



The new MOON

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**Recent findings are challenging much
of what we thought we knew about
Earth's nearest neighbor.**



With humans' initial exploration of the Moon at the dawn of the space age came the birth of modern planetary science, which seeks to understand the complex history of our solar system in enough detail to piece together the story of how we got to where we are. To what extent was Earth an inevitable outcome of planetary evolution? To what extent was it a quirk of fate?

The Moon is critical to unraveling that story. Much of Earth's history has been erased by tectonic processes and erosion; its earliest crust appears to have disappeared without a trace.¹ But the Moon has been well preserved. We have samples of its primordial crust, and its cratered surface records the history of more than 4 billion years of asteroid and comet bombardment—a barrage that also showered Earth.

The timeline etched into the Moon's face can be a startling reminder of how short our own time on Earth has been. Tycho, the bright, rayed crater that stands out sharply on the Moon's southern nearside, is among the body's newest landmarks. Yet when it formed from an impact around 100 million years ago, the dinosaurs were still around to witness what was for them a near miss. When Copernicus, another young lunar crater, formed some 800 million years ago, trees had not yet appeared on Earth and the pre-Pangaea supercontinent Rodinia was still intact.

In the past decade, the world's interest in the Moon, both as a cornerstone in our understanding of the solar system and as a stepping-stone from which to explore that system, has undergone a revival. After the last Apollo astronaut returned to Earth in 1972 and the Soviet Luna program's robotic landers returned their last lunar sample in 1976, lunar science went relatively quiet. There were no lunar missions in the 1980s and just two, the US's *Clementine* and *Lunar Prospector*, in the 1990s.

Then, starting in 2007 with Japan's *Kaguya* lunar orbiter, a new group of missions began the second era of lunar exploration. *Kaguya's* suite of remote-sensing instruments provided new information about the Moon's composition. India's *Chandrayaan-1* obtained radar and near-IR spectra that led to new insights about volatiles—water, hydrogen, helium, and other molecules that readily vaporize under typical conditions at the lunar surface. Four NASA-operated missions—the *Lunar Reconnaissance Orbiter* (LRO), *Lunar Crater Observation and Sensing Satellite* (LCROSS), *Gravity Recovery and Interior Laboratory A* and *B*, and *Lunar Atmosphere and Dust Environment Explorer*—mapped the Moon from radio to UV wavelengths, revealed the presence of water ice, obtained highly precise gravity maps,

and studied the movement of dust and volatiles at the lunar surface. Finally, on 14 December 2013, China's *Chang'e 3* and its *Yutu* rover touched down in the Imbrium basin—the first soft landing on the Moon since 1976.

Where has this burst of renewed lunar investigation left us? Last year, in a crowded room at the Lunar and Planetary Institute in Houston, Texas, the lunar science community convened to discuss what we've learned in the

past decade, identify the most important outstanding questions in lunar science, and decide where our field should go next. In this article, I'll discuss some of the insights, hypotheses, and paradigm shifts that emerged from that meeting. Some ideas are new, others are fresh perspectives on old problems, and still others represent the reopening of cases that were previously considered closed. Collectively, they suggest that the Moon, an object of the human gaze since time immemorial, still guards many secrets.

Not so dry

Some parts of the lunar surface never see the Sun. Due to the minimal axial tilt of the Moon, regions in impact craters and other topographic lows near the lunar poles remain shielded from direct sunlight year-round. Figure 1 shows the permanently shadowed regions, or PSRs, of the lunar south pole. Theories dating back to the early 1960s posited that PSRs could hold trapped water ice and other volatiles. That hypothesis, together with volatiles' potential value as a resource for a lunar outpost and for deep-space exploration, provided the impetus for what is now a very active line of research: the hunt for lunar water.

In recent years, scientists have made significant advances in that pursuit. Neutron-absorption data collected by *Lunar Prospector* and the LRO provided definitive evidence of large amounts of hydrogen sequestered in both polar regions;² the depressed fluxes of cosmogenic neutrons in those regions were attributed to an abundance of hydrogen nuclei, which efficiently absorb neutrons. Although neutron-absorption data provide no information on the form of the hydrogen, radar measurements in and around the south pole's Shackleton and Cabeus Craters are suggestive of relatively pure ice: At low phase angles, the radar exhibits a coherent backscatter effect marked by a polarization that's consistent with scattering by crystalline water.³

The case for water isn't closed, however. Studies based on higher-resolution data from the Earth-based Arecibo Observatory and Green Bank radio telescopes showed that the radar



FIGURE 1. AN ILLUMINATION MAP of the lunar south pole shows permanently shadowed regions (black) that receive no direct sunlight and potentially harbor thermally stable water. Such regions are typically found in topographic lows, such as the floors of impact craters. The map covers latitudes 88°–90° S; the brightest areas receive sunlight over 90% of the time. (Image courtesy of NASA/GSFC/Arizona State University.)

signature seen in PSRs also appears in some sunlit polar regions and could plausibly be due to the presence of rock-strewn crater deposits.⁴ But according to interpretations of radar measurements collected by *Chandrayaan-1* and the *LRO*, when geologic context is considered, rocky deposits alone can't explain the radar signatures produced by some PSRs.⁵

Optical measurements have helped to clarify the matter to some degree. Whereas neutron and radar measurements penetrate a meter or more into the lunar soil, optical measurements probe only the surface. Still, they can paint a rich picture. For instance, far-UV reflectance observations by the *LRO*'s Lyman Alpha Mapping Project revealed strong water-absorption features—evidence for a small amount of surface frost—restricted to locations that, according to the *LRO*'s IR radiometer, never get warmer than 110 K, the cold-trap temperature above which water-ice sublimates.⁶ Likewise, the orbiter's laser altimeter indicates that PSRs have elevated albedo in the near-IR and that the albedo increases with decreasing temperature—characteristics consistent with, but not definitive of, the presence of water and other surface volatiles.⁷

But not all locales where water is thermally stable show evidence of frost. And the frosty areas suggested by the *LRO*'s UV and IR instruments are poorly correlated with the hydrogen-rich areas identified by its neutron detector data. In fact, in some regions exhibiting enhanced hydrogen, ice is not thought to be thermally stable at any depth.⁸

Although the distribution, abundance, and form of volatiles at the lunar poles remain unknown, water's presence is certain in at least one locale. On 9 October 2009, a NASA Centaur rocket crashed at nearly 9000 km/h into the Cabeus Crater, liberating a plume of dust and vapor witnessed by *LCROSS* and the *LRO*. Measurements confirmed that water made up around 5% of the mass of the ejecta plume.⁹

Whence the water?

Assuming substantial amounts of water and other volatiles are present at the poles, how did they get there? Some water de-

posits may have been emplaced by cometary and asteroidal impacts. A portion of that water would be expected to vaporize and eventually find its way to the poles, where it would be cold-trapped as water ice. Another possible source is the solar wind, which irradiates the lunar surface with streams of hydrogen, long known to alter the chemistry of exposed grains of soil and to darken those grains with time. In 2009 three spacecraft observed near-IR absorptions corresponding to fundamental OH vibrations.¹⁰ The features were seen at both high and low latitudes; the low-latitude absorption was strongest at the coldest temperatures, closest to the lunar night. One possible explanation is that hydrogen from the solar wind binds loosely with mineralogically bound oxygen and then escapes when the temperature rises as either molecular hydrogen or water. The volatiles would eventually either be lost to space or become cold-trapped at the poles.

Alternatively, some water may be native to the Moon—or at least have arrived early on in lunar history. Fewer than 10 years ago, the consensus among planetary scientists was that nearly all the Moon's primordial volatiles vaporized during the impact that created it—a fiery collision between Earth and a Mars-sized planetesimal—and that those volatiles were lost to space as the Moon accreted from the impact's debris. (See the article by Dave Stevenson, *PHYSICS TODAY*, November 2014, page 32.) In fact, the low levels of volatiles measured in lunar samples—less than one ppb—were considered supporting evidence for the giant-impact hypothesis. But new, sensitive techniques such as ion microprobe mass spectrometry have found water concentrations of hundreds of ppm in returned lunar samples,¹¹ suggesting that water is about as abundant in parts of the Moon's mantle as it is in parts of Earth's.¹² Near-IR observations hint at the presence of water in recently uplifted crustal material, another clue that at least some of the Moon's water is native rather than generated by the solar wind.¹¹

The new work is leading theorists to reassess the giant impact and its effect on volatiles. It has also led them to explore the idea that the Moon's water—and Earth's—could have been delivered after the fiery impact, possibly by comets. Isotopic ratios have the potential to help distinguish between various sources of early water and elucidate the origin of Earth's water, but they likely require laboratory measurements of lunar samples.

Although remote-sensing missions and sample analyses have shed light on certain properties of lunar volatiles, in other aspects we remain in the dark. We know relatively little about the processes that control the redistribution, retention, and loss of volatiles. We don't know how much ice is trapped at the poles and at what depths. And we don't know whether water ice and other volatiles could reasonably be extracted to, say,

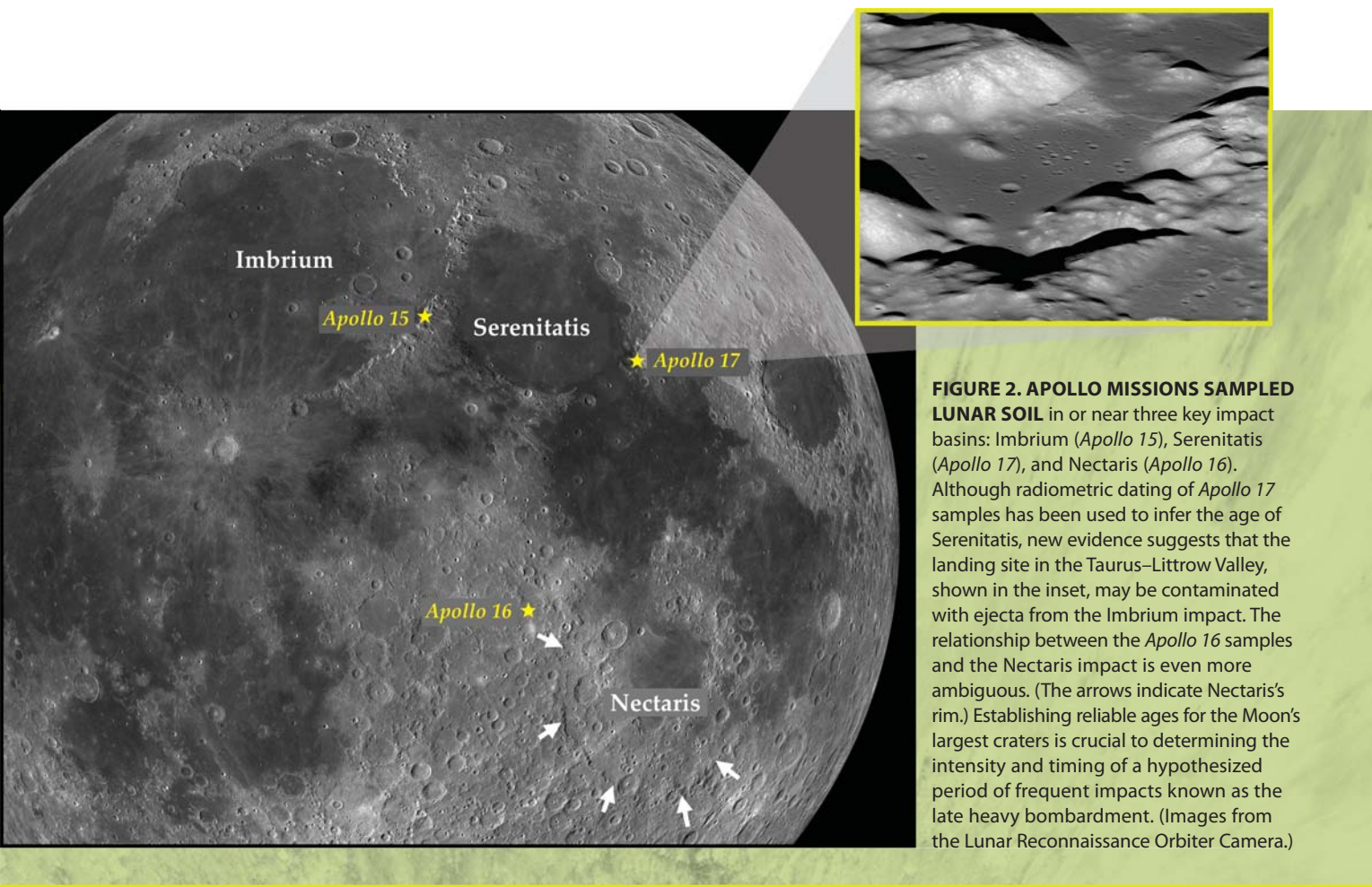


FIGURE 2. APOLLO MISSIONS SAMPLED LUNAR SOIL in or near three key impact basins: Imbrium (*Apollo 15*), Serenitatis (*Apollo 17*), and Nectaris (*Apollo 16*). Although radiometric dating of *Apollo 17* samples has been used to infer the age of Serenitatis, new evidence suggests that the landing site in the Taurus–Littrow Valley, shown in the inset, may be contaminated with ejecta from the Imbrium impact. The relationship between the *Apollo 16* samples and the Nectaris impact is even more ambiguous. (The arrows indicate Nectaris’s rim.) Establishing reliable ages for the Moon’s largest craters is crucial to determining the intensity and timing of a hypothesized period of frequent impacts known as the late heavy bombardment. (Images from the Lunar Reconnaissance Orbiter Camera.)

support a sustained human presence on the Moon or produce rocket fuel.

Some of those questions may soon be resolved. The *LRO* team is developing new strategies to measure lunar hydration, including monitoring PSRs that have been in darkness for many years but are now emerging into sunlight due to orbital precession. Also, NASA is building three new CubeSats: *Lunar Flashlight*, which will map surface frost; *LunaH-Map*, which will chart hydrogen to depths greater than 30 cm; and *Lunar IceCube*, which will examine the distribution of water as a function of latitude and time of day. (For more on CubeSats, see *PHYSICS TODAY*, November 2014, page 27.) A fourth proposed mission, the rover *Resource Prospector*, would land and extract volatiles from polar soil.

The Moon and the cataclysm

All told, the Apollo missions of the late 1960s and early 1970s returned more than 2000 moon rocks to Earth. Many of those rocks have been radiometrically dated to around 3.9 billion years ago, when they presumably formed from melts generated during impact events. Surprisingly, relatively few samples record impacts from the 600 million years of the Moon’s existence before that time. Assuming early impacts were a result of debris being swept up in the end stages of planetary accretion,¹³ they should have become rarer as the Moon aged. To explain the discrepancy, theorists proposed the so-called late heavy bombardment, a spike in large impacts that occurred after the first wave of accretion had died down. Some previously unexpected event would have to have caused that bombardment.

Solar-system-wide scenarios have been contrived to explain what the event might have been.¹⁴ One scenario, known as the Nice model, posits that the outer planets were initially much closer to the Sun and that their outward migration scattered objects that had been in stable orbits. Not only would that scattering have caused the late heavy bombardment suffered by the Moon, it would have had massive effects across the whole of the inner solar system, with important implications for the emergence of life on Earth. If the Nice model is correct, many of the objects bombarding the inner solar system were from the proto-Kuiper Belt; they would have delivered water and, perhaps, prebiotic material to the terrestrial planets.

But theorists have frequently called into question just how “heavy” the late heavy bombardment really was. And in the past decade, new studies of the Moon have energized the debate.

As conventional wisdom has it, the Serenitatis basin, whose rim was sampled by *Apollo 17*, formed from an impact around 3.89 billion years ago, just 50 million years before the impact that formed the neighboring Imbrium basin, sampled during several missions (see figure 2). Based on stratigraphic relationships between craters, theorists initially concluded that three basin-forming impact events occurred in the interval between Serenitatis and Imbrium. But new examinations of those relationships and of the impact craters superposed on Serenitatis¹⁵ have revised the number to 25. If we accept the conventional ages of Serenitatis and Imbrium, then the late heavy bombardment was even more intense than previously thought; it would have been a true cataclysm, with a basin forming every 2 million years.

But can we accept the conventional wisdom? New work has



FIGURE 3. A RECENT METEOROID IMPACT was identified by comparing a “before” image from 2012 (left) with an “after” image taken under identical lighting conditions in 2013 (center). The ratio of the two images (right) clearly shows an 11 m crater. Immediately surrounding the crater are areas of high and low reflectance and faint rays that stretch farther out. The landscape changes are due to the deposition of ejecta and to the churning of the soil by impact debris. (Images from the Lunar Reconnaissance Orbiter Camera.)

shown that Imbrium ejecta likely litter the *Apollo 17* landing site, so the samples thought to date the Serenitatis impact may instead date the formation of the Imbrium basin.¹⁵ If so, we’re left with diminished evidence that the late heavy bombardment occurred at all—and increased evidence of the monumental effect that the Imbrium impact had on the nearside lunar landscape.

Serenitatis figures pivotally in our understanding of the late heavy bombardment in large part because we’ve collected so few samples that can be definitively linked to known crater-forming events. The *Apollo 16* landing site is not so distant from the Nectaris basin, but the evidence that samples collected there date to the actual formation of the basin is even more tenuous than it is for Serenitatis. It’s possible that Imbrium is the only basin whose true age we know.

The obvious answer to the quandary is to collect samples that definitively date the formation of large impact basins such as Serenitatis, Nectaris, Crisium, South Pole–Aitken, and Orientale. But the ambiguous results from Serenitatis demonstrate the importance of careful sample-site selection. The currently available trove of orbiter data will no doubt aid in such site selection, as will future missions to collect high-resolution images of the lunar surface. Advancing our understanding of the timing of events on the Moon is critical for clarifying the timing of events on Mercury, Mars, and even early Earth: The lunar time scale is the foundation on which the others are built.

Not dead yet

Although the Moon’s most intense geologic activity occurred early in its history, it is a more dynamic place than once thought. Impact events continue to reshape the surface, and we are now able to measure the rate of crater formation. By taking images of the same lunar terrain at different times and then comparing them, we can identify craters that formed in the intervening period. Most of that work has been done with images from the Lunar Reconnaissance Orbiter Camera (LROC), which can have pixel scales as small as 50 cm.

Early attempts to compare LROC images with decades-old photographs from the *Apollo* missions required an enormous amount of manual effort and—despite the lengthy interval in

which new craters could accumulate—led to the identification of only a handful of new craters. Once LROC acquired a sizable collection of high-resolution “before” images, however, it began a dedicated campaign to reimage the surface under identical illumination conditions. Figure 3 shows an example of the subtle changes that can be detected by comparing before and after images.

It turns out that the lunar surface is changing at a remarkable pace: A new 10-m-diameter or larger crater forms about once every 23 days, about one-third faster than standard models predict. And each crater affects substantially more surface area than was previously appreciated.¹⁶ For example, ejecta from a crater 10 m in diameter can strike and churn up soil tens of kilometers away. So far only a few hundred resolvable primary impact craters have been identified, the largest being 70 m in diameter, but images show tens of thousands of surface changes that are likely caused by secondary impacts of ejecta from those newly formed craters. That result is important for understanding how rapidly the surface overturns and exposes new material to the solar wind, but it will also inform the design of any future long-term outposts on the Moon. Furthermore, the primary impact rate has important considerations for Earth: The impact rate for objects large enough to survive passage through Earth’s atmosphere is the same on Earth as it is on the Moon.

Another recent, and likely ongoing, process is tectonic deformation—the surface manifestation of billions of years of cooling and contracting. That deformation takes the form of lobate scarps, which are the surface expression of thrust faults: As the Moon’s liquid outer core solidifies and contracts, its brittle overlying crust is forced to give way. LROC’s high-resolution images reveal lobate scarps that cut across craters less than 10 m in diameter, too small to have survived for long on the surface. Those faults must therefore have been active recently, within the past 50 million years, and they may be active today.¹⁷

The orientations of thousands of newly discovered scarps indicate that Earth-induced tidal forces significantly contribute to stresses in the Moon’s crust. Those forces are small compared with those of global contraction—the Moon’s daily tidal swelling is only around 10–20 cm—but they add up over the course of a lifetime.

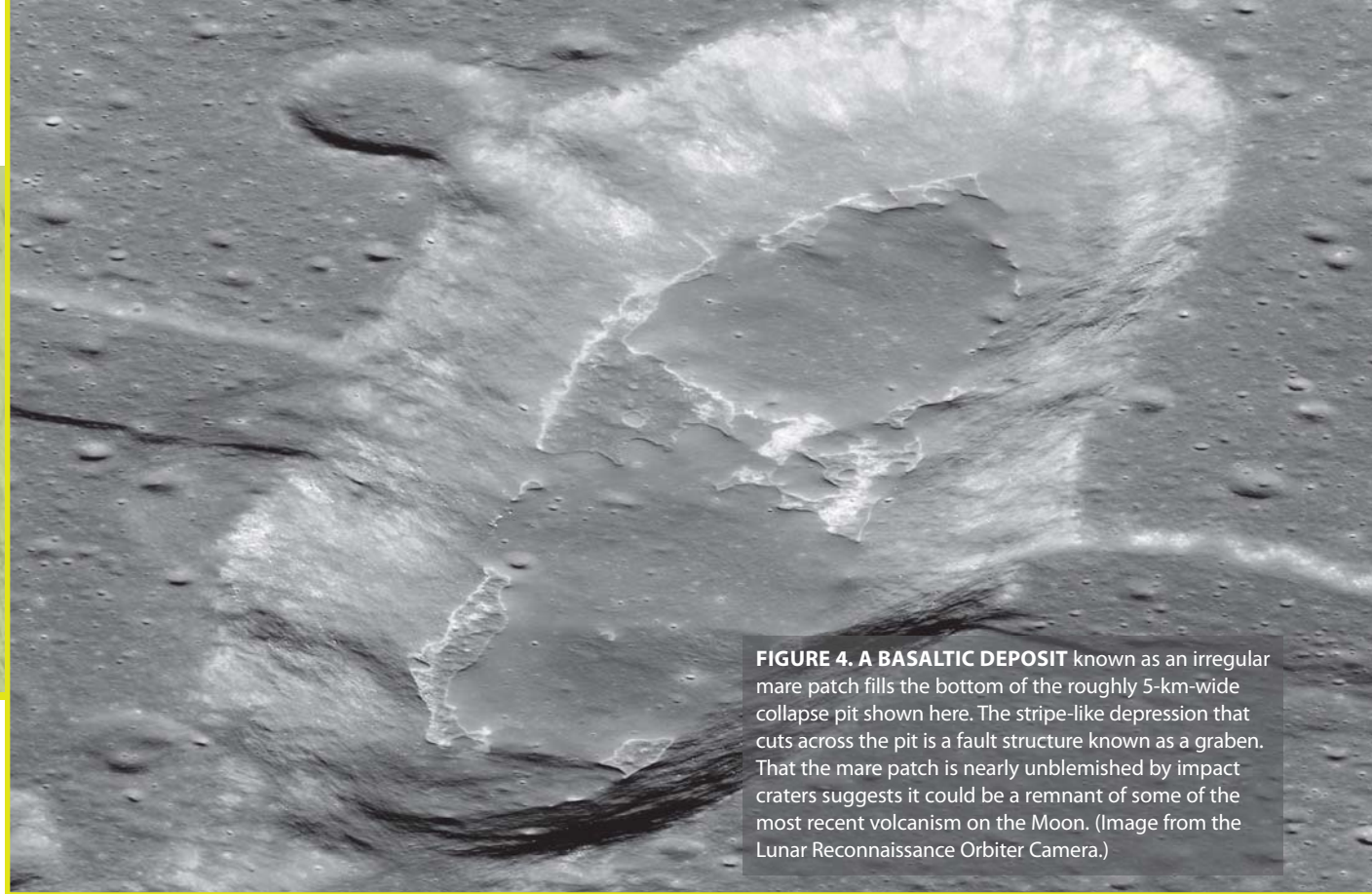


FIGURE 4. A BASALTIC DEPOSIT known as an irregular mare patch fills the bottom of the roughly 5-km-wide collapse pit shown here. The stripe-like depression that cuts across the pit is a fault structure known as a graben. That the mare patch is nearly unblemished by impact craters suggests it could be a remnant of some of the most recent volcanism on the Moon. (Image from the Lunar Reconnaissance Orbiter Camera.)

Lunar cooling is critical to another geologic process that has shaped the Moon's crust and yielded information about its interior: volcanism. Lunar volcanism was dominated by eruptions of basaltic lavas not unlike those that spill today from Earth's Hawaiian volcanoes and mid-ocean ridges. But because the Moon is smaller, it cooled faster and its eruptions largely ceased 1 billion to 2 billion years ago. (We don't know that number as precisely as we'd like.)

However, scattered across the nearside are small patches, between 100 m and 5 km across, with compositions and morphologies consistent with basaltic deposits. (See figure 4.) That those so-called irregular mare patches are largely unblemished by impact craters and have sharp, steep topographic boundaries suggests that they are very young; the steep slopes wouldn't have survived for long under the relentless rain of meteoroid impacts. The discovery raises the tantalizing prospect that the last dregs of lunar volcanism may have occurred within the past 100 million years, which is startlingly recent given what we know, or think we know, about the thermal history of the Moon.¹⁸ But irregular mare patches also contain a host of contradictions. They aren't as rocky as one would expect for such young features, and they have no directly analogous volcanic counterparts on Earth. Now that more than 70 of those patches have been discovered, new hypotheses for their formation continue to emerge. It will be fascinating to see how the story shakes out. Confirmation or refutation of the patches' proposed young ages will likely require a sample return mission.

What's next?

Although orbital missions clearly still have a critical role, the attendees of the Houston meeting vigorously agreed that surface exploration, both human and robotic, and sample return will be necessary to address the important open questions in

lunar science. The number and variety of exploration sites they proposed—easily more than 50 locations across the near and far sides—bespoke the community's excitement.

So how can we get back to the Moon? Lunar missions are likely to be proposed to NASA's Discovery Program, which funds low-cost missions that address high-priority science questions anywhere in the solar system (except the Sun and Earth). Six additional projects, including one to return samples from the Moon's largest and oldest impact event, the South Pole–Aitken basin, can be proposed to the agency's New Frontiers Program, which funds more complicated and costly missions that address specific gaps in scientific knowledge. There is no guarantee, however, that a lunar mission will be among the next round of proposals selected by Discovery and New Frontiers. And NASA currently has no dedicated exploration program for the Moon as it does for Mars.

Lunar science and human exploration enjoy a mutually beneficial relationship that dates back more than half a century. The early era of lunar exploration led in the late 1960s and early 1970s to the first geologic fieldwork conducted on another solar-system body. Lunar scientists still enthusiastically pore over that fieldwork's bounty, revisiting samples with new techniques and ideas and making new discoveries from old observations. Thirteen years ago US officials called for NASA astronauts to be back on the Moon to stay by 2020. But exploration is inextricably linked to politics, and rapidly shifting political priorities can thwart the long-term planning efforts necessary to realize a sustained program of exploration. Those efforts are even more complicated when multinational politics are involved and political "realities" are at play. For instance, US scientists are currently barred from using NASA funding for bilateral research projects with Chinese scientists. (See *PHYSICS TODAY*, December 2013, page 24.)

Nonetheless, the world is pressing forward with lunar exploration. South Korea, India, and Russia have plans for orbital and landed missions. In November 2017 China plans to launch *Chang'e 5*, the first lunar-sample return mission in four decades. The following year, *Chang'e 4* and its small rover will conduct the first landing on the far side of the Moon. The *Resource Prospector*, the only landed mission currently being formulated by NASA, is targeted to launch early in the 2020s.

The European Space Agency has proposed a "moon village" as a natural follow-up to the International Space Station. The international effort would use public and private partnerships to build a sustained human presence on the Moon, but so far it is more a concept than a plan. And then there are private projects, among them the Google Lunar X Prize, which will award \$20 million to the first team to land and move a robot at least 500 m on the surface of the Moon. Five teams now have launch contracts in place for 2017.

For now, the *LRO* is the only dedicated lunar mission that is still fully operating. Launched as part of NASA's Exploration Systems Mission Directorate (now the Human Exploration and Operations Mission Directorate) but currently run by the Science Mission Directorate, it is exemplary of the constructive interplay between science and exploration. Its current extended mission is funded through 2018, but it has the fuel to run for years beyond that. Hopefully it will still be circling the Moon as the next generation of missions arrives at the lunar surface to make new measurements, collect new samples, and further advance our quest to understand the history of the solar system.

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