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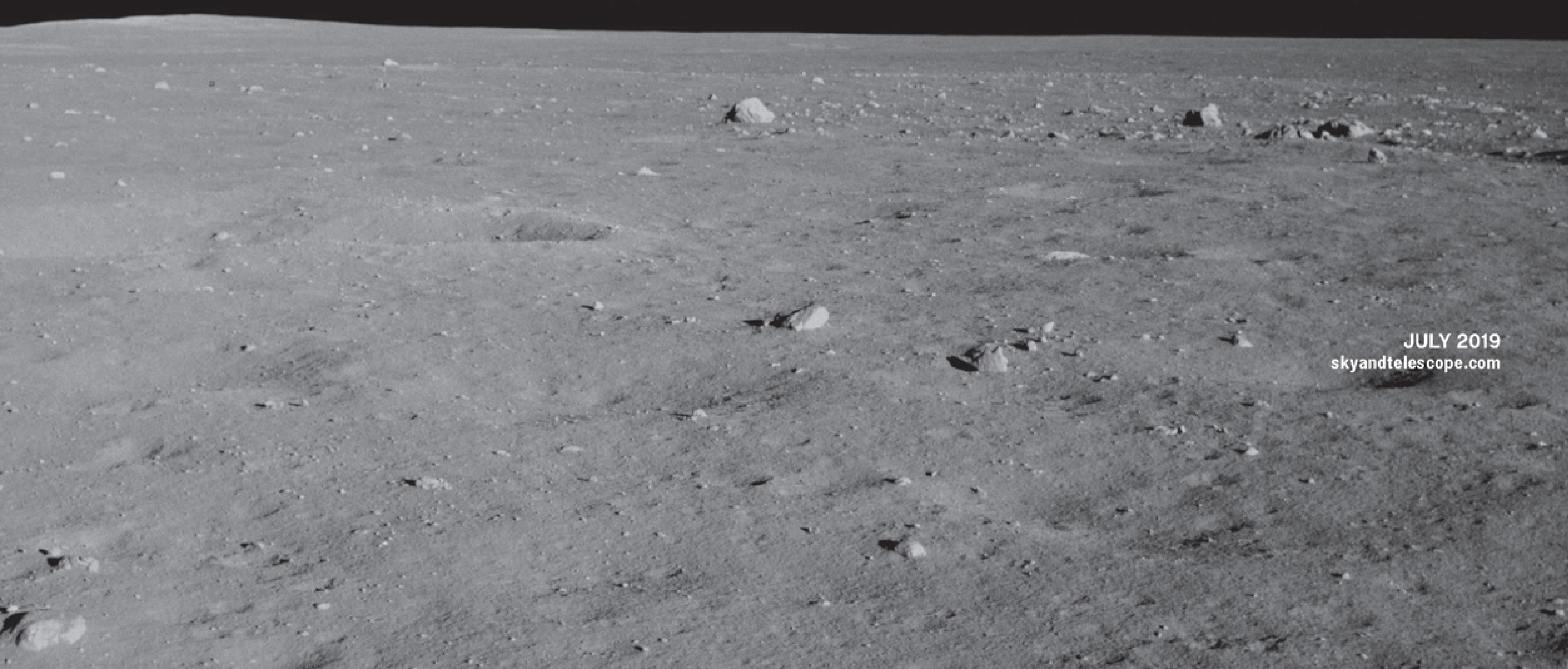
SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

SPECIAL ISSUE

THE Moon



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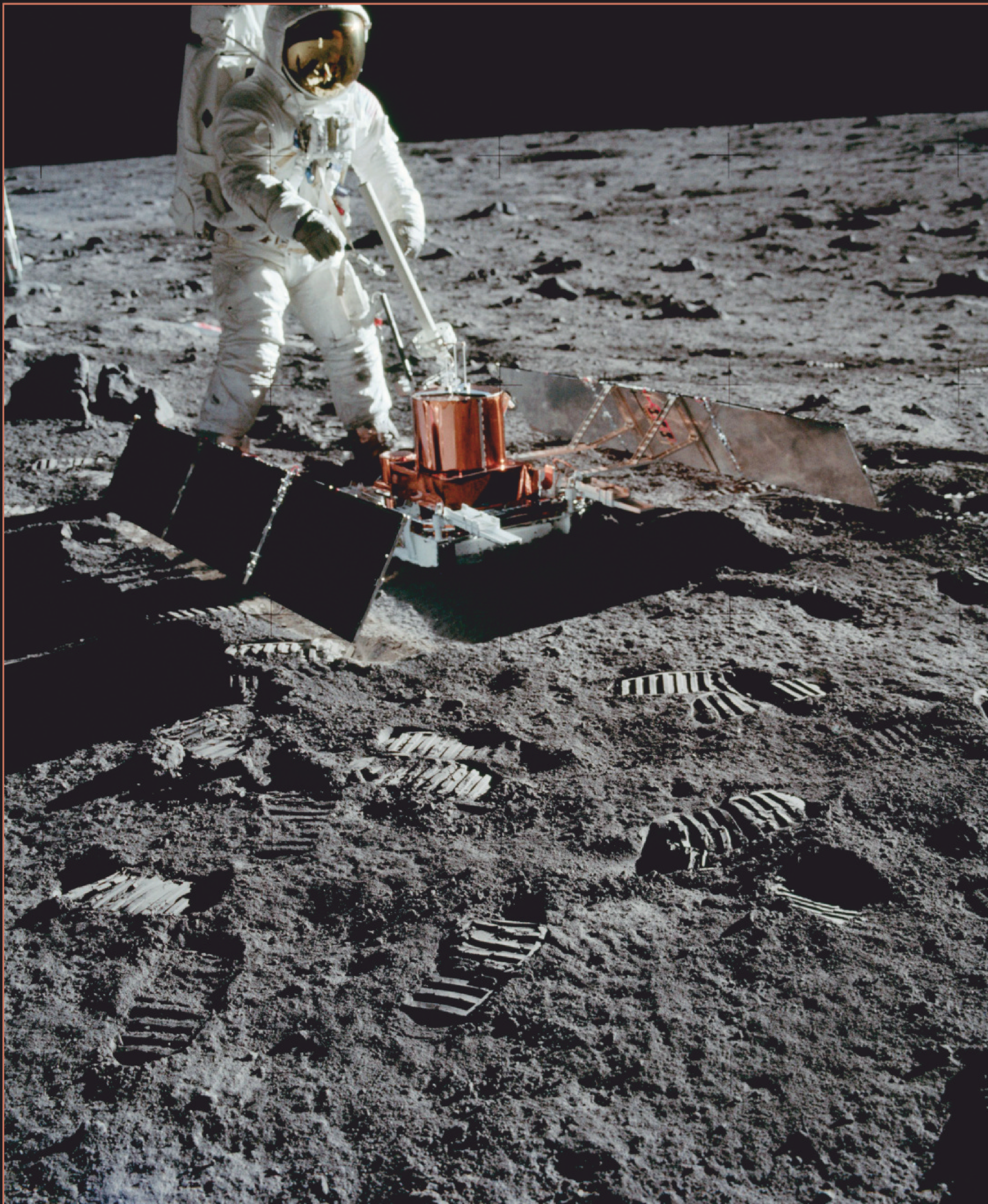
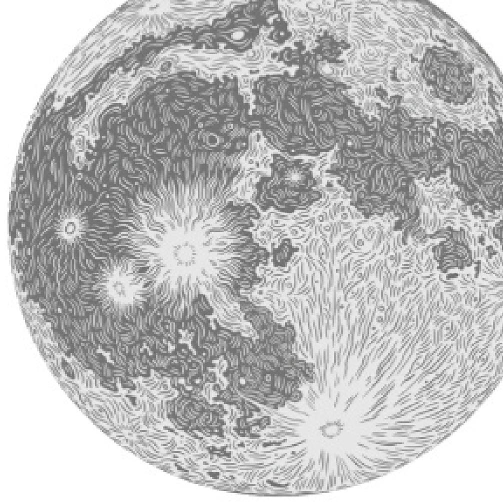


LUNAR SCIENCE Apollo 11 astronaut Buzz Aldrin sets up a seismometer on the Moon. The instrument worked for three weeks, detecting moonquakes and gathering information about the Moon's internal structure. Later missions' seismometers transmitted data until 1977.

NASA



The Science of APOLLO

Samples brought back by the astronauts revolutionized our picture of the Moon.

September 17, 1969, found me in one of many white buildings on the campus of NASA's Manned Spacecraft Center in Houston, Texas. I had been summoned there by a telegram. It had been nearly two months since astronauts first stepped onto the lunar surface, and while the world was still enchanted, NASA had called scientists to get to work on an often-underappreciated aspect of the Apollo missions: samples.

In response to President Kennedy's 1961 challenge to America to land a man on the Moon and return him safely to Earth by the end of the decade, NASA had designed and implemented an audacious and dangerous space program. The pinnacle of this program was the Apollo 11 mission, which on July 20th placed Neil Armstrong and Edwin (Buzz) Aldrin on the lava plain of Mare Tranquillitatis, near the lunar equator. They stayed there for 21 hours and 36 minutes, then returned to Earth — along with 22 kg (49 pounds) of Moon rocks and soil, more properly called *regolith*. ("Soil" is a misleading term to use for the loose, dusty impact debris that covers the Moon's surface, since it contains none of the humus and water that allow plants to grow in terrestrial soil.)

Those precious samples arrived at the Lunar Receiving Laboratory (LRL) in Houston on July 25th, where the curatorial staff evaluated and sorted them. Fifty-four days later, I came to pick up my 10-gram allocation — about the weight of a single AAA battery. To the untrained eye, the rocky debris didn't look like much. But thanks to those hard-won samples, our understanding of the Moon's history would never be the same.

Uniting the Team

Knowing in advance that it wanted scientists to study material collected on the Moon, NASA issued an invitation in the early 1960s to qualified individuals to submit proposals to be lunar sample investigators. About 140 principal investigators from around the world were chosen. Their projects included studying the chemical and isotopic compositions, the physical properties, and the mineralogy and petrography ("min-pet," the latter is the descriptive end of the rock-classification business) of the lunar materials.

I was approved as a min-pet principal investigator (PI). I am a hard-rock petrologist (Virginia Tech, MIT), which means I study igneous and metamorphic rocks instead of sedimentary ones. Once in college I overheard a business-school guy tell his girlfriend that soft-rock geologists work for oil companies and drive Cadillacs, while hard-rock geologists are lean and hungry. I liked that — it made me quietly proud of the choice I had made.

In graduate school I had focused my hard-rock passion on stony meteorites when I learned that they are the oldest rocks we can find, meaning they might contain information about the origin of Earth. Beginning in 1958, I spent my career (with a few diversions) at the Smithsonian Astrophysical Observatory (SAO) in Cambridge, Massachusetts. My boss in the Apollo era was Fred Whipple, the first director of the SAO, and he encouraged me to set up a meteorite laboratory.

At first I worked alone. But once accepted to the lunar sample program, I knew I needed help. I recruited two freshly minted petrology PhDs, John Dickey from Princeton and Ben Powell from Columbia, and I enlisted Ursula Marvin, a

▶ **THE TEAM** The author and his team stand in their laboratory at the Smithsonian Astrophysical Observatory. From left: the author, Ben Powell, Ursula Marvin, John Dickey, and Janice Bower.

TEAM: JOAN ELIZABETH DICKEY; PHOTO TEMPLATE: ROBINOLIMB / DIGITALVISION VECTORS / GETTY IMAGES; MOON SKETCH: LEAH TISCIONE / *S&T*

▲ **SIGN HERE PLEASE** Upon arrival in the Lunar Receiving Laboratory in Houston, scientists were met with a table of paperwork along with their samples.

◀ **HANDLE WITH CARE** The first Apollo 11 samples, safe in their protective packaging, arrive at NASA's Manned Spacecraft Center in Houston on July 25, 1969.

mineralogist and X-ray diffraction expert who was already at SAO. I also hired Janice Bower, a remarkably adept and adaptable graduate of Wentworth Institute of Technology, to operate and service the instrument critical to much of our work, called an *electron probe microanalyzer*. Electron probes reveal the chemical makeup of mineral samples by analyzing the X-rays created when the samples are bombarded by a beam of accelerated electrons in a vacuum. Together, we five would be the SAO lunar sample team.

Precious Vials

When I arrived in a windowless room at the Manned Spacecraft Center in Houston, I found several fellow PIs huddled around a table covered with sample vials and paperwork. Along with the NASA research grant each of us was awarded, the paperwork included much legalistic detail about my responsibility to safeguard my samples: They were not mine, I was only borrowing them from NASA. (I had already taken steps to have a small safe installed in my lab, bolted through its bottom to the concrete floor.)

At last I received two polyethylene cylinders, each about five inches tall, containing my group's lunar samples. Opening these, I found packing material and two much smaller plastic vials, labeled 10085,24 and 10084,108. The first contained 11 grams of coarse lunar fines, larger than 1 millimeter in size and mostly smaller than 2 mm. The second held 5 grams of "fine fines," particles smaller than 1 mm in diameter. The LRL curatorial staff had sieved the bulk soil sample collected by the astronauts into these fractions. With NASA's concerns about security fresh in my mind, I borrowed a needle and thread from one of the secretaries in the room and sewed both small vials into one pocket of my sports jacket for the trip home.

I boarded an Eastern Airlines flight to Boston with a stopover in Washington, D.C. In the plane I found a half dozen or so other scientist friends and acquaintances who were also flying home to Boston or D.C. with lunar samples they had picked up in Houston. We were all psyched and had much high-spirited conversation in the plane's aisle. We were probably obnoxiously loud. All this made me very warm, so I tore off my jacket and stuffed it in an overhead bin. Not until much later did I realize I had parted company with those two precious vials. Fortunately they survived, or this would be a very different story.

NASA's warnings about safety didn't forbid showing the samples (carefully) to the public, and I couldn't resist inviting my family, then our neighbors and their kids, to gaze up close at pieces of the Moon. The next day I displayed them in our lab for personnel at the Harvard Observatory and their families. Everyone was excited and curious, never mind the grains' nondescript gray appearance.

When my group was finally alone with our lunar samples, we examined them under a binocular microscope. To our surprise, we found that not all of our regolith samples were pulverized mineral dust, as I had pessimistically assumed. The coarse-fines sample (10085,24) consisted of miniature rocks, each with a distinctive texture and assemblage of minerals. We had hundreds of separate lunar samples in our tablespoonful! So we set to work to study as many of those rock-ettes as we could in the time we had. It wasn't much: NASA had decreed that on January 5, 1970, all of the lunar sample investigators were to convene at the Albert Thomas

SAMPLE ARRIVAL: NASA; PI HUDDLE: THE AUTHOR

Convention Center in Houston, Texas, and present the results of their studies. Counting from when I picked up our vials, that gave us just 110 days.

Petrographers study rocks in thin sections, slices about 30 micrometers thick (a human hair is about that diameter) on glass microscope slides. These rock slivers are created by a rather tedious process of diamond sawing, grinding, and polishing on the surfaces of spinning laps. NASA would make thin sections and send them to us, but these would be few and long in coming. So we prepared our laboratory to make our own. Soon our lab was a beehive of activity as we sectioned, photographed, and analyzed 1,676 coarse-fine particles in batches on slides for our electron microprobe.

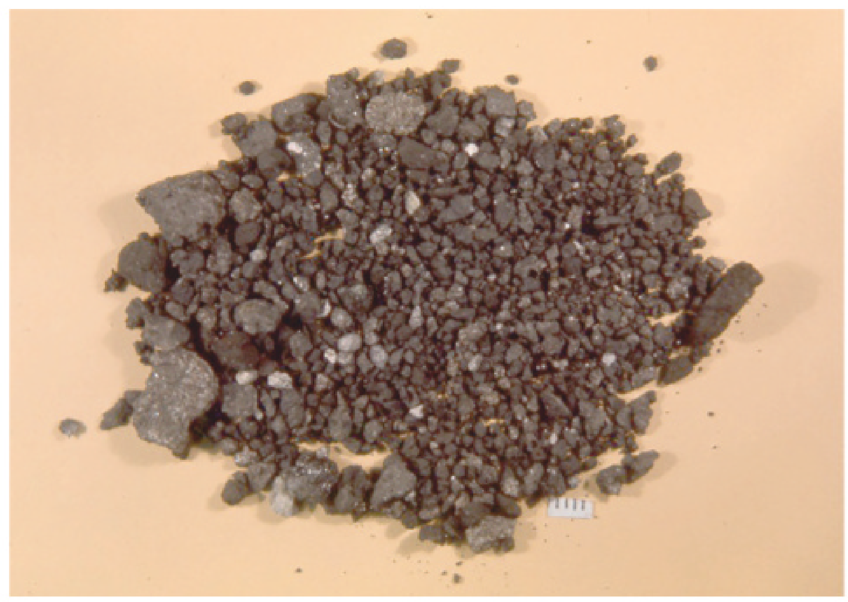
The Discovery

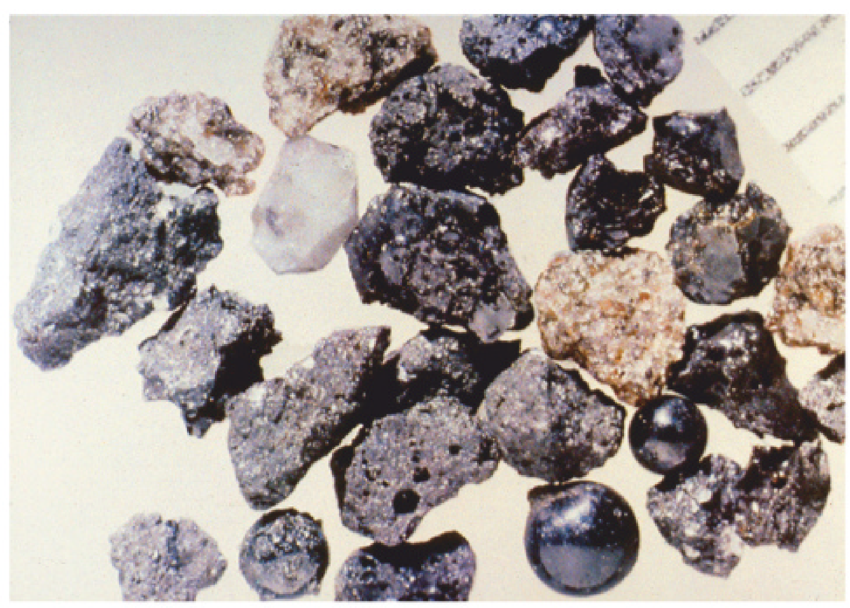
As data accumulated, it became clear what the Mare Tranquillitatis regolith consists of. About half of our fragments were *soil breccias*, volumes of fine lunar dust that impacts had crammed together and lithified into rock. Since impacts also create the regolith itself, you could say that destructive impacts giveth lunar soil and they taketh it away by consolidating it into breccia (an Italian word meaning broken).

About 5% of the remaining particles were *glasses*, volumes of rock or soil that had been melted by the energy of impacts and then had cooled rapidly in the near-vacuum conditions on the lunar surface. The amount of impact-melted glass in the Apollo samples surprised everyone.

Another 40% of the regolith was particles of *crystalline igneous rocks*, solidified directly from lava. Scientists had long known that the lunar maria must be lava plains, and you might expect that, as representatives of the solidified lava that lies beneath Tranquility Base, the rocks brought back to Earth would all have fairly similar compositions. But that was not to be the case. Debris from a cratering impact can travel great distances before it comes to rest on the surface, and so particles at any one point have come from many far-flung sources. Most of the igneous particles in our samples consisted of hardened basaltic lava, but there were many varieties, differing in chemistry and texture.

However, another 3–4% of the particles were something quite different and unexpected: a white type of once-molten rock called *anorthosite*. Anorthositic rocks consist principally of the mineral anorthite ($CaAl_2Si_2O_8$). They are rare on Earth; an important deposit lies in the Adirondack Mountains of New York. John Dickey, reading the microprobe analysis of a colorless glass droplet in our collection, was the first to say the word out loud: "That's an anorthosite composition." No one had predicted that the Moon would contain a rock type so rich in aluminum and calcium as anorthosite.



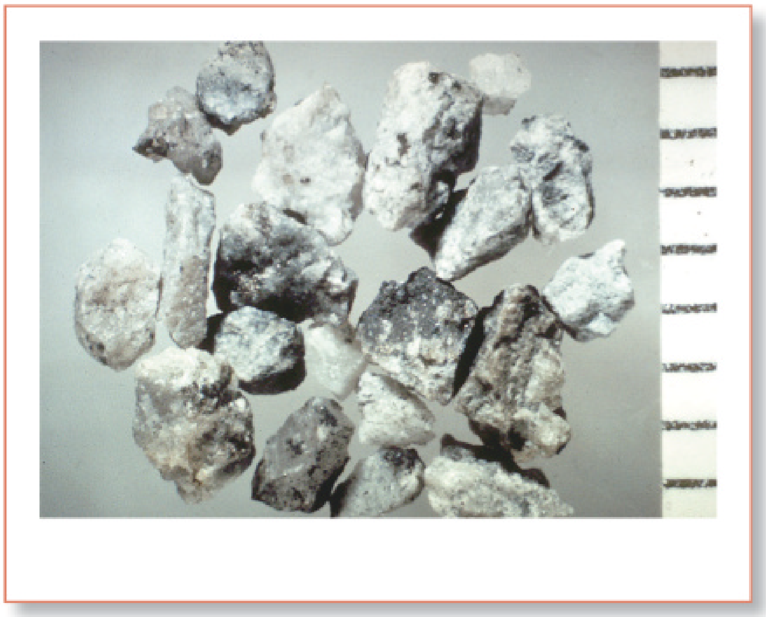


▶ **SMALL BUT PRICELESS** *Top:* The author's two capsules (front-most) sit with a collection of other Apollo 11 samples in Houston. *Center:* The team's coarse-fine grains. *Bottom:* A close-up of some washed and sorted particles. The scale lines in both grain images are in millimeters.

THE AUTHOR (3)

Why Anorthosite on the Moon?

This find puzzled us. It is not enough for scientists to describe things; the whole point is to understand them. First, where had the light-colored anorthositic particles come from? That question was not so hard to answer. The Apollo lander *Eagle* had set down on the edge of the dark, basalt-filled Mare Tranquillitatis, only about 50 km from the beginning of the whiter lunar highlands, called terrae. Impacts on the terra regolith surely would have scattered some of it over into the mare regolith. This must have been the source of the anorthositic fragments in our sample.



▲ **SURPRISE DISCOVERY** Pieces of the white igneous rock anorthosite puzzled the team when discovered in the samples. Scale is in millimeters.

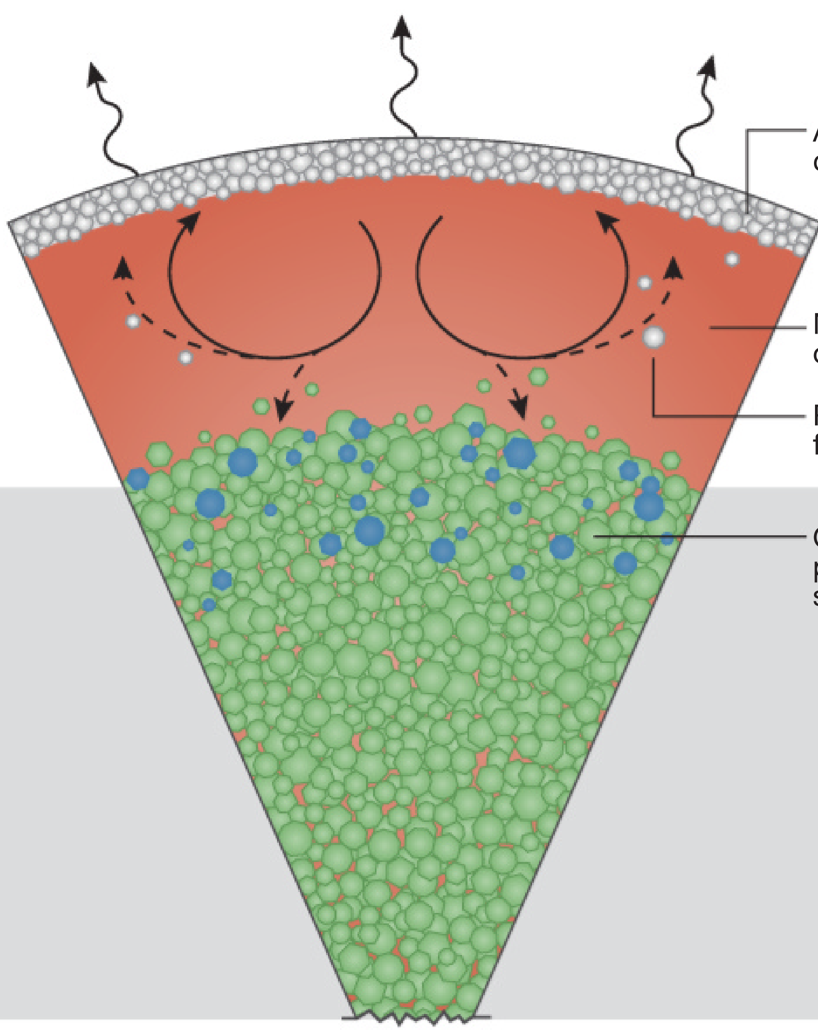
Second, did this unexpected composition hold for all of the terra rock that covers most of the Moon, or just that corner of it? Terrae make up more than 80% of the lunar surface, counting both the near- and farside hemispheres; if all that rock is anorthositic, then it must comprise a significant fraction of our planet's natural satellite.

An earlier robotic mission to the Moon, Surveyor 7, appeared to hold the answer to that question. Surveyor 7 carried a device called an *alpha-scattering surface analyzer*, which measured the chemical composition of the ejecta blanket surrounding the large crater Tycho, whose dramatic rays splay across the face of the Moon. Tycho is in lunar highlands material 1,600 km from Tranquility Base. Although ambiguities in the instrument's data (in particular the device's inability to distinguish between calcium and potassium) had left the analysis somewhat unsatisfying, the result was consistent with an anorthositic composition there, too.

Generalizing boldly, a highly reflective, anorthosite-rich crustal layer seems to cover the whole Moon like a thick veneer, except where giant impactors have blasted holes through it that later filled with basaltic lava.

Can we estimate the thickness of this layer? Yes, using the principle of *isostasy*. Rock has plastic properties over long periods of time, meaning a heavy load on the crust will push rock below it aside, making room for the load to sink. Because of isostasy, a mountain range can stand only if the mountains are less dense than the rock beneath them, so they can "float" in it like enormous rocky icebergs. The lunar crust, with a density of only 2.9 g/cm^3, floats 3 km above the denser interior material (the Moon's overall density is 3.3 g/cm^3). That elevation would only be possible if the crustal thickness is about 25 km. A lot of anorthosite!

Third, where did this layer of rare anorthite-rich rock come from? It must have solidified out of a huge amount of cooling magma. The experimentally determined crystallization sequence for molten rock with a lunar composition predicts a specific order of mineral formation: Olivine crystallizes first, then pyroxenes and calcic feldspar (anorthite), then feldspar richer in sodium. Olivine is dense, and it would tend to sink to the floor of a magma layer during crystallization. Anorthite is lighter, and under some circum-



▶ **FORMING THE LUNAR CRUST** If the Moon began largely (or completely) molten, then as it cooled its constituent minerals would separate. Dense olivine and pyroxene would sink in the magma. Then feldspar minerals, which include anorthosite, would crystallize. Feldspars would float in the denser magma, and so they would rise to the magma ocean's surface, where they would form a crust like that found by the Apollo astronauts.

stances it would tend to float rather than sink, accumulating at the top of the body of magma like a thick rock froth. This seems to be the only possible explanation for the Moon's anorthositic crust.

How much magma would it take to form the lunar crust this way? Assuming a plausible bulk chemical composition for the Moon, it turns out that most or all of the Moon must have melted in order for 25 km of anorthite crystals to float to the top! I coined the term *magma ocean* to describe this huge molten mass, and the term stuck.

Rewriting Lunar History

I persuaded my group that this anorthosite story was what I (as our principal investigator) should stress in my talk at the impending Apollo 11 Lunar Science Conference.

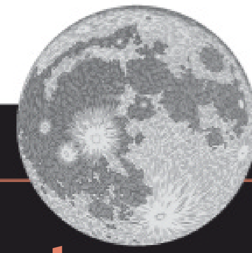
The conference was a colorful experience. It began with a cocktail party at Rice University. NASA had told us that we should not release our findings to the public; we should save them instead for a special issue of *Science* magazine that was to be dedicated to the first lunar-sample reports. Most of us took that to mean we should not even spill the beans to other research groups — though this was not NASA's intent — so the party was an amusing cat-and-mouse game in which most of us were trying to find out what our colleagues had learned without revealing our own discoveries.

The first two days of the conference featured results from the elite research groups (ours was a no-name team in comparison). Jerry Wasserburg's self-styled "Lunatic Asylum" at Caltech, for example, used the ratio of two strontium isotopes to determine that the basaltic mare was 3.65 billion years old, about a billion years younger than the solar system.

At a banquet on the second evening of the conference, astrophysicist Fred Hoyle spoke on whether someday we might realize that Apollo's most important contribution was not the political victory it represented but the majestic view the astronauts gave us of the whole pale blue Earth in the firmament. He compared the situation to one from the composer Handel's time, and his words so struck me that I wrote them down:

> *Our judgment of what were the significant issues in past times differs tremendously from contemporary judgment. In the middle of the 18th century, the English celebrated victory at the end of a seven-year European war. Someone had the idea of getting George Frideric Handel, who was then an old man, to write a suite of music to celebrate the famous victory. An astute commentator, two centuries later, remarked that the whole meaning and purpose of this seven-year war had now been lost, and that in retrospect it appeared like an elaborate device to get old man Handel out of retirement and to get him to write his* Music for the Royal Fireworks.

Perhaps, Hoyle thought, future generations would forget the Apollo program's political achievements and instead remember a greater success: that the Apollo astronauts' view



Grains from the Past

Investigators' tests indicated that basaltic rocks collected by Apollo 11 astronauts had an age of more than 3½ billion years; the crust was about a billion years older. Samples brought back in November 1969 by the Apollo 12 team, on the other hand, were about 500 million years younger. These rocks all formed at extremely high temperatures. The findings suggested that, in the words of a *New York Times* report from the conference, "the moon had a history of fiery, cataclysmic upheavals."

▼ **APOLLO 11 VIEW OF THE MOON** The Apollo 11 crew took this photo while homeward-bound, some 19,000 km (10,000 nautical miles) from the Moon. This picture should look a little abnormal: It catches some of the lunar farside's highlands (right), unseen from Earth. Mare Crisium lies at center; Mare Tranquillitatis, where the team landed, is the lunar sea directly to Crisium's left.

SAMPLES: THE AUTHOR; DIAGRAM: GREGG DINDERMAN / *S&T*, MOON PHOTO: NASA; MOON SKETCH: LEAH TISCIONE / *S&T*

▲ **THE CONFERENCE** Attendees collect materials *(left)* and people study samples *(right)* at the Apollo 11 Lunar Science Conference in Houston. The meeting was the first of what would become the annual Lunar and Planetary Science Conference, which meets every spring in The Woodlands, Texas.

brought home Earth's fragility to its inhabitants and inspired them to take better care of their home.

If only.

My presentation for the SAO group came at 5:20 p.m. Wednesday afternoon — the last talk of the day, when everyone was tired and looking forward to dinner. But the anorthositic-crust story interested people, and no one else had told it. Several groups had noticed and described the anorthositic particles in their own samples, but none had pursued their meaning. Other min-pet groups tended to focus on the larger rocks, fragments of the titanium-rich basaltic lava that filled Mare Tranquillitatis. Still, everybody's reports painted a picture of a molten history for the Moon.

This consensus would soon answer a burning question the media had been asking us: Did the Moon form hot or cold? There was no way of knowing prior to Apollo 11. The betting had been on a "cold" Moon — one that slowly accreted alongside Earth, or perhaps was caught gravitationally — because that was the opinion of chemist Harold Urey, a highly respected Nobel laureate. In order to distance himself from his earlier work on the atomic bomb, Urey had interested himself in the chemistry of the solar system. On the basis of much hard thinking but little observational evidence, he formulated a model to account for the solar system. In this model, small *primary objects* formed in dusty gas and then were caught in the cloud that collapsed to form the Sun and planets. In this model, the Moon is a surviving primary object that Earth captured into orbit.

The Apollo 11 evidence of a once-molten Moon laid this concept to rest. Our picture, with the anorthite floating to the surface during the crystallization of a magma ocean, could not be reconciled with it. And ultimately, it was our magma ocean scenario that itself rose to the top. Within a few years, scientists realized that the Moon was likely instead created by a giant planetary collision, in which a Mars-size body spalled off a disk of molten debris from the early Earth, with our planet and its orbiting satellite coalescing from the debris (*S&T:* Aug. 2018, p. 26). Such a process easily could have been energetic enough to account for the initial molten state of the Moon.

It is gratifying that our analysis of just a few rocky chips changed forever our view of Earth's companion. Often when we reflect on Apollo 11's importance, we focus on the political, cultural, and historical sectors. Of course, these are important. But doubtless one of the program's greatest impacts was the revolution it brought to lunar science.

▶ **BIG NEWS** A young girl holds the July 21, 1969, issue of *The Washington Post* in this photo taken by her father and posted decades later online by her son.

■ Retired planetary scientist **JOHN A. WOOD** has studied meteorites, lunar samples, and Venus to understand the solar system's origins. Since 2004 he has turned his talents to oil painting.

WEBLINK: Listen to the Apollo 11 mission recordings at **https://archive.org/details/Apollo11Audio**.

CONFERENCE: LUNAR AND PLANETARY INSTITUTE (2); GIRL WITH PAPER: RUFUS330CI / WIKIMEDIA COMMONS / PUBLIC DOMAIN

EARTHRISE The Apollo 11 astronauts took this photo of our home planet early on July 20th (Universal Time) as they came around the limb of the Moon, before the landing. The lunar terrain is the region near Mare Smythii.

NASA