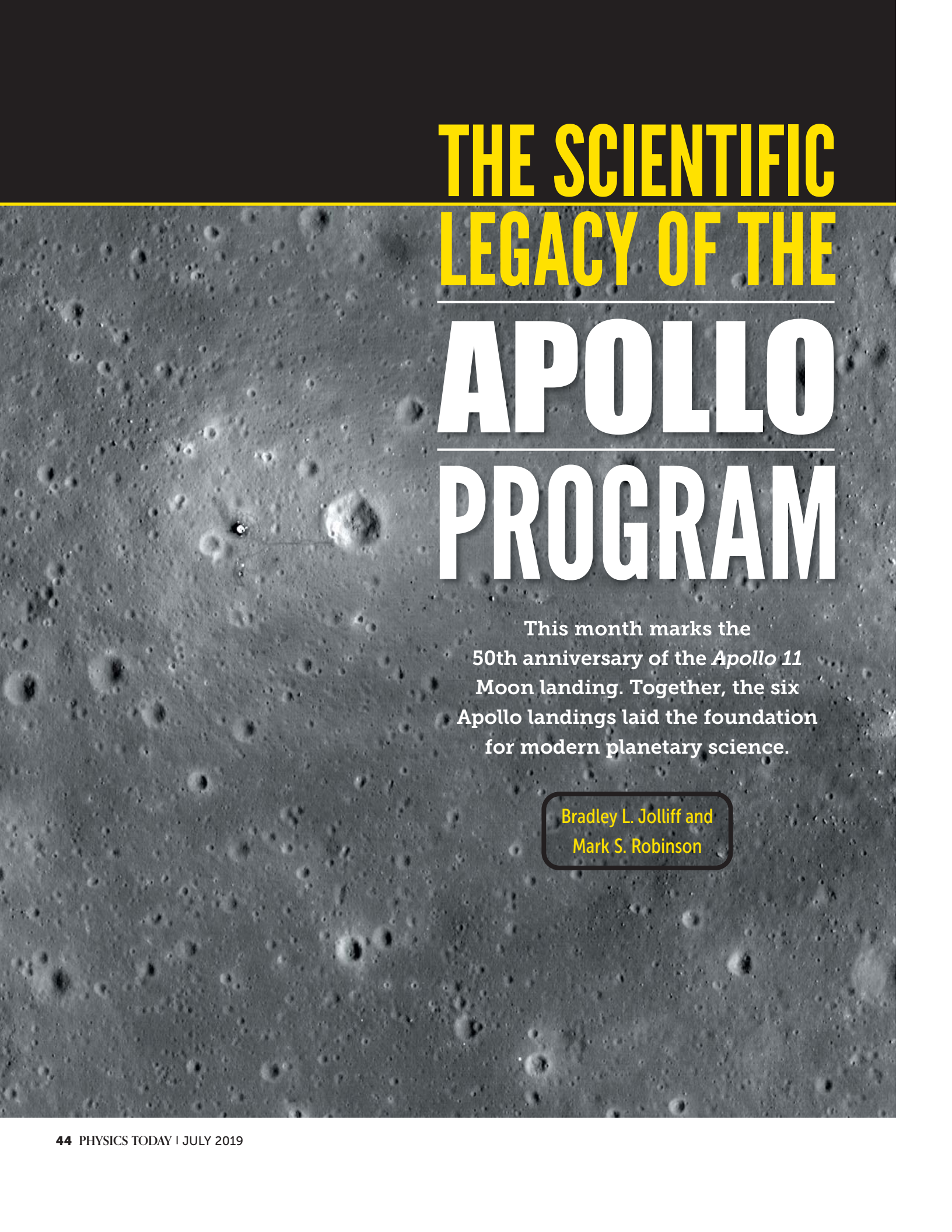




THE SCIENTIFIC LEGACY OF THE APOLLO PROGRAM

This month marks the
50th anniversary of the *Apollo 11*
Moon landing. Together, the six
Apollo landings laid the foundation
for modern planetary science.

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On 20 July 1969, *Apollo 11* astronauts Neil Armstrong and Edwin “Buzz” Aldrin landed on the Moon while Michael Collins orbited in the command module *Columbia*. “Tranquility Base here. The *Eagle* has landed” became one of the most iconic statements of the Apollo experience and set the stage for five additional Apollo landings.

Each of the Apollo missions explored carefully selected landing sites and conducted a variety of experiments to probe the lunar interior and measure the solar wind. Well-trained astronauts made geologic observations and collected samples of rock and regolith, the impact-generated layer of debris that composes the lunar surface. Over a half century of study, the samples have revealed abundant information not only about the Moon’s origin and history but also about the workings of our solar system.

Apollo 11

Results from the *Apollo 11* mission established key paradigms of lunar and planetary science. After a harrowing descent to the surface, Armstrong set the *Eagle* down on the cratered basaltic plains of *Mare Tranquillitatis*. Extravehicular activity was brief—just two and a half hours during that first mission—and included setting up surface experiments and exploring a small cluster of craters near the lunar module and Little West Crater some 60 meters away, as shown in figure 1. Aldrin’s iconic *Apollo 11* footprint photo revealed much about the lunar soil, including its fine-grained nature, its cohesiveness, and its ability to pack tightly together.

The Early Apollo Scientific Experiment Package contained, among other instruments, a passive seismometer and a laser-ranging retroreflector. Although designed to work for only three weeks, the seismometer provided a first key look at lunar seismic data. The seismometers brought to the Moon during the *Apollo 12*, *14*, *15*, and *16* missions were used as a larger network

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to probe the interior structure and measure thousands of moon-quakes that would eventually be detected.

The retroreflector on *Apollo 11* was the first of five eventually delivered to the Moon. Active laser ranging still precisely measures the Moon's distance as it slowly recedes from Earth. Some 22 kg of samples were collected during that mission. (Collectively, the missions returned a total of 382 kg of material, and the last, *Apollo 17*, carried 111 kg.) The regolith, used as filler in the rock box, was separated from the rocks back on Earth and analyzed for its contents. The fine-grained particles, labeled 10084 and known as "Armstrong's packing soil," may be the most studied geologic sample in history.

The rocks turned out to be largely basalt—volcanic rock formed by partial melting in a planet's (or moon's) interior. They contained higher concentrations of titanium than any basalts on Earth but were otherwise made of familiar minerals, primarily the Mg-Fe-Ca silicate mineral pyroxene, the Ca-Al silicate mineral plagioclase, and the Fe-Ti oxide ilmenite.

Radiometric dating found the basalts to be more than 3.5 billion years old, and isotopic relationships between rock and regolith materials suggested that the Moon itself is ancient, having formed earlier than 4.4 billion years ago.¹ Although the volcanic rocks contain vesicles, indicative of gas release upon eruption, they lack evidence of any other alteration and are nearly devoid of water, carbon dioxide, and other volatiles. (See the Quick Study by Lindy Elkins-Tanton, *PHYSICS TODAY*, March 2011, page 74.) Lunar rocks are also completely barren of any signs of life.

The regolith samples proved invaluable in the rich variety of materials contained within them (see, for example, figure 2). Meteor and asteroid impacts, pervasive in lunar history, ejected bits of rock tens to hundreds of kilometers in all directions. Volcanic glasses, impact glasses, and breccias—rock fragments that became mixed during those impacts—were all part of the regolith. So were agglutinates, a new type of welded soil particle produced by micrometeorite impacts in the regolith. Mixed in with that local material were small fragments of plagioclase-rich rock (anorthosite) from the distant highlands.

In 1970 geologist John Wood and others inferred that anorthosite crystals floated toward the surface of a magma ocean, where they accumulated to form a plagioclase-rich crust.² Denser minerals such as pyroxene and olivine, by contrast, sank to form the lunar mantle. The Moon thus formed hot and underwent differentiation early in its history. (See *PHYSICS TODAY*, February 2008, page 16, and the article by Dave Stevenson, November 2014, page 32.) That early history was unraveled from only a handful of small rock fragments found in the regolith.

Building on success

Apollo 12 followed quickly in November 1969. The lunar module *Intrepid* executed a pinpoint landing within walking distance of the pre-*Apollo Surveyor 3* spacecraft. The landing site

afforded the possibility of sampling not only local rocks and regolith but also materials ejected from Copernicus Crater, 350 km away. Part of *Apollo 12*'s payload included a seismometer, magnetometer, solar-wind spectrometer, and ion and dust detectors—all powered by a radioisotope thermoelectric generator. In addition to taking hardware from *Surveyor 3* for the trip back to Earth, the astronauts explored several craters and collected material excavated from different depths to establish a stratigraphy of the subsurface.

Besides several types of basalts, the astronauts sampled rocks that were likely part of a spoke-like ray of material ejected from Copernicus Crater. Among the materials were ropy glasses and nonbasaltic rocks, which offered evidence that the crater had formed 800 million years ago.³ The inferred age of Copernicus Crater and subsequent dating of other impact craters and volcanic surfaces became the foundation for lunar chronology. The ground-truth data allow us to relate the size

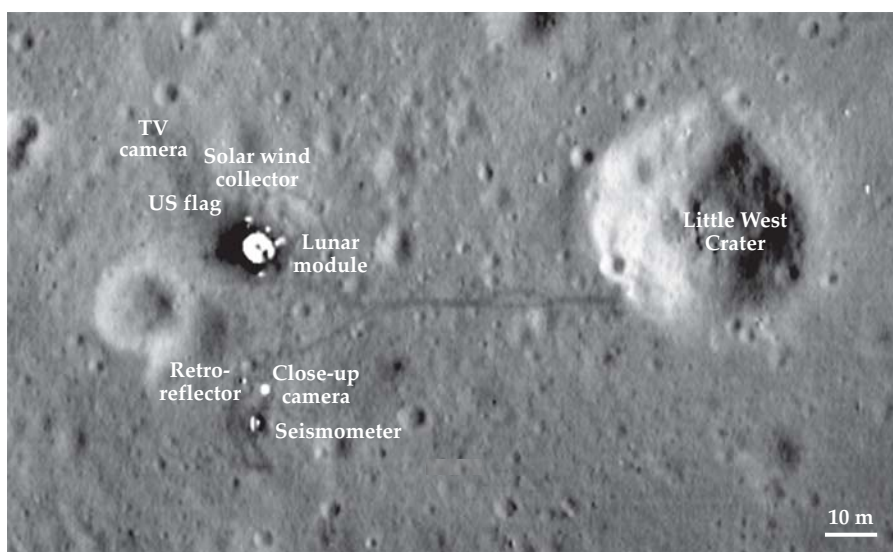


FIGURE 1. THE APOLLO 11 LANDING SITE shows locations where a US flag, television camera, and surface experiments were placed by astronauts Neil Armstrong and Edwin "Buzz" Aldrin. As they placed instruments and walked around the landing site, the disturbed soil left a visible path. (Image courtesy of NASA/GSFC/ASU.)

and frequency of impact craters per unit area to the age of the surface under study (see figure 3). And that relationship forms the basis for the relative chronologies of impact and volcanic events on the solar system's other rocky planets—Mercury, Venus, and Mars.⁴

The *Apollo 12* samples proved remarkably diverse. The material known as KREEP—rich in potassium, rare-earth elements, and phosphorus—was found in impact-melt rocks and rare granites. Several types of basalt, distinct from those found at the *Apollo 11* landing site, came from the underlying sequence of lava flows.

The *Apollo 14* lunar module *Antares* was the first to land on terrain that differed from flat volcanic plains. Analysis of orbital photos of the location, known as the Fra Mauro formation, indicates that the rocks there came from the enormous Imbrium basin-forming impact event, which occurred more than 600 km to the north. Fra Mauro breccias were determined to have

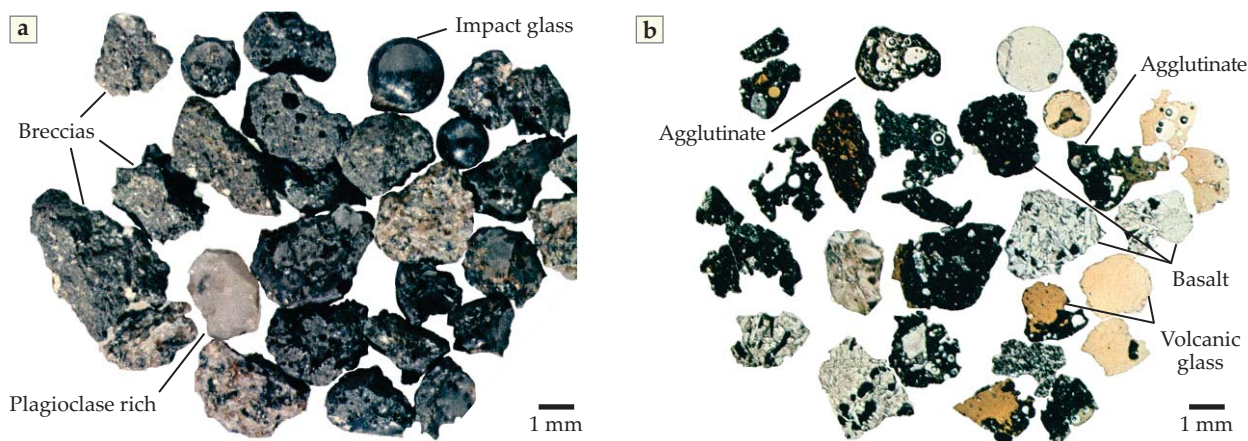


FIGURE 2. SOIL PARTICLES FOUND IN THE MOON'S SURFACE DEBRIS, or regolith, during the *Apollo 11* mission. **(a)** Shown here are rock fragments (impact breccias); volcanic and impact glasses; fused particles (agglutinates); a light-colored, plagioclase-rich fragment; and pieces of volcanic basalt. **(b)** The same rock particles are sliced optically thin for study by transmitted-light microscopy. (Images are from John Wood, Smithsonian Astrophysical Observatory.)

formed about 3.9 billion years ago. Because Imbrium is known from relative stratigraphy to be one of the youngest of the impact basins, almost all the other basins must have formed before that time. Excavated from deep in the lunar crust, the Imbrium rocks are rich in KREEP.⁵ Exposure ages of samples ejected from the nearby Cone Crater revealed the crater to be 50 million years old, providing another key datum in lunar chronology.⁶

Apollo 15 and 16

Launched in the summer of 1971, *Apollo 15* was the first of the so-called J missions, which included the first lunar rover and longer extravehicular activity—nearly 19 hours on the lunar surface—during which astronauts collected some 77 kg of samples and explored more complex geology. The lunar module *Falcon* landed on another flat mare deposit close to the spectacular Apennine mountains. Some peaks rise up to 4000 m above the landing site and are part of the rim of the Imbrium basin. A key mission goal was for the astronauts to traverse the base of Mons Hadley Delta, one of the Apennine peaks, to search for ancient crustal material brought up from the depths when the basin was formed.

One of the most remarkable finds was a clod of green pyroclastic glass beads, which represented material from deep in the mantle brought up rapidly, without crystallizing, to the surface during the eruption of a massive fire fountain. Perhaps the most famous of the samples whose collection was enabled by the rover was “Seatbelt Rock,” a highly vesicular basalt shown in figure 4 and discovered by mission commander David Scott. Knowing that the astronauts were short on time and that mission control would not approve a stop to collect the rock, Scott used the excuse of stopping to fasten his seatbelt—hence the name—during which he quickly picked it up.⁷

Trained to look for coarsely crystalline rocks that might represent deep crustal material, Scott and others recognized the importance of yet another sample, “Genesis Rock,” by its light color and coarse, reflective crystal facets. The rock proved to be anorthosite, considered a plagioclase flotation cumulate of the magma ocean and thus a pristine sample of lunar crust. Iso-

topic analyses confirmed that the rock is indeed ancient—more than 4 billion years old. But analyses also revealed a complex thermal and shock history that obscures when it actually formed. Collection and documentation of the rocks in their geologic contexts, along with precise locations and descriptions by the astronauts, enabled the construction of exquisitely detailed maps and cross sections of the landing sites.⁸

Another advance with the J missions was addition of the Scientific Instrument Module (SIM) on the *Endeavor*. It enabled systematic orbital remote sensing using panoramic and mapping cameras; x-ray and gamma-ray spectrometers, which determined elemental compositions; and a laser altimeter for topography. SIM bay observations by the *Apollo 15*, *16*, and *17* missions provided an approximately equatorial swath of data for the lunar surface that researchers used to extrapolate from “Apollo-zone” areas to the entire Moon. The J-mission orbital observations had to last the scientific community until the 1990s, when the *Clementine* and *Lunar Prospector* spacecraft acquired global remote sensing.

Apollo 16 was the only mission that explored lunar highlands far from the maria. The lunar module *Orion* gently landed near mountainous terrain known as the Descartes highlands. The main scientific goal was to investigate the origin of the Cayley plains, a region adjacent to those highlands and thought, prior to the mission, to have formed from silica-rich rocks and ash deposits. The Cayley plains actually overlap the mountainous Descartes formation and are thus younger. From orbital photography, geologists interpreted the Descartes formation as ejecta from the ancient Nectaris basin, whose rim is less than 300 km away.

Apollo 16 astronauts took advantage of the sampling opportunities afforded by two impact craters, North Ray and South Ray, by landing between them. Using the rover, they sampled ejecta from both to determine their ages—yet more data points for the lunar chronology. The relatively smooth Cayley plains were shown to have formed as an impact-related deposit, most likely by material ejected from Imbrium. Among the rocks ejected from North Ray and South Ray Craters were impact-melt, fragmental, and regolith breccias. The latter, composed

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of lithified regolith, were significant because they provide a time-stamped snapshot of the output of the Sun via trapped solar-wind gases at the time the regolith breccias formed.

The largest Apollo sample ever returned was a 12 kg breccia nicknamed “Big Muley,” after Bill Muehlberger, who led the *Apollo 16* and *17* field geology teams. The side of the rock that faced up on the lunar surface is dotted with an abundance of pits from its exposure to micrometeorites. An important legacy of the Apollo missions is the superb training that was incorporated into the program. That training allowed the astronauts to work directly with scientists at mission control to optimize the fieldwork. The approach culminated with the inclusion on *Apollo 17* of a geologist astronaut, Harrison Schmitt.

Peaks and valleys

Apollo 17 landed in the beautiful Taurus–Littrow Valley, completing the Apollo program in December 1972. The lunar module *Challenger* placed the astronauts in a geologically complex area on the edge of the Serenitatis basin. The valley itself is defined by peaks, shown in figure 5, that tower 2500 meters above the basalt-flooded floor. Mission objectives included ascertaining the age of the basin, determining the age and composition of the basalts, and collecting pieces of ancient crust excavated during the basin’s formation.

Mission planners had identified a large, regional pyroclastic ash deposit in orbital images and wanted to find and sample some of that material. A cluster of secondary impact craters, aligned along a ray from the 2400-km-distant Tycho Crater, was seen in the valley along with a light mantle deposit, formed by avalanche, at the base of South Massif. Scientists hypothesized that the craters and the mantle deposit formed as ejecta from Tycho Crater struck the area. Astronauts sampled the light mantle deposit for researchers to determine Tycho’s age, as had been done for Copernicus Crater during the *Apollo 12* mission.

Additionally, Schmitt discovered a deposit of orange glass beads as an exposed layer in the rim of Shorty Crater. That material was pyroclastic as well. The color was related to their high Ti content, quite different from the very low Ti of the *Apollo 15* green glasses. Like the green glass, however, the orange-glass soil became one of the most important of the Apollo samples, oft sought for study because it represents one of the most pristine samples of the lunar interior, unmodified by crystallization processes.

Basalts of the Taurus–Littrow Valley formed 3.7–3.8 billion years ago. Impact-melt breccias were sampled from boulders at the base of North and South Massifs, their ages just a few tens of millions of years older than the breccias from Imbrium. Because of the considerably more advanced degradation of Serenitatis basin, it was apparent that many impact basins had formed in that time interval, amounting to a cataclysmic bombardment as also suggested by lead-isotopic analyses.⁹ Sam-

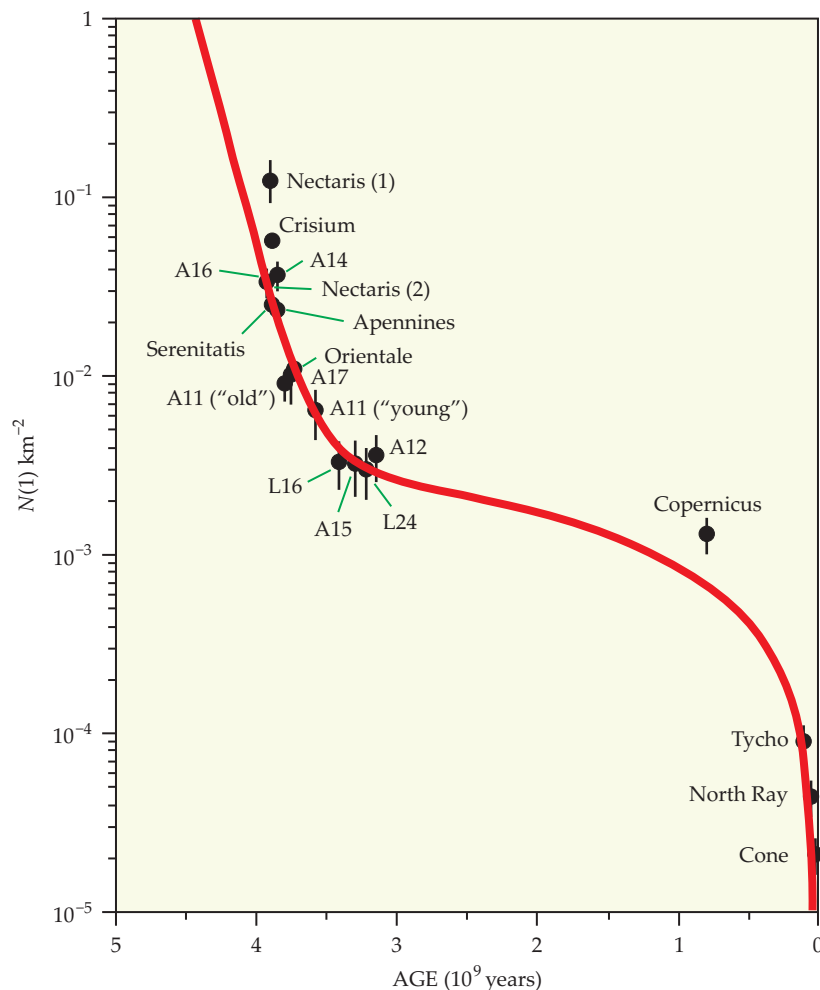


FIGURE 3. LUNAR CHRONOLOGY is based on the ages of lunar samples that represent surfaces on which impact crater size–frequency distributions have been determined. $N(1)$ refers to the number of craters that are 1 km in diameter or larger, and the plot relates that number to the crater accumulation time. Numbered labels “A” and “L” refer to Apollo and Luna missions, respectively. Measurements of crater size and frequency distributions come from orbital photographs. (The method and plot are adapted from ref. 4; the age data are taken from ref. 5.)

ples collected on the light mantle deposit and elsewhere in the valley had exposure ages of around 110 million years, and that age was assigned to the Tycho impact event.¹⁰ Ancient crustal rocks greater than 4.0 billion years old were also found among the *Apollo 17* samples. They continue to provide the grist for tests of hypotheses about the origin of the Moon’s ancient crust.

Unlike its predecessors, *Apollo 17* carried an active seismic experiment designed to determine the subsurface structure by picking up signals generated by explosive charges. Other experiments probed surface electrical properties, determined the effects of exposure of biological materials to cosmic rays, and used a traverse gravimeter to help map out subsurface structure. The orbiting command service module *America* carried a microwave sounder, an IR radiometer, a far-UV spectrometer, mapping and panoramic cameras, and a laser altimeter. The orbital data sets provided by those instruments would be the last

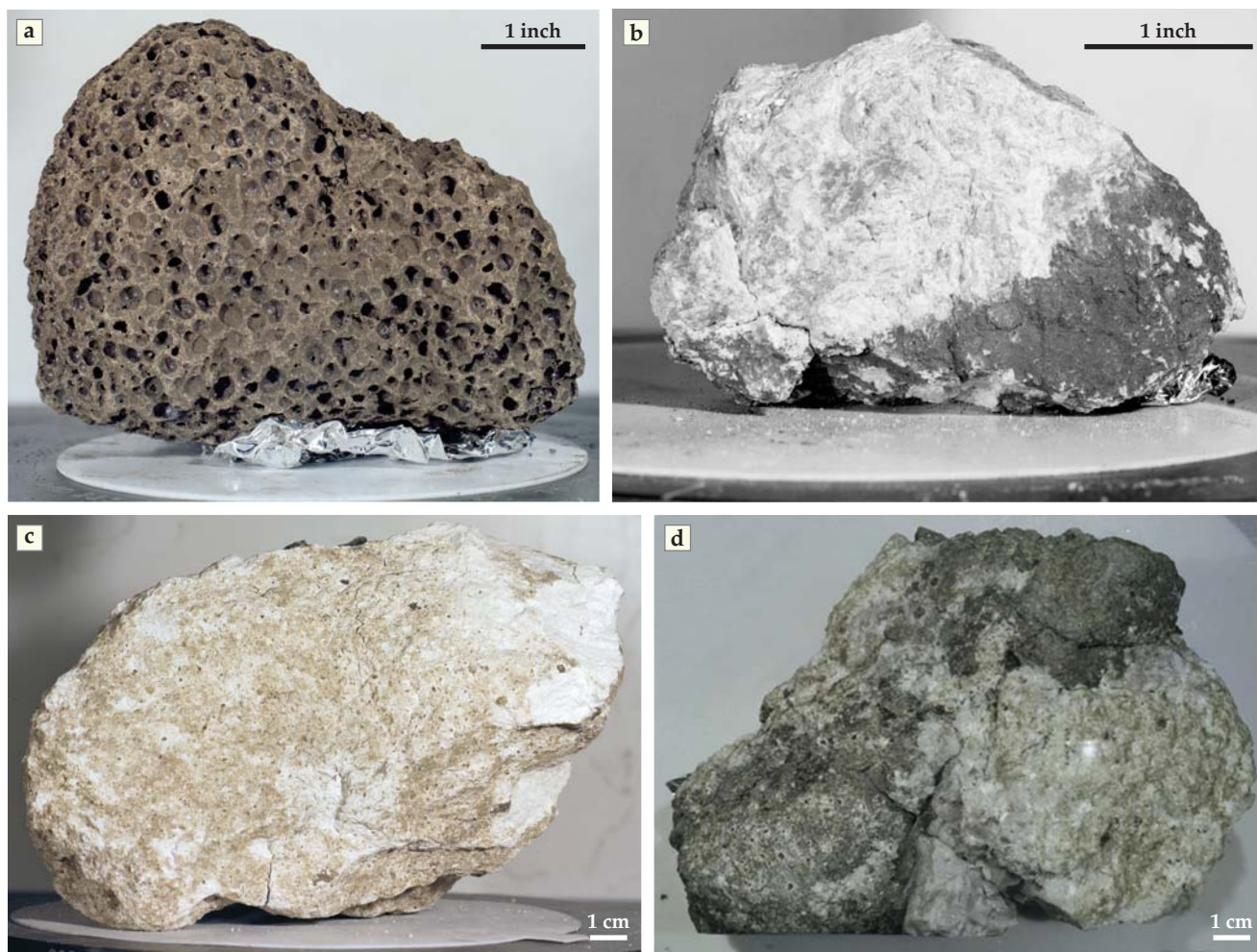


FIGURE 4. ROCKS COLLECTED during *Apollo 15* and *Apollo 16*. **(a)** “Seatbelt Rock” 15016 is a vesicular (porous) basalt. (Adapted from NASA photo S71-46632.) **(b)** “Genesis Rock” 15415 is made of ferroan anorthosite, a major rock type of the lunar crust. (Adapted from NASA photo S71-44990.) **(c)** A 1.8 kg sample of anorthosite, 60025. (Adapted from NASA photo S72-42586.) **(d)** This top surface of an 11.7 kg breccia, 61016, known as “Big Muley,” contains numerous tiny impact craters, or zap pits. (Adapted from NASA photo S98-01215.)

direct measurements scientists would have from lunar orbit for more than two decades.

Surface geophysics

The seismic array deployed by *Apollo 12*, *14*, *15*, and *16* continued to transmit data to Earth until September 1977, when the array and other instruments were turned off. More than 12000 seismic events were detected altogether. Some 7000 of them came from deep moonquakes, which were correlated with tidal forces exerted by Earth’s gravity. Others were attributable to meteoroid impacts, the deliberate crashes of booster rockets, and shallow thermal moonquakes caused by the heating and expansion of the crust.

Seismic data provided information about the thickness of the lunar crust, changes in the seismic velocity as waves crossed the crust–mantle boundary, deeper seismic discontinuities in the mantle, and a deep zone of seismic attenuation. Early work estimated the average crustal thickness at 60 km, but modern analyses place it between 30 and 40 km.^{11,12}

Ranging to the lunar retroreflectors from Earth continues today. The Moon’s irregular rotational motions indicate a partially fluid core. The 2011 Gravity Recovery and Interior Laboratory (GRAIL) mission confirmed a partially molten deep-mantle zone and constrained the size of the fluid outer and

solid inner core.¹³ (See *PHYSICS TODAY*, January 2014, page 14.) Coupled with the available Apollo seismic data, the new gravity measurements significantly improve our understanding of the Moon’s internal structure.

Samples and curation

The Apollo samples are broadly similar to Earth materials in mineralogy and chemical composition. But their chemistry is distinctly lunar. Moon rocks formed under extremely low oxygen fugacity such that most of the iron they contain is divalent (Fe^{2+}) and most samples contain at least a small amount of iron metal (Fe^0). The Fe–Ti oxides are mostly ilmenite (FeTiO_3), but also contain ulvöspinel (Fe_2TiO_4), armalcolite ($(\text{Fe,Mg})\text{Ti}_2\text{O}_5$) (first found in lunar rocks and named after *Armstrong*, *Aldrin*, and *Collins*), and tranquillityite ($\text{Fe}_8(\text{Zr,Y})_2\text{Ti}_3\text{Si}_3\text{O}_{24}$), a new mineral named for the Sea of Tranquility, where it was found.

The basalts provide insights into the lunar mantle and early differentiation processes. Variations in basalt types reflect a heterogeneous mantle, which lacks a homogenizing process such as Earthlike convection. Owing to ground-truth samples from Apollo, we can infer basalt types from other areas using remote sensing. Volcanic glasses occur in regolith samples from all Apollo sites, with a wide variety of compositions, spanning TiO_2 concentrations from less than 1 weight percent to more

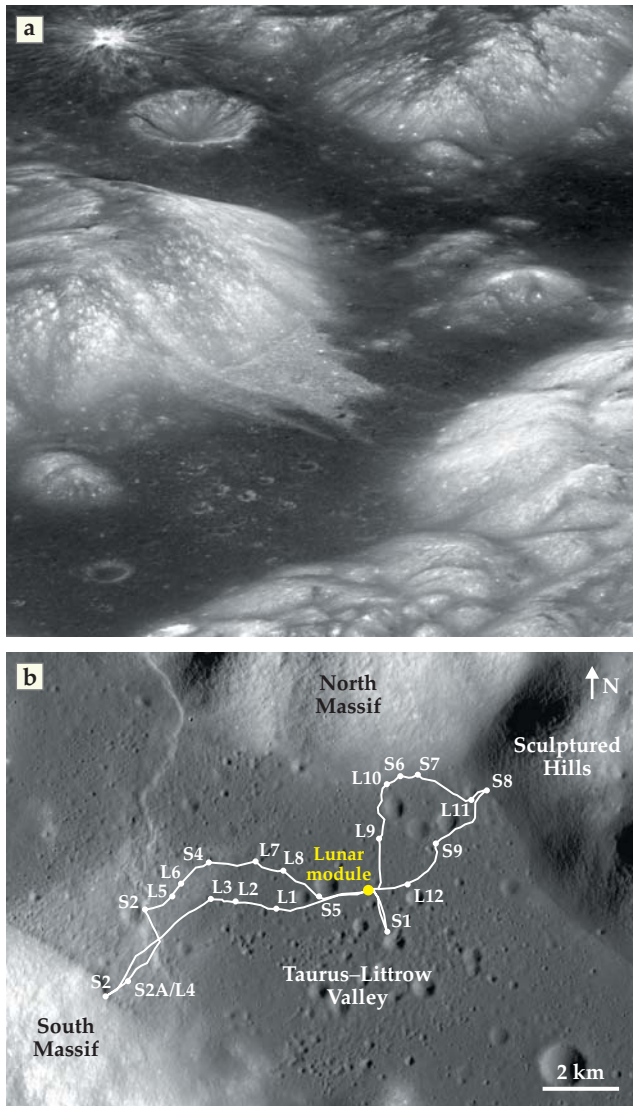


FIGURE 5. TAURUS-LITTROW VALLEY, the landing site for *Apollo 17*. **(a)** In this oblique, 18-km-wide scene looking generally to the west, *Mare Serenitatis* is at the upper right. North is to the right. (Image courtesy of NASA/GSFC/ASU.) **(b)** This view of the valley (the lower left part of panel a) shows the astronaut traverses. Numbered labels “S” and “L” refer to sampling stations and lunar-roving-vehicle stops, respectively. (Image courtesy of NASA/GSFC/ASU.)

than 16 weight percent. Those compositions reflect the heterogeneity of the mantle and late-stage magma-ocean processes that led to areas within the mantle of widely different Ti contents.

During the Apollo program, scientists had the foresight to recognize the value of the samples and established the Curatorial Facility at Johnson Space Center. They set protocols for curation, handling, and allocation in a way that would preserve portions of all samples for future generations, with special care given to the rarest and most important of them.

The protocols ensured that nearly 40 years after they were collected, samples would be available for analysis of indigenous OH and H₂O in volcanic glasses, phosphate minerals, and melt inclusions using new and highly sensitive analytical methods. Those studies revealed that the Moon did not form as depleted of volatiles as was once thought.^{14–16} (See also *PHYSICS TODAY*, Janu-

ary 2016, page 17.) Rather, the Moon heavily degassed the volatiles during the magma-ocean and later volcanic stages. The precise measurement of remanent magnetism in lunar samples revealed that the Moon had an early core dynamo until sometime between 3 billion and 4 billion years ago (reference 17; see also the article by David Dunlop, *PHYSICS TODAY*, June 2012, page 31).

Gateway to the solar system

The Apollo era exploration and decades of study of lunar samples laid a foundation of knowledge about Earth’s nearest neighbor and provided a cornerstone for planetary science. Apollo showed the Moon to be ancient, some 4.5 billion years old and made of materials similar to those on Earth, but consistent with the Moon’s smaller size, lower pressure, lack of atmosphere, and lack of any obvious aqueous alteration. Its minerals and rocks bore evidence of an early magma ocean and differentiation into a mantle and crust. Heating and remelting of the interior produced voluminous basaltic volcanism 3–4 billion years ago. From study of Apollo samples and data came the concept of the Moon’s formation via a giant impact on early Earth, which still stands as the leading hypothesis for the origin of the Moon. Apollo surface samples gave us our first look at alteration by exposure to galactic cosmic rays, energetic solar particles, and meteorites, ranging from microscopic to asteroidal.

Perhaps the most far-reaching scientific legacy of Apollo is the ongoing exploration of our solar system. The Apollo samples provided the first evidence of the so-called late, heavy bombardment of asteroids, thought to have spiked around 3.9–4.0 billion years ago. Models of the early solar system’s orbital dynamics suggest that shifts in the orbits of Jupiter and Saturn may have destabilized early asteroid and cometary belts and led to that cataclysm some 500 million years after the solar system formed.¹⁸

The Apollo samples and explorations showed that the key to testing those dynamical models is on the Moon, awaiting the next round of surface exploration and sample collection.

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