VOL. 100 • NO. 7 • JULY 2019

EOS®

Earth & Space Science News

100 YEARS

Time to Take a Hard Look at Geoengineering

How to Keep Rivers Flowing When Dams Are in Demand

What Made the Largest Geoid Anomaly in the World?

THE (NEW) SCIENCE OF APOLLO

AGU 100

ADVANCING EARTH AND SPACE SCIENCE

APOLLO'S LEGACY

50 Years of Lunar Geology

Samples of the Moon's surface brought back by Apollo astronauts ushered in a new era of planetary science. Scientists today continue the legacy.

By Kimberly M. S. Cartier

Apollo 15 astronaut James Irwin collects samples near the eastern rim of Imbrium Basin, not far from the lunar roving vehicle (opposite), with the lunar module in the background. Credit: NASA/Lunar and Planetary Institute

July 20, 1969, will forever be carved into the history books: the day that humankind took its first small step into the cosmos. The dawn of a new scientific era came just 4 days later.

When Apollo 11 splashed down on 24 July, planetary scientists knew they would soon get their hands on the first samples of material brought back from the surface of the Moon.

Apollo 11 astronauts brought back a scant 22 kilograms of material for scientists to study. Each subsequent Apollo mission—except Apollo 13, of course—brought back more and more rocks, soil samples, and drill cores. All told, the Apollo astronauts carried back to Earth 382 kilograms from six different areas of the Moon's surface, each sample stored in a container that preserved a Moon-like environment.

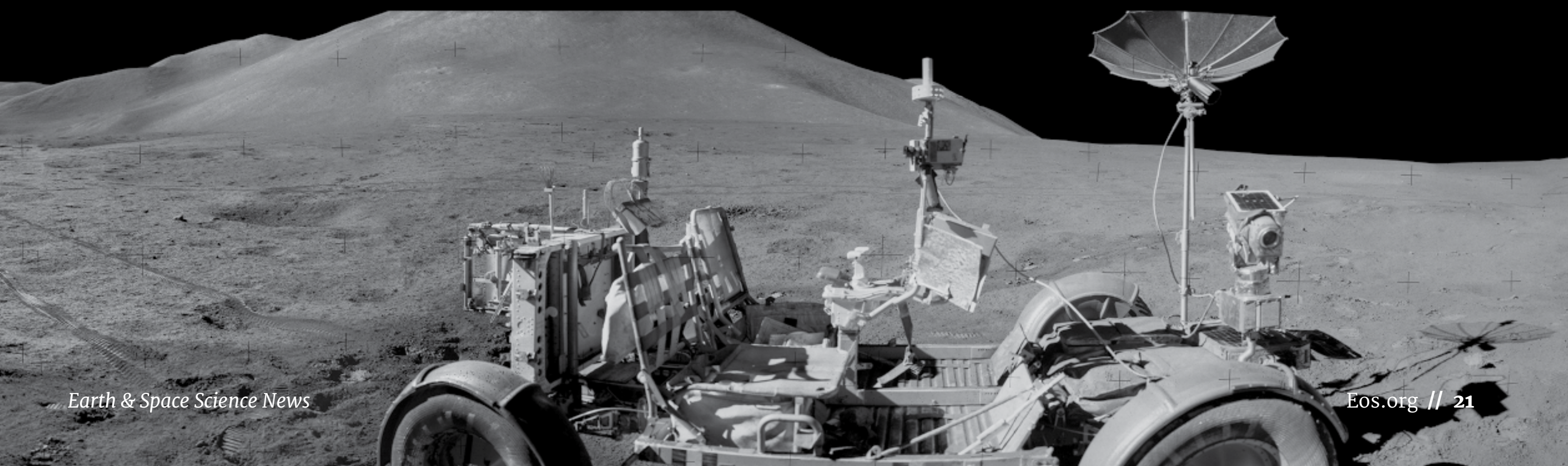
The initial impressions of the Apollo samples proved for the first time some facts about the Moon that may seem obvious today: There is not now and there likely never has been life on the Moon; meteor impacts throughout the Moon's history have pulverized the surface; and the Moon and Earth share many geochemical similarities.

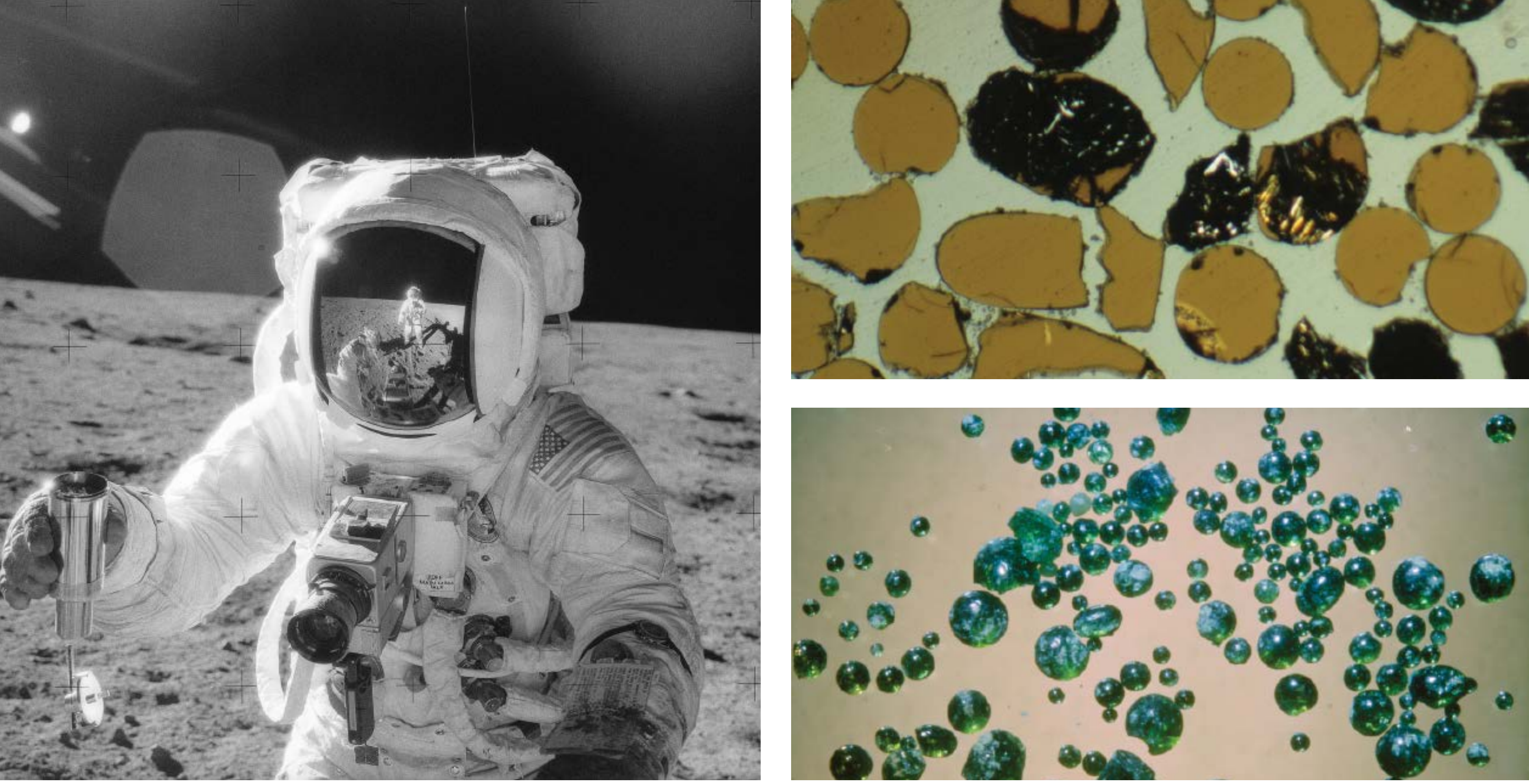
But technology, computer power, and scientific knowledge have grown exponentially since humans last stepped foot on the Moon in 1972. Thanks to the foresight of NASA leaders of the time, some of the Apollo samples were curated so that future scientists could study pieces of the Moon that hadn't been exposed to Earth's atmosphere.

"What we like to say is that sample return missions allow scientists not yet born to use instruments not yet developed to answer questions not yet asked," Jamie Elsila, an astrochemist at NASA Goddard Space Flight Center in Greenbelt, Md., told *Eos.*

Today "we're asking some of the same questions that the scientists back then were asking," Elsila said. "Because [NASA] preserved these samples and curated them carefully, now we're able to go back and try to answer these questions."

As post-Apollo scientists studied carefully doled-out lunar samples, they discovered much more about the





Left: Apollo 12 astronauts collected 34 kilograms of soil and rocks from the Moon's surface that they brought back to Earth for scientists to study. Seen here, Alan Bean holds up a filled sample tube during an extravehicular activity on 20 November 1969. Charles "Pete" Conrad is reflected in his visor. Top right: Lunar sample 74220 contains orange soil discovered near Taurus-Littrow Valley during the Apollo 17 mission. A 2.1-millimeter-wide thin section of some of the glass is seen here in transmitted light. Bottom right: Apollo 15 astronauts brought back regolith samples that included clods of green soil. Within the soil were small spheres of green volcanic glass, like these that were found in sample 15426. Credits, clockwise from left: NASA/Marshall Space Flight Center; D. Kring/NASA/Lunar and Planetary Institute; NASA/Johnson Space Center, Lunar and Planetary Institute

Moon and its history than scientists of the 1970s could have. Here are some of the most notable discoveries about our celestial neighbor that have come from Apollo samples over the past 50 years.

The Rough Life of Lunar Regolith

Life as a soil grain on the lunar surface is tough. Nowadays it's rare for a large impact to happen on the Moon, but microscopic impacts happen all the time.

"The lunar regolith is being bombarded by micrometeorites and high-energy particles from the solar wind," explained Richard Walroth, an instrument developer at NASA Ames Research Center in Mountain View, Calif.

Earth's atmosphere protects its surface from these microscopic hits. On the airless Moon, however, tiny meteorites, cosmic rays, and superfast ions from the Sun constantly strike the surface. This process, called space weathering, makes the lunar regolith literally rough around the edges.

"The grains melt at the very edge and form things called agglutinates," Walroth said, which are mineral fragments fused together by glass. "They also get a little nanophase iron too. They're like nanoscale droplets, essentially of metallic iron in glass."

Walroth and his team have developed instruments to look at the mineralogy and weathering of agglutinates and other Apollo samples.

The samples returned by Apollo astronauts bear the scars of space weathering, but some of the regolith samples were shielded from one type of weathering for millions of years.

"Shadowed soils…were collected at the surface but underneath the overhangs of boulders," said Barbara Cohen, a planetary scientist at NASA Goddard Space Flight Center. "In that case, we think that they were shadowed from things like micrometeorite impacts, but they were still exposed sometimes over seasonal and day-and-night cycles to things like solar wind."

"They might have a different total exposure history" than soils that were exposed to all types of space weathering processes, Cohen said. Comparing soils collected in different places will help Cohen and her team tease out which processes cause the different weathering signatures they see in Apollo samples.

"Space weathering is a global process," Walroth said, but "every part of the Moon's going to get affected by it a little bit differently."

Something Old, Something Slightly Less Old

It turns out that lunar rocks become discolored as they age, and close-up study of the Apollo samples helped explain why.

"Space weathering is a really complex set of processes that affect these grains very much at the nanoscale," Katherine Burgess, a geologist at the U.S. Naval Research Laboratory in Washington, D.C., told *Eos*. Burgess uses transmission electron microscopy to study how weathering chemically alters the surfaces of planetary bodies.

Space weathering processes "have huge impacts in how planetary bodies look spectroscopically from spacecraft and telescopes and change their optical properties," she explained. "That's generally referred to as reddening or darkening."

By studying the Apollo samples over the past 50 years, "we've figured out that the main cause of these optical changes is the formation of [nanophase iron] rims that

> “Returned samples are an investment in the future.”

are up to a couple of hundred nanometers thick,” Burgess said.

How much a grain has been altered by weathering processes can tell researchers how long it was left exposed on the surface. This is key to understanding the Moon’s geologic history and how long it takes for surface rocks to be buried underground.

“You know, we say that Neil Armstrong’s boot prints will be there forever,” Walroth said, “but in reality, they are eventually going to be buried by all the regolith. It’ll just take a long time.”

What’s become clear to lunar geologists is that apart from large and small meteorite impacts that churn up the regolith, the Moon’s surface is still aging, just very slowly. “These are processes that take place over millions of years,” he said.

Change on the (Solar) Wind

Space weathering does more than just rough up the lunar regolith, said planetary geologist Natalie Curran. It can also change the regolith’s composition.

“Cosmic rays from outside of the solar system produce noble gases in these samples,” said Curran, who works at NASA Goddard Space Flight Center. “The cosmic rays basically interact with elements in the rock—so things like oxygen, silicon, or magnesium—and they form actual noble gases.”

“There were very relatively low abundances of noble gases in the rock to start with,” she said, because the Moon’s original stock of volatile gases is long lost to space. “So the more exposed to the space environment and the more cosmic rays hit that sample, the more isotopes of noble gases are produced.”

The Sun, too, has its own noble gases to impart to the Moon’s surface through the solar wind.

Solar wind noble gases “get implanted into the surface of these very, very small grains, and they have a different isotope ratio to what the cosmic ray–produced noble gases have,” Curran said. “So we can measure all these noble gases in a sample and then look at the different isotopes to see which noble gas is produced from each of the different reservoirs.”

Noble gas analysis is another way that scientists can learn more about the signatures of different space weathering processes. Curran and Cohen are working to do just that.

“We’re interested in seeing the differences between things that are completely exposed all the time and these things that were partially eclipsed by boulders at some point in their history,” Cohen said. “If some effects shut off and others keep going, then we would be able to say, ‘Oh, that’s what the signature of this other effect looks like.’”

Glass, Glass Everywhere

The lunar surface might seem to be all shades of gray, but that’s definitely not the case everywhere on the Moon. Apollo 17 astronauts Harrison Schmitt and Eugene Cernan and CapCom Robert Parker learned this firsthand. Here’s a short excerpt from a recording of the moment of discovery:

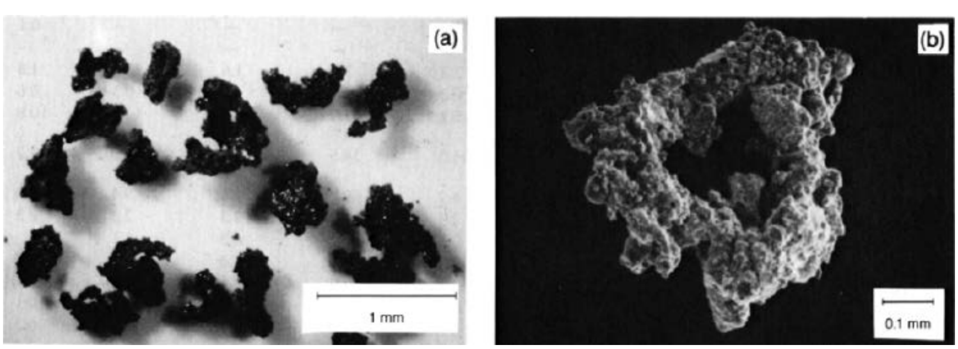
Schmitt: *It’s all over! Orange!*
Cernan: *Don’t move it until I see it.*
Schmitt: *I stirred it up with my feet.*
Cernan: *Hey, it is! I can see it from here!*
Schmitt: *It’s orange!*
Cernan: *Wait a minute, let me put my visor up. It’s still orange!*
Schmitt: *Sure it is! Crazy!*
Cernan: *Orange!*
Schmitt: *I’ve got to dig a trench, Houston.*
Parker: *Copy that. I guess we’d better work fast.*
Cernan: *Hey, he’s not going out of his wits. It really is.*
Parker: *Is it the same color as cheese?*

The orange soil is actually a deposit of microscopic orange glass mixed with the beige-gray regolith. These glass beads formed when ancient lunar “fire fountains” belched up molten magma, some of which condensed into droplets of pyroclastic glass and rained down onto the lunar surface 3.5 billion years ago.

“What most people don’t realize is that the soil on the Moon is about 20% glass beads” in the areas we’ve sampled, Darby Dyar, a planetary scientist at Mount Holyoke College in South Hadley, Mass., told *Eos*. Dyar, also at the Planetary Science Institute in Tucson, Ariz., has been studying lunar glass beads since she was in graduate school.

Apollo 15 samples contained similar glass beads that were tinted green. “What you see is, there’s about 5% to 20% of these little rounded glass beads which come from the volcanic glass fire fountains,” she said.

“The lunar soil is really fascinating in and of itself. The little glass beads are just one component of a really fascinating material,” Dyar said.



These typical lunar soil agglutinates are from Apollo 11 lunar sample 10084. (a) NASA photo S69-54827, an optical microscope photograph of a number of agglutinates with a variety of irregular shapes. (b) NASA photo S87-38812, a scanning electron photomicrograph of a ring-shaped agglutinate with a glassy surface coated with small soil fragments. Credit: The Lunar Sourcebook, *via Lunar and Planetary Institute*

No Water Above, but Traces Below

"At the time the Apollo samples came back," Dyar said, "the techniques that we had to analyze them at that time indicated...that there was absolutely no water on the Moon. Certainly, no hydrous minerals, you know, no micas, no clay minerals, no amphibole." On Earth, these minerals form in the presence of water.

Other tests for lunar water looked at the ratios of different iron molecules. "That tells us something about how much oxygen was around when these materials formed," she explained.

In a water-poor environment, iron will usually lose two electrons and exist in ferrous minerals, which are considered reduced. If there is any water around, that water can steal a third electron and create ferric compounds, which are oxidized.

"By 1980, the dogma was that the Moon was both completely dry and completely reduced," Dyar said.

More advanced techniques and more sensitive instruments changed that dogma. Close looks into the volcanic glass beads found that they contain signatures of water, something that has been recently confirmed. And recent research has found that ionized hydrogen from the solar wind creates trace amounts of water in the lunar regolith.

"In the last decade, we're suddenly revolutionizing our idea about what the interior of the Moon looks like," Dyar said. "It looks like it might actually have had, at the time these were erupted, significant amounts of both water and oxygen around. That's quite paradigm shifting."

> "In the last decade, we're suddenly revolutionizing our idea about what the interior of the Moon looks like."

Amino Acids from Afar

"When the Apollo astronauts first brought these samples back," Elsila said, "there was a lot of interest in understanding amino acids and potential organic compounds relevant to life in these samples."

Although it is still unclear how life began on Earth, scientists thought it possible that the collision that formed the Moon out of Earth's crust and mantle also could have transferred the building blocks of life to the Moon.

"In the 1970s, there were a lot of studies looking for amino acids in lunar samples, and they were detected, but the origins weren't able to be determined at that point," Elsila said. There were fierce debates about whether the amino acids were really from the Moon or from accidental contamination.

A few years ago, Elsila led a team that reexamined amino acids in Apollo 16 and Apollo 17 samples to pinpoint their origins.

"We found that they were probably a combination of terrestrial contamination just from the sampling process and the curation process," Elsila said, "but also some amino acids that seem to be indigenous to the lunar surface." Lunar amino acids have a molecular structure distinctly different from terrestrial ones, her team found.

How did those amino acids get there? "The ones we found are similar to amino acids that we've detected in meteorites and other extraterrestrial materials that have probably undergone abiotic chemistry," Elsila said.

Meteorites might have implanted those amino acids on the Moon long ago. Alternately, Elsila said, the molecules' precursors might have blown in on the solar wind and undergone abiotic chemistry to form amino acids. Comparing lunar amino acids from areas exposed to impacts but not the solar wind and vice versa could help solve that mystery.

Investing in the Future

In the next few months, NASA will give scientists access to some never-before-studied Apollo samples. Those samples have never tasted Earth's atmosphere. They've been kept in the same condition they were in when Apollo astronauts brought them back almost 50 years ago.

"Returned samples are an investment in the future," said Lori Glaze, acting director of NASA's Planetary Science Division in Washington, D.C. "These samples were deliberately saved so we can take advantage of today's more advanced and sophisticated technology to answer questions we didn't know we needed to ask."

The research teams NASA selected to look at the samples will work with one another to create a holistic view of the Moon's geologic history as told by the Apollo program. Many of the necessary tests will change those samples forever. But lunar geologists are already looking toward future exploration and future sample return missions to answer our lingering questions about the Moon.

"Unless you're willing to put a rock on the lunar surface and wait a billion years," Walroth said, "it's going to be really hard to answer those questions. But that's why we hope to get material from more and more places around the Moon."

"Our Apollo samples all came from the nearside equatorial region," Cohen said. "We didn't have the context, the global context for them at the time that we sent those missions and got those rocks back. And so saying that we've really sampled the Moon, well, we really have only sampled a very small part of it."

"There are lots of places left to go," she said.

Author Information

Kimberly M. S. Cartier (@AstroKimCartier), Staff Writer