Analytical Capabilities: In-situ vs Mass of Returned Lunar Samples

The Immense Science Value of Lunar Samples

- Terrestrial records of the first few billion years of Earth's history are largely lost to time, due to the actions of plate tectonics, volcanism, and erosion by oceans, rain, and wind.
- The Moon is spared many of these processes, with lunar samples ranging in age from a few hundred million years to more than 4 billion years old.
- Lunar samples therefore represent immensely valuable scientific records for the Earth-Moon system, as well as for Mars and other planets.

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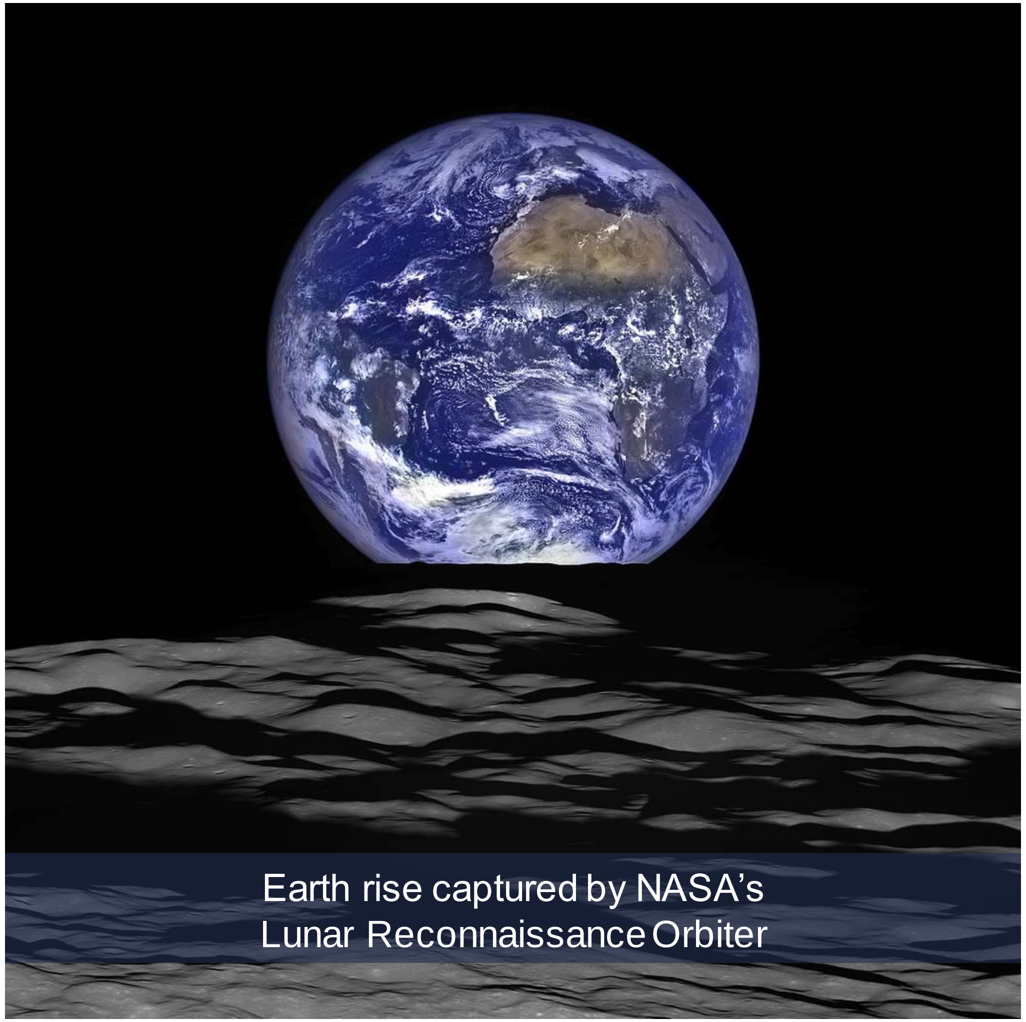
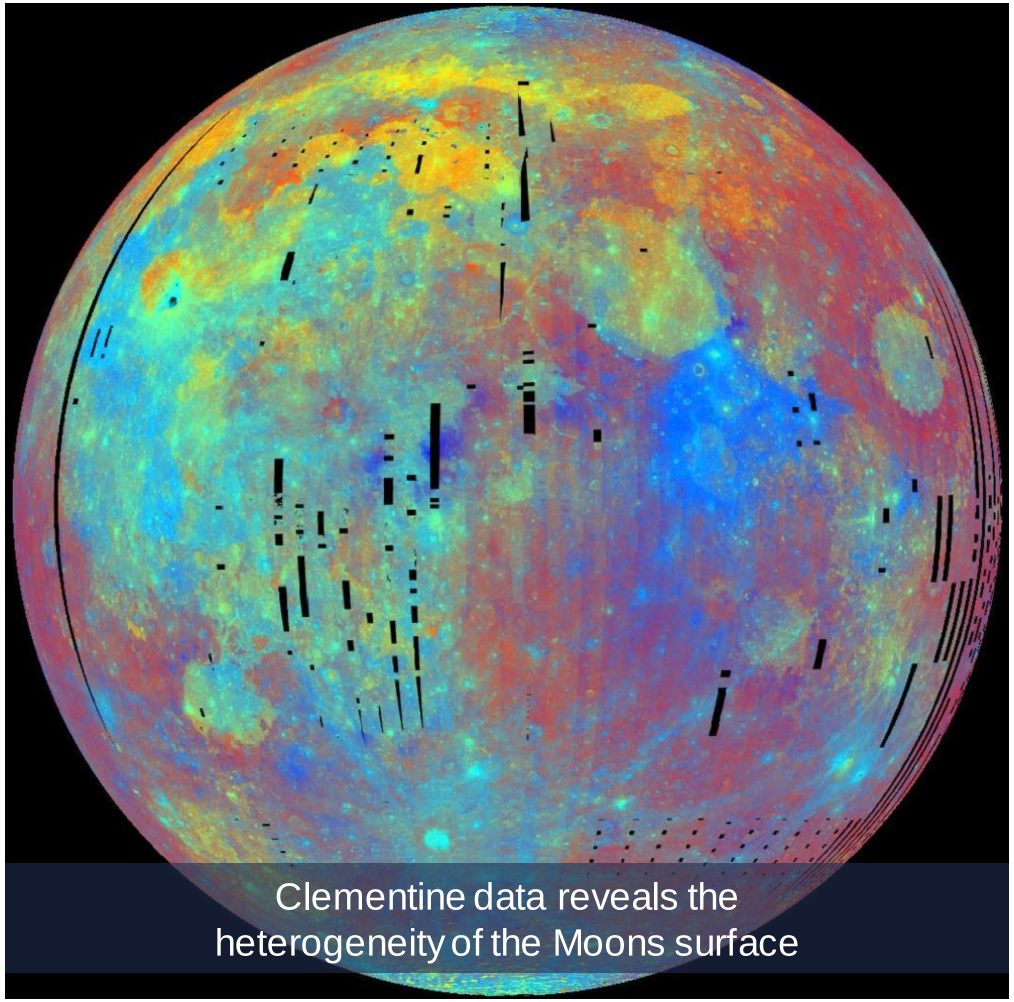


Earth rise captured by NASA's Lunar Reconnaissance Orbiter

Apollo and Artemis

- **The Apollo missions collected 382kg of lunar samples. However, samples were taken from similar areas of the Moon**
- **Many regions of the Moon, including diverse geologic terrains, and the lunar poles, remain unsampled**
- **Even within the Apollo landing sites, some collected rock types are represented by only a single sample. Other rock types even at these landing sites were likely not sampled.**
- **More samples, from more diverse sites, are needed to fully understand lunar history**



Clementine data reveals the heterogeneity of the Moons surface

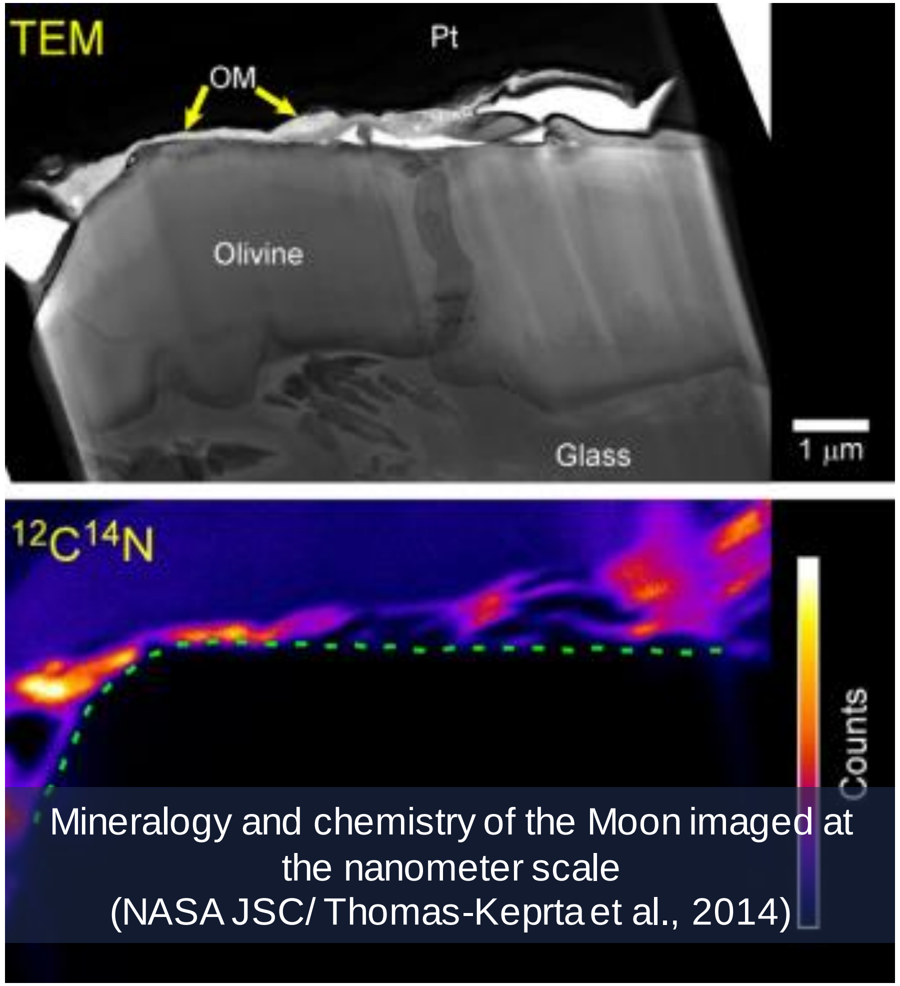
What Can We Achieve In Situ?

- **Miniaturization of scientific instruments enable significantly more science to be conducted by missions today than was possible during Apollo.**
- **A wide range of imaging, spectroscopy, and mass spectrometry can be conducted by mission instruments.**
- **Mission instruments are capable of characterizing mineralogy, identifying chemical compounds, and – for a subset of targets – provide useful information on the age of a sample.**
- **Many more opportunities are available for in situ analyses due to the number of smaller, lighter, and uncrewed missions.**

The VIPER rover, funded by NASA's CLPS program, will include several spectrometers and a drill

What Can We Achieve with Sample Return?

- **Sample return provides access to laboratories and instruments on Earth which have vastly superior accuracy and precision than is possible on small mission instruments.**
- **Complex sample preparation is required for many types of scientific analyses, e.g. separation of components, acid digestion, ion chromatography.**
- **A tailored analytical workflow can be followed for even tiny aliquots of individual samples, ranging from 3D analyses, to detailed mineralogy and chemistry, and age dating of a sample.**
- **Samples can be curated for years or even decades and be re-analyzed as scientific instruments and knowledge improve.**



Mineralogy and chemistry of the Moon imaged at the nanometer scale
(NASA JSC/ Thomas-Keprta et al., 2014)

Looking to the Future

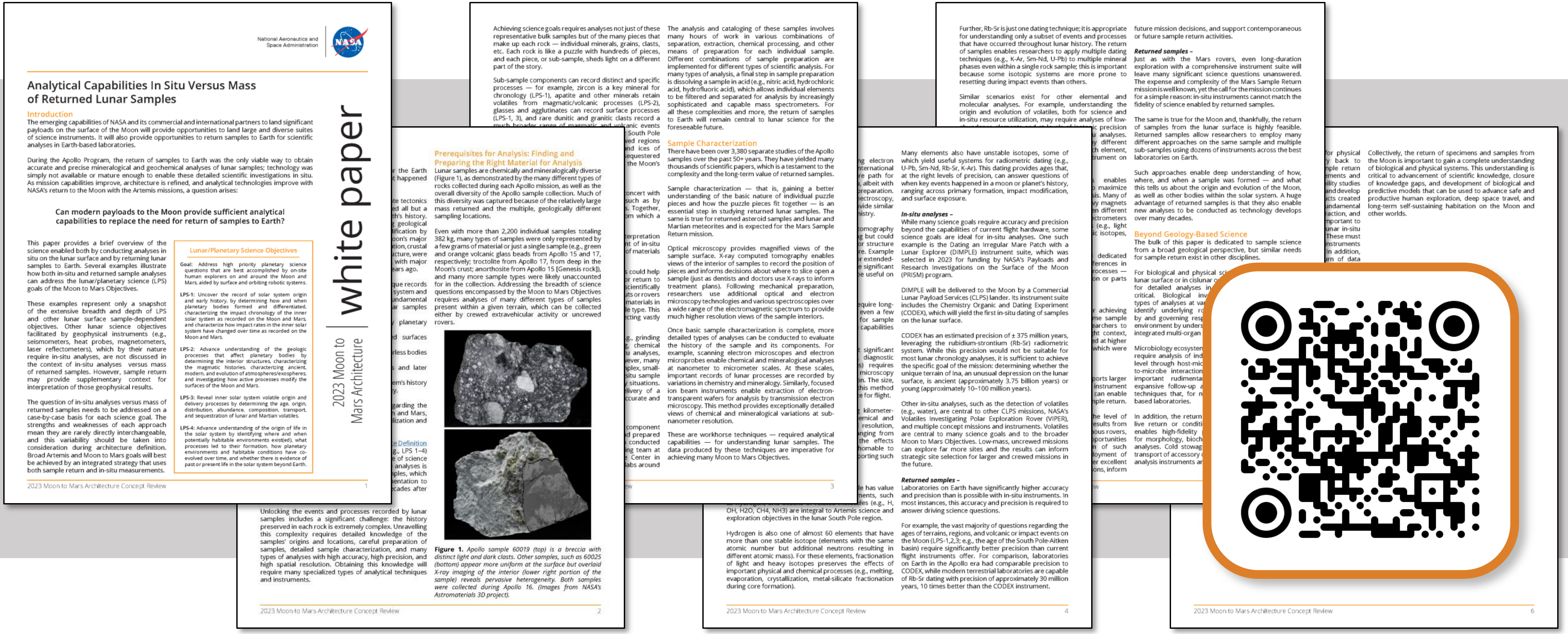
- **Some science questions can currently be answered by in situ instruments, while many others require sample return.**

- **Continued development of mission instruments will enable more science questions to be addressed in situ, especially for small or uncrewed missions where sample return is not viable.**

- **However, many laboratory instruments, as well as the infrastructure required to prepare samples for analysis (e.g., separation of components, acid digestion, ion chromatography), are difficult to reconcile with miniaturization.**

- **The question of what can be achieved in situ versus returned samples should be addressed on a case-by-case basis; broad Artemis and Moon-to-Mars objectives are achievable only though an integrated strategy involving both in situ analysis and return of samples to Earth.**

White Paper



National Aeronautics and
Space Administration

Analytical Capabilities In Situ Versus Mass of Returned Lunar Samples

white paper

2023 Moon to Mars Architecture

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.

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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).*

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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.

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

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.

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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.

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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.

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.

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.

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