunar samples to Earth. Several examples illustrate how both in-situ and returned sample analyses can address the lunar/planetary science (LPS) goals of the Moon to Mars Objectives.

These examples represent only a snapshot of the extensive breadth and depth of LPS and other lunar surface sample-dependent objectives. Other lunar science objectives facilitated by geophysical instruments (e.g., seismometers, heat probes, magnetometers, laser reflectometers), which by their nature require in-situ analyses, are not discussed in the context of in-situ analyses versus mass of returned samples. However, sample return may provide supplementary context for interpretation of those geophysical results.

The question of in-situ analyses versus mass of returned samples needs to be addressed on a case-by-case basis for each science goal. The strengths and weaknesses of each approach mean they are rarely directly interchangeable, and this variability should be taken into consideration during architecture definition. Broad Artemis and Moon to Mars goals will best be achieved by an integrated strategy that uses both sample return and in-situ measurements.

Lunar/Planetary Science Objectives

Goal: Address high priority planetary science questions that are best accomplished by on-site human explorers on and around the Moon and Mars, aided by surface and orbiting robotic systems.

LPS-1: Uncover the record of solar system origin and early history, by determining how and when planetary bodies formed and differentiated, characterizing the impact chronology of the inner solar system as recorded on the Moon and Mars, and characterize how impact rates in the inner solar system have changed over time as recorded on the Moon and Mars.

LPS-2: Advance understanding of the geologic processes that affect planetary bodies by determining the interior structures, characterizing the magmatic histories, characterizing ancient, modern, and evolution of atmospheres/exospheres, and investigating how active processes modify the surfaces of the Moon and Mars.

LPS-3: Reveal inner solar system volatile origin and delivery processes by determining the age, origin, distribution, abundance, composition, transport, and sequestration of lunar and Martian volatiles.

LPS-4: Advance understanding of the origin of life in the solar system by identifying where and when potentially habitable environments exist(ed), what processes led to their formation, how planetary environments and habitable conditions have co-evolved over time, and whether there is evidence of past or present life in the solar system beyond Earth.

white paper

2023 Moon to
Mars Architecture

Lunar Samples as Unique But Complex Records

The Moon serves as a historical archive for the Earth and inner solar system, recording events that happened billions of years ago.

Geological processes on Earth — such as plate tectonics and erosion by wind and rain — have erased all but a few rocks from the first billion years of Earth's history. By contrast, the Moon lacks major ongoing geological activity, with the exception of surface modification by impact events and space weathering. The Moon's major structural characteristics, including core formation, crustal formation, and the freezing of the interior structure, were largely established about 4 billion years ago, with major volcanic events complete by about 3 billion years ago.

Samples of the Moon therefore preserve unique records of the most ancient history of the Earth-Moon system and of the inner solar system (including Mars). Fundamental science achieved through analysis of lunar samples includes, but is far from limited to:

- Understanding the evolution of rocky planetary bodies.
- Establishing absolute ages of cratered surfaces throughout the solar system.
- Understanding the space weathering of airless bodies in the solar system.
- Constraints on the formation locations and later adjustments in orbits of the gas giants.
- Improved understanding of our solar system's history as it revolved around the Milky Way galaxy.

Lunar samples also provide information regarding the origin and evolution of volatiles on the Moon and Mars, with implications for both in-situ resource utilization and science.

While documents such as the [Artemis III Science Definition Report](#) and the Moon to Mars Objectives (e.g., LPS 1–4) capture many major science goals, the scope of science achievable through lunar (and Mars) sample analyses is vast. This is especially true for returned samples, which can be studied with ever-improving instrumentation to address new science questions for many decades after the completion of the original mission.

Unlocking the events and processes recorded by lunar samples includes a significant challenge: the history preserved in each rock is extremely complex. Unravelling this complexity requires detailed knowledge of the samples' origins and locations, careful preparation of samples, detailed sample characterization, and many types of analyses with high accuracy, high precision, and high spatial resolution. Obtaining this knowledge will require many specialized types of analytical techniques and instruments.

Prerequisites for Analysis: Finding and Preparing the Right Material for Analysis

Lunar samples are chemically and mineralogically diverse (Figure 1), as demonstrated by the many different types of rocks collected during each Apollo mission, as well as the overall diversity of the Apollo sample collection. Much of this diversity was captured because of the relatively large mass returned and the multiple, geologically different sampling locations.

Even with more than 2,200 individual samples totaling 382 kg, many types of samples were only represented by a few grams of material or just a single sample (e.g., green and orange volcanic glass beads from Apollo 15 and 17, respectively; troctolite from Apollo 17, from deep in the Moon's crust; anorthosite from Apollo 15 [Genesis rock]), and many more sample types were likely unaccounted for in the collection. Addressing the breadth of science questions encompassed by the Moon to Mars Objectives requires analyses of many different types of samples present within a given terrain, which can be collected either by crewed extravehicular activity or uncrewed rovers.

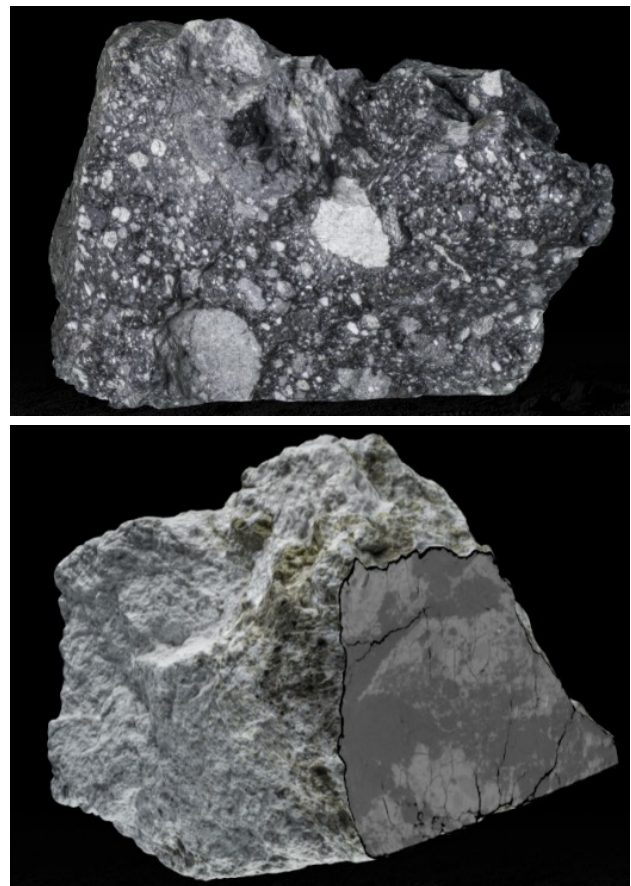


Figure 1. Apollo sample 60019 (top) is a breccia with distinct light and dark clasts. Other samples, such as 60025 (bottom) appear more uniform at the surface but overlaid X-ray imaging of the interior (lower right portion of the sample) reveals pervasive heterogeneity. Both samples were collected during Apollo 16. (Images from NASA's Astromaterials 3D project).

Achieving science goals requires analyses not just of these representative bulk samples but of the many pieces that make up each rock — individual minerals, grains, clasts, etc. Each rock is like a puzzle with hundreds of pieces, and each piece, or sub-sample, sheds light on a different part of the story.

Sub-sample components can record distinct and specific processes — for example, zircon is a key mineral for chronology (LPS-1), apatite and other minerals retain volatiles from magmatic/volcanic processes (LPS-2), glasses and agglutinates can record surface processes (LPS-1, 3), and rare dunitic and granitic clasts record a much broader range of magmatic and volcanic events than basalt alone (LPS-2). Exploring the lunar South Pole region and associated permanently shadowed regions will require analyses of regolith, rocks, and ices of different origins, which were deposited and sequestered by different natural mechanisms throughout the Moon's history (LPS-3).

In-situ analyses –

Collection of samples is best conducted in concert with broader surface geological investigations, such as by trained crew and/or with in-situ instruments. Together, these provide better context for the site from which a sample is collected.

Geologic context is crucial for the correct interpretation of analyzed samples. Continued development of in-situ techniques could rapidly identify the diversity of materials within and between terrains.

If fast and accurate enough, these techniques could help ensure that collected samples — whether for return to Earth or further in-situ analyses — include all scientifically important components. For example, astronauts or rovers could target the collection of low-abundance materials in a site otherwise dominated by another sample type. This could reduce the need for “luck” or for collecting vastly more sample mass than needed.

A limited amount of sample preparation (e.g., grinding to smaller fragments or powder, heating, chemical digestion) may be required for some in-situ analyses, as the Mars rovers have demonstrated. However, many lunar samples (e.g., Figure 1) exhibit such complex, small-scale heterogeneity that comprehensive, in-situ sample preparation will likely be impractical in many situations. Some lunar science goals will require delivery of a prepared, high-quality sample to a suitably accurate and precise instrument.

Returned samples –

For Apollo samples, tens of thousands of component pieces have been painstakingly extracted and prepared for laboratory analyses. This work has been conducted across five decades by the sample processing team at curation facilities at NASA's Johnson Space Center in Houston and hundreds of scientists in other labs around the world.

The analysis and cataloging of these samples involves many hours of work in various combinations of separation, extraction, chemical processing, and other means of preparation for each individual sample. Different combinations of sample preparation are implemented for different types of scientific analysis. For many types of analysis, a final step in sample preparation is dissolving a sample in acid (e.g., nitric acid, hydrochloric acid, hydrofluoric acid), which allows individual elements to be filtered and separated for analysis by increasingly sophisticated and capable mass spectrometers. For all these complexities and more, the return of samples to Earth will remain central to lunar science for the foreseeable future.

Sample Characterization

Lunar samples are chemically and mineralogically diverse (Figure 1), as demonstrated by the many dif There have been over 3,380 separate studies of the Apollo samples over the past 50+ years. They have yielded many thousands of scientific papers, which is a testament to the complexity and the long-term value of returned samples.

Sample characterization — that is, gaining a better understanding of the basic nature of individual puzzle pieces and how the puzzle pieces fit together — is an essential step in studying returned lunar samples. The same is true for returned asteroid samples and lunar and Martian meteorites and is expected for the Mars Sample Return mission.

Optical microscopy provides magnified views of the sample surface. X-ray computed tomography enables views of the interior of samples to record the position of pieces and informs decisions about where to slice open a sample (just as dentists and doctors use X-rays to inform treatment plans). Following mechanical preparation, researchers use additional optical and electron microscopy technologies and various spectroscopies over a wide range of the electromagnetic spectrum to provide much higher resolution views of the sample interiors.

Once basic sample characterization is complete, more detailed types of analyses can be conducted to evaluate the history of the sample and its components. For example, scanning electron microscopes and electron microprobes enable chemical and mineralogical analyses at nanometer to micrometer scales. At these scales, important records of lunar processes are recorded by variations in chemistry and mineralogy. Similarly, focused ion beam instruments enable extraction of electron-transparent wafers for analysis by transmission electron microscopy. This method provides exceptionally detailed views of chemical and mineralogical variations at sub-nanometer resolution.

These are workhorse techniques — required analytical capabilities — for understanding lunar samples. The data produced by these techniques are imperative for achieving many Moon to Mars Objectives.

In-situ analyses –

The development of miniaturized scanning electron microscopes (e.g., Mochii, which flew on the International Space Station) demonstrates a viable future path for some detailed sample characterization in situ, albeit with some limitations regarding surface sample preparation. Other techniques, such as laser Raman spectroscopy, have been deployed on Mars rovers and provide similar opportunities for characterizing sample chemistry.

However, techniques like X-ray computed tomography have yet to be employed in a mission setting but could provide useful information on the 3D interior structure and mineralogy of lunar samples in the future. Example use cases would include uncrewed missions or extended-duration stays; sample triaging would require significant improvements in speed and automation to be useful on shorter missions.

Returned samples –

Many sample characterization techniques require long-duration analyses (hours to days) to study even a few millimeters of material. Other techniques for sample characterization are currently far beyond the capabilities of in-situ instruments.

For example, characterizing very small but significant features (e.g., delicate surface structures, diagnostic chemical zonation at mineral boundaries) requires techniques such as transmission electron microscopy and associated focused ion beam preparation. The size, complexity, and underlying technologies of this method would be extremely challenging to miniaturize for flight.

The use of synchrotron facilities, requiring kilometer-scale light paths, enables exceptional chemical and mineralogical investigations at high spatial resolution, with applications to lunar science goals ranging from understanding magmatism to exploring the effects of space weathering. It is currently unfathomable to miniaturize the enormous infrastructure supporting such facilities for in-situ analyses.

Accuracy and Precision

Essentially every element in the periodic table has value in lunar science. For example, volatile elements, such as hydrogen, and dozens of related molecules (e.g., H, OH, H₂O, CH₄, NH₃) are integral to Artemis science and exploration objectives in the lunar South Pole region.

Hydrogen is also one of almost 60 elements that have more than one stable isotope (elements with the same atomic number but additional neutrons resulting in different atomic mass). For these elements, fractionation of light and heavy isotopes preserves the effects of important physical and chemical processes (e.g., melting, evaporation, crystallization, metal-silicate fractionation during core formation).

Many elements also have unstable isotopes, some of which yield useful systems for radiometric dating (e.g., U-Pb, Sm-Nd, Rb-Sr, K-Ar). This dating provides ages that, at the right levels of precision, can answer questions of when key events happened in a moon or planet's history, ranging across primary formation, impact modification, and surface exposure.

In-situ analyses –

While many science goals require accuracy and precision beyond the capabilities of current flight hardware, some science goals are ideal for in-situ analyses. One such example is the Dating an Irregular Mare Patch with a Lunar Explorer (DIMPLE) instrument suite, which was selected in 2023 for funding by NASA's Payloads and Research Investigations on the Surface of the Moon (PRISM) program.

DIMPLE will be delivered to the Moon by a Commercial Lunar Payload Services (CLPS) lander. Its instrument suite includes the Chemistry Organic and Dating Experiment (CODEX), which will yield the first in-situ dating of samples on the lunar surface.

CODEX has an estimated precision of ± 375 million years, leveraging the rubidium-strontium (Rb-Sr) radiometric system. While this precision would not be suitable for most lunar chronology analyses, it is sufficient to achieve the specific goal of the mission: determining whether the unique terrain of Ina, an unusual depression on the lunar surface, is ancient (approximately 3.75 billion years) or young (approximately 10–100 million years).

Other in-situ analyses, such as the detection of volatiles (e.g., water), are central to other CLPS missions, NASA's Volatiles Investigating Polar Exploration Rover (VIPER), and multiple concept missions and instruments. Volatiles are central to many science goals and to the broader Moon to Mars Objectives. Low-mass, uncrewed missions can explore far more sites and the results can inform strategic site selection for larger and crewed missions in the future.

Returned samples –

Laboratories on Earth have significantly higher accuracy and precision than is possible with in-situ instruments. In most instances, this accuracy and precision is required to answer driving science questions.

For example, the vast majority of questions regarding the ages of terrains, regions, and volcanic or impact events on the Moon (LPS-1,2,3; e.g., the age of the South Pole-Aitken basin) require significantly better precision than current flight instruments offer. For comparison, laboratories on Earth in the Apollo era had comparable precision to CODEX, while modern terrestrial laboratories are capable of Rb-Sr dating with precision of approximately 30 million years, 10 times better than the CODEX instrument.

Further, Rb-Sr is just one dating technique; it is appropriate for understanding only a subset of events and processes that have occurred throughout lunar history. The return of samples enables researchers to apply multiple dating techniques (e.g., K-Ar, Sm-Nd, U-Pb) to multiple mineral phases even within a single rock sample; this is important because some isotopic systems are more prone to resetting during impact events than others.

Similar scenarios exist for other elemental and molecular analyses. For example, understanding the origin and evolution of volatiles, both for science and in-situ resource utilization, may require analyses of low-abundance elements and at levels of isotopic precision that are difficult to achieve through in-situ analyses. Return of samples to Earth enables many different types of specialized instruments to study each element, isotope, and molecule. Essentially every instrument on Earth becomes part of the analytical suite.

Development of different instruments enables researchers to tailor analytical conditions to maximize the accuracy and precision of a specific analysis. Many of these instruments rely on exceptionally heavy magnets to provide sufficient mass separation between different isotopes. Even a small suite of mass spectrometers capable of measuring a handful of groups (e.g., light elements, transition metals, heavy radiogenic isotopes, noble gases) requires many metric tons.

Researchers need these instruments and dedicated components because of the very slight differences in chemistry that are imparted by geological processes — often variations measured in parts per million or parts per billion.

Suites of Instruments

It is common practice — and essential for achieving many scientific goals — to analyze the same sample with multiple techniques. This enables researchers to place the different puzzle pieces in the right context, (e.g., which are older or younger, which formed at higher temperatures, which formed close together, which were brought together by a later impact event).

In-situ analyses –

The development of an architecture that supports larger payloads opens the possibility of landing instrument suites for in-situ analyses. Such an approach can enable detailed sample science in the absence of sample return.

The Mars rovers exquisitely demonstrate the level of science that can be achieved by integrating results from multiple types of instruments. CLPS, autonomous rovers, and crew deployment will provide multiple opportunities for the development and implementation of such instrument suites for the Moon. The deployment of carefully selected instrument suites could offer excellent site context, answer a subset of science questions, inform

future mission decisions, and support contemporaneous or future sample return activities.

Returned samples –

Just as with the Mars rovers, even long-duration exploration with a comprehensive instrument suite will leave many significant science questions unanswered. The expense and complexity of the Mars Sample Return mission is well known, yet the call for the mission continues for a simple reason: in-situ instruments cannot match the fidelity of science enabled by returned samples.

The same is true for the Moon and, thankfully, the return of samples from the lunar surface is highly feasible. Returned samples allow researchers to employ many different approaches on the same sample and multiple sub-samples using dozens of instruments across the best laboratories on Earth.

Such approaches enable deep understanding of how, where, and when a sample was formed — and what this tells us about the origin and evolution of the Moon, as well as other bodies within the solar system. A huge advantage of returned samples is that they also enable new analyses to be conducted as technology develops over many decades.

Beyond Geology-Based Science

The bulk of this paper is dedicated to sample science from a broad geological perspective, but similar needs for sample return exist in other disciplines.

For biological and physical sciences conducted on the lunar surface or in cislunar orbit, the return of specimens for detailed analyses in Earth-based laboratories is critical. Biological investigations require different types of analyses at various levels of physiology. These identify underlying root mechanisms both affected by and governing responses to the space exploration environment by understanding impacts to individual and integrated multi-organ systems.

Microbiology ecosystem and pathogenicity investigations require analysis of individual specimens at the genetic level through host-microbial interactions and microbe-to-microbe interactions. In-situ analyses will provide important rudimentary data that requires more expansive follow-up analyses using instruments and techniques that, for now, are only available in Earth-based laboratories.

In addition, the return of specimens will require either live return or conditioned stowage (freezers), which enables high-fidelity preservation of the specimens for morphology, biochemical, and molecular biological analyses. Cold stowage may also be required for the transport of accessory chemicals and solutions for in-situ analysis instruments and of the specimens themselves.

Although much of the data and imagery for physical sciences investigations can use telemetry back to Earth, some investigations will require sample return to complete the analyses. For example, elements and materials used for combustion and flammability studies will require post-burn analyses to understand and develop models for propulsion and fire safety. Products created from science instruments examining the fundamental properties of materials, braising, volatile extraction, and soft matter/granular flow and particles are important to close knowledge gaps for development of lunar in-situ resource utilization methods and processes. These must be analyzed in Earth-based laboratories with instruments capable of the depth of analyses required. In addition, if telemetry bandwidth is limited, the return of data recorders and memory cards will be required.

Collectively, the return of specimens and samples from the Moon is important to gain a complete understanding of biological and physical systems. This understanding is critical to advancement of scientific knowledge, closure of knowledge gaps, and development of biological and predictive models that can be used to advance safe and productive human exploration, deep space travel, and long-term self-sustaining habitation on the Moon and other worlds.

Conclusion

Sample return is an absolute necessity to properly achieve the lunar/planetary science goals of the Moon to Mars Objectives. Returned samples enable analyses by the world's best laboratories and instruments, supported by teams of scientists and engineers. Returned samples will also serve as ongoing resources to the worldwide scientific community for the coming decades, enabling fundamental insights into the Moon and other bodies in our solar system.

In-situ analyses/instruments can address a subset of the lunar/planetary science goals, and deployment of in-situ instruments to multiple lunar terrains during low-mass, uncrewed missions will provide broader insights than can be achieved through larger and/or crewed missions alone.

Many of the inherent limitations of in-situ analyses (e.g., sample preparation, accuracy and precision, time needed for analyses) mean that even a fleet of in-situ instruments would not currently address many lunar science goals. However, continued development of in-situ instruments will ensure that they are capable of more and more unique, standalone science in the future. Further, as we test and develop in-situ technologies on the Moon during the early Artemis missions, NASA can leverage these expanding capabilities for long-duration crewed missions to the Moon and future missions to Mars.

Overall, the most efficient strategy for lunar science and exploration includes careful integration of in-situ analyses and sample return. Current and anticipated near-term in-situ analytical capabilities do not replace the need for sample return; the balance between the two should be carefully considered on a case-by-case basis, with science representatives involved in all stages of mission concept and architecture definition.