

What are we learning from Moon rocks?

Six missions to the Moon have yielded a treasure-trove of samples, providing insight into its origin, mineralogy, and evolution. **by Meenakshi Wadhwa**

Astronauts first set foot on the Moon on July 20, 1969, and there is now an entire generation of young adults who were born well after this seminal event in human history. Likely, many of them are not aware that the Apollo astronauts brought many hundreds of Moon rocks to Earth between 1969 and 1972. Now, more than 40 years later, where are these Moon rocks, and how much is left of them? What have we learned from them? And perhaps most importantly, is there anything more we can learn from them?

Rocky statistics

During the six manned missions to the lunar surface (Apollos 11, 12, 14, 15, 16, and 17), 12 astronauts explored six sites on the Moon's nearside and brought back 2,196

samples of rocks, soils, and cores with an original mass of about 839.9 pounds (381 kilograms). Of this mass, NASA distributed about 32 pounds (14.5kg) of carefully chosen samples to the science community. Researchers have analyzed approximately half this mass, and, with few exceptions, every one of those Apollo samples has been part of a detailed study.

Another 30 pounds (13.6kg) of Moon rocks are on long-term loan to various institutions around the world, mostly for exhibition purposes. Most of the Apollo samples, however, reside in safekeeping at the Lunar Sample Laboratory at Johnson Space Center in Houston. There, a dedicated team whose mandate is to protect, preserve, and distribute samples for future studies curates them.

Scientists continue to learn much from what the astronauts brought back. The

fundamental insights gained from the study of the samples include ideas about how and when the Moon formed, how planetary orbits have evolved through time, and where and why water and other volatiles may be present on the Moon.

These new insights are literally changing our views of not only our lone natural satellite but also of Earth and our solar system. In fact, we are literally seeing a “new Moon” through the studies of these old samples that have now been with us for more than four decades.

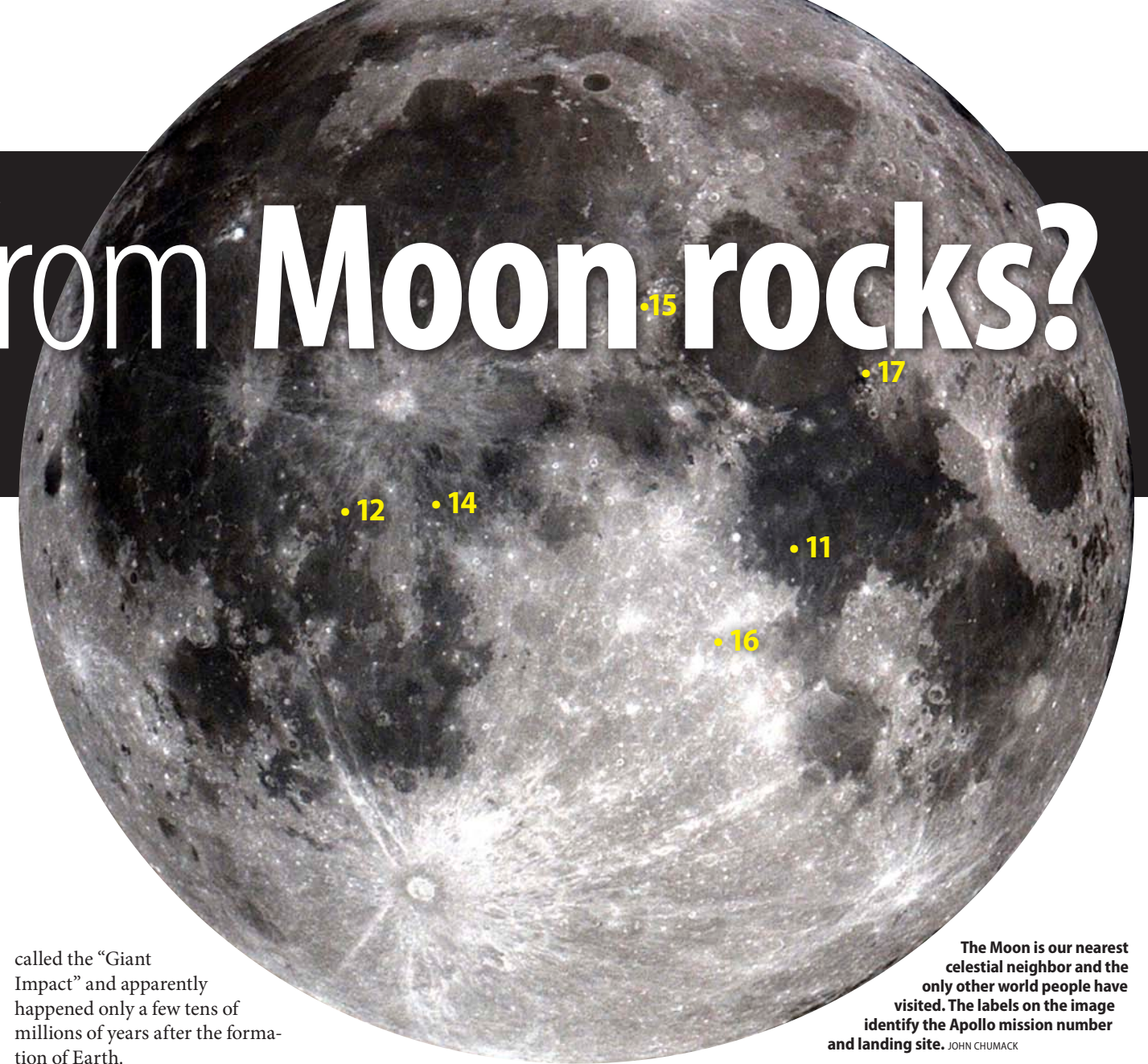
The Moon's origin and age

Studies of the lunar samples have told us that compared to Earth, the Moon has few volatile and siderophile (those that have an affinity for iron) elements but high quantities of refractory elements (those that remain stable at high temperatures). Yet isotope abundances of elements like oxygen indicate that Earth and the Moon have an ancestral relationship.

Based on such studies, the current best hypothesis is that the Moon formed when a Mars-sized planetary body slammed into the newborn Earth close to 4.5 billion years ago. This catastrophic event is popularly



Astronauts collected this basaltic sample from the Taurus-Littrow Valley during the Apollo 17 mission. Researchers have learned about the complex history of volcanism on the Moon from studying such rocks. NASA



The Moon is our nearest celestial neighbor and the only other world people have visited. The labels on the image identify the Apollo mission number and landing site. JOHN CHUMACK

called the “Giant Impact” and apparently happened only a few tens of millions of years after the formation of Earth.

Recent advances in computing capabilities allow us to model this giant impact process. We now can explain many of the previously puzzling chemical features of the rocks the Apollo missions brought back from the Moon.

The chronology of lunar samples (based on dating methods that use various radioactive isotopes) can tell us about the detailed time sequence as well as processes involved in the Moon's formation and evolution. Soon after the Apollo 11 astronauts returned the first Moon rocks, scientists suggested that the Moon had an exceedingly hot beginning. Most of its crust likely formed from the solidification of a global

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Processing of Moon rocks occurs in the Lunar Sample Laboratory at Johnson Space Center in Houston. The laboratory became operational in 1979, 10 years after astronauts returned the first lunar samples. The facility stores more than 90 percent of the samples returned by the Apollo missions. MEENAKSHI WADHWA



The author felt right at home in the Lunar Sample Laboratory. All sample handling is done inside glove boxes, such as the one shown here, that contain an atmosphere of clean, dry nitrogen.



This Apollo 16 impact-melt breccia contains a variety of light-colored clasts (fragments of pre-existing minerals or rock fragments). Some even enclose others, suggesting multiple generations of impacts and breccia formation on the Moon. Determining the ages of such impact melts can tell scientists something about the bombardment history of the Moon and Earth during the earliest stages of our solar system. NASA



Apollo 17 astronaut Harrison Schmitt — who was also a geologist — collects samples during his time on the Moon in December 1972. NASA

ocean of molten magma (lava) that was perhaps hundreds of miles deep.

In this scenario, the oldest rocks exposed on the Moon's surface should be those enriched in an aluminum-rich silicate mineral called plagioclase. Such material probably floated to the top of this solidifying magma ocean.

However, careful measurements of the ages of these Moon rocks give a range from close to the formation age of the solar system (about 4.5 billion years ago) to almost 200 million years later. This wide span in



This Apollo 16 sample is anorthositic breccia. In 2011, a team of scientists determined a lunar age of 4.360 billion $\pm$ 3 million years from this rock. The result suggests that the Moon is younger than researchers previously thought, or that the idea of such rocks forming as an early flotation crust from a lunar magma ocean may not hold. NASA

ROCK COLLECTING FOR NASA

With each subsequent Moon landing, Apollo astronauts collected more lunar samples than during the previous mission.

Mission	Site	Amount
Apollo 11	Sea of Tranquility	47.8 pounds (21.7kg)
Apollo 12	Ocean of Storms	75.8 pounds (34.4kg)
Apollo 14	Fra Mauro	94.6 pounds (42.9kg)
Apollo 15	Hadley-Apennine	169.3 pounds (76.8kg)
Apollo 16	Descartes Highlands	208.8 pounds (94.7kg)
Apollo 17	Taurus-Littrow	243.6 pounds (110.5kg)



This sample from Apollo 15 contains green glass beads (inset). The largest are about 150 micrometers in diameter. The beads formed as a result of volcanism on the Moon. Recent measurements of the amount of water in such beads have shown that the Moon may not be as dry as scientists had previously thought. NASA

the ages of these plagioclase-rich rocks suggests that the Moon's crust likely formed by a process more complicated than the simple solidification of a magma ocean.

The lunar cataclysm hypothesis

Moon rocks also have helped us learn about the impact history and the orbital dynamics of planets, asteroids, and comets. Based on the ages of rocks heated and melted by large impacts, the idea of the lunar cataclysm (also called the Late Heavy Bombardment) was born, which also has implications for the quantity of impacts and the origin of life on Earth.

According to this hypothesis, sometime between 3.8 and 4.1 billion years ago, there was a huge increase in the number of asteroids and comets hitting the Moon. In fact, a recent study of Apollo samples searching for surviving impactor fragments found that most of the material hitting the Moon during this period was from asteroids.

If the lunar cataclysm hypothesis is correct, then this means that huge impacts also pummeled Earth, which may have delayed the beginnings of life on our planet. Dynamical simulation models show that the lunar cataclysm itself was likely the outcome of the migration of the gas giant planets early in the history of our solar system.



Gary Lofgren shows off a display case containing a sample from the Apollo 16 lunar mission. Lofgren has been the laboratory's Lunar Sample Curator since 1997 and just retired last year. MEENAKSHI WADHWA

That movement deflected some asteroids into the inner solar system. Researchers call this the Nice Model after the location of the laboratory (in Nice, France) where it originated in the 1990s.

Water on the Moon

For decades following the return of the Apollo samples, researchers thought the Moon's interior was essentially devoid of any water (less than one part in a billion).



The Core Sample Vacuum Container (CSVC) holds an entire drive tube section. Apollo 16 and Apollo 17 astronauts collected one each. After the samples arrived at Johnson Space Center, the curators placed both CSVCs in an additional vacuum container with a much better seal. Both containers remain sealed in the center's Curation Storage Vault. They will remain there in pristine condition for future studies. NASA

Recent advances in analytical instruments, however, have helped scientists find evidence of water and other volatile elements (like sulfur, fluorine, and chlorine) locked inside lunar rocks and minerals, indicating that the Moon is not as bone-dry as originally believed.

Although still only a fraction of the water that is in Earth's interior, the amount estimated inside the Moon — from a few to tens of parts per million — is substantial enough to require a re-evaluation of our ideas about how water came to the inner rocky planets. The latest findings highlight the fact that we can gain important new insights by applying modern, state-of-the-art techniques to samples that astronauts brought back from the Moon decades ago.

The gift that keeps giving

The wonderful thing about having most of the Apollo Moon samples preserved in pristine condition at the Lunar Sample Laboratory is that they will be available for all kinds of future studies, many that we cannot even predict at present.

One of the more intriguing findings from recent spacecraft data (such as from the Moon Mineralogy Mapper instrument on Chandrayaan-1 and the LCROSS experiment on the Lunar Reconnaissance Orbiter) is the possible presence of water or hydroxyl (OH⁻) in polar and nonpolar regions of the Moon.

If we can confirm the widespread presence of these compounds on the Moon's surface, it would be an important factor in determining the feasibility of future human exploration and long-term habitation of the Moon. In fact, there already may be



The Core Storage Area in the Pristine Lunar Sample Vault holds several of the most important lunar samples the astronauts returned. MEENAKSHI WADHWA



Researchers handle Moon rocks inside nitrogen-vented glove boxes in the Lunar Sample Laboratory.

samples in our possession that could help confirm or refute this idea.

Astronauts returned samples of lunar soil and two drive tube (a method of obtaining a soil sample as deep as 27.5 inches [70 centimeters]) sections taken during Apollo 16 and Apollo 17 in special vacuum-tight, sealed containers. Both drive tube sections and one soil sample remain sealed.

It is likely that state-of-the-art instrumentation now available would detect any water or hydroxyl in them. In fact, a consortium of researchers is in the process of carefully planning additional analyses of one of these sealed samples to answer some of the most pressing questions arising from recent spacecraft observations.

Still a lot to learn

The Apollo samples returned more than four decades ago continue to provide a basis by which we can analyze the latest spacecraft data from the Moon. Through careful management, NASA's Johnson Space Center makes them available for today's scientists and future generations to help answer some of the most fundamental questions about our solar system.

We must remember, however, that these samples represent only a tiny fraction of the lunar nearside. Many other mysteries remain. Hopefully, the analysis of more and diverse samples returned by future missions to other areas of the Moon will unravel them. ☾