5 percent of its surface. Our picture of lunar evolution, built up painstakingly over 30 years of mapping, sampling, remapping, and continuous reevaluation, is one of a small planet, intensely active for its first 600 million years, declining slowly over the next 500 million, and nearly quiescent for the remainder of its history, a silence punctuated only by the rare impact, causing the Moon to slowly oscillate like a bell.

Thus the story of the Moon is the story of the early solar system, a time when worlds collided, globes melted, planetary crusts shattered under the onslaught of a barrage of impacting debris, and dull-red, glowing lava flows coated the surfaces of lifeless worlds. The story is one of a truly alien landscape—and it was all reconstructed from the simple observations of a few carefully chosen features.

Chapter 3

The Exploration of the Moon

The United States went to the Moon not to advance science but to demonstrate to the world that its system of values was superior to that of its Communist competitor. Likewise, the country stopped going to the Moon not because it had scientific reasons but because the political objectives responsible for the creation of the Apollo program had been satisfied. Although the story has been well told elsewhere (see the Bibliography), I want to briefly review the account of the exploration of the Moon because knowing something about how the task was approached helps us to appreciate more fully the nature of our current understanding of the Moon and its history.

A Bold Challenge and a Tough Problem

The launch of the Soviet satellite *Sputnik* in October 1957 sent shock waves through the very fiber of American society. How could a nation that we considered our technical inferior produce the world's first Earth-orbiting satellite? The ability of the Soviets to fly *Sputnik* presented a horrible implication: If they could launch a satellite, they could surely lob a nuclear warhead directly into the heart of the United States. Such a technical challenge could not go unanswered, and with the creation of the National Aeronautics and Space Administration (NASA) by Congress in 1958, the United States began its long, sputtering climb into the space age.

Initial American efforts were not auspicious. Failure and delay characterized the early space program, including spectacular fireballs as rockets exploded on the launchpad and during liftoffs. With the successful launch of *Explorer 1* into Earth orbit by Wernher von Braun and his colleagues in January 1959, the nation was finally on track. Over the next several years the United States seemed to be catching up to the Soviets as it orbited many satellites and prepared to send men into the unknown, following the trail blazed by robotic precursors. But once again the Soviets struck first, launching Yuri Gagarin into Earth orbit in April 1961, a full month before the Mercury program's first suborbital flight, by Alan Shepard in the spacecraft *Freedom 7* in May. This success of the Soviets, coupled with the rather spectacular failure of the invasion of Cuba by a CIA-trained Cuban army in exile, caused the new American president, John F. Kennedy, to search desperately for a field on which the Americans could challenge the Soviets. After due consideration, Kennedy decided to set a decade-long goal of landing a man on the Moon and returning him safely to Earth.

The goal of a manned landing on the Moon provided a suitable challenge—a task believed to be one that the United States could win. A look at the problem was sobering, however. A trip to the Moon and back would traverse over a million kilometers of space; at the time, the U.S. distance record with man was about 500 km. The trip would last at least a week; Shepard had been in space for about 15 minutes. A trip to the Moon would require a rocket with several million pounds of thrust, capable of carrying at least 100–300 tons into low Earth orbit; Shepard's *Redstone* booster rocket for *Freedom 7* developed about 80,000 pounds of thrust, and his Mercury spacecraft weighed about 1 ton. To advocate a trip to the Moon by a nation whose total experience in manned spaceflight was the flight of *Freedom 7* was audacity indeed!

The exact way that the United States would go to the Moon remained a contentious issue. The principal competing ideas in the "mode decision" (as it was called) revolved around space rendezvous, in which two spacecraft would meet in space to exchange people, cargo, or fuel. The question was, should the lunar craft be assembled for flight in Earth orbit, refueling from an orbiting tanker (a mode called *Earth-orbit rendezvous*), or should it be launched all at once, sending down a very small lander from lunar orbit and then returning a man back to the

spacecraft orbiting the Moon (a mode called *lunar-orbit rendezvous*)? Although lunar-orbit rendezvous seems natural to us today, in 1961 no one had ever achieved *any* type of rendezvous in space, let alone conducted one a quarter of a million miles away from Earth. What finally tipped the balance in favor of this risky technique was a study of the launch booster requirements for each mode; an Earth-orbit rendezvous would require a "superbooster" of over 14 million pounds of thrust. Although such a booster was designed in a preliminary manner, it was decided that our best chances were with the lunar-orbit rendezvous technique, a mode that would require "only" a booster that could develop about 7.5 million pounds of thrust, a vehicle later called *Saturn 5* (Plate 4).

The fact that the United States was going to the Moon did not guarantee that we would explore it scientifically. However, some information about our destination was needed to ensure a safe voyage and landing. We needed to learn how to control spacecraft at lunar distances, how to maintain an orbit around the Moon, and how to land and operate safely where we did not know the surface conditions. Such an abundance of ignorance virtually ensured that we would be undertaking precursor missions, missions that would not only blaze the trail but also, invariably, advance our understanding of the Moon and its environment in major ways.

As described in Chapter 1, Eugene Shoemaker had anticipated lunar voyages and had already been studying the Moon to prepare for this upcoming golden opportunity. Because the basic geological framework of the Moon had been comprehended (see Chapter 2) and because its near-side topography and geology were being mapped and its environment characterized, it was a relatively straightforward task to devise an exploration plan that would logically address and answer the key unknowns. We had to understand the surface layer, both to ensure a safe Apollo landing and to comprehend the geology of the returned samples. To find large smooth areas, we needed detailed maps of the potential landing sites on the Moon. We had to map the gravity field of the Moon, to ensure that the Command-Service Module (CSM) spacecraft would remain safely in precisely known orbits and to guarantee that the Lunar Module (LM) spacecraft could make a pinpoint landing and later rendezvous with the orbiting command ship. Such were the knowledge requirements for a voyage to the Moon; how were these requirements satisfied?

The Robot Precursors: Ranger, Surveyor, and Lunar Orbiter

Three principal flight projects added to our pre-Apollo understanding of the Moon (Fig. 3.1), and they still provide data of scientific value today. Collectively, they showed that the surface, though dusty, did not contain deep pools of quicksand-like dust waiting to swallow unsuspecting spacecraft. Smooth, boulder-free areas in the maria were identified and mapped. Nearly the entire surface of the Moon was photographed at resolutions 10 times better than could be obtained from Earth, allowing us to extend our geological mapping to the entire globe and illustrating the nature of the terrain types and their implications for lunar history. We even made the first chemical analyses of the surface, confirming the volcanic origin of the maria and finding something unusual and unexpected in the highlands.

The Soviets had beat us to the punch in photographing the Moon from up close when its *Luna 3* spacecraft succeeded in returning pictures of the far side in 1959. The U.S. Ranger program started in late 1959 and originally was a principally scientific mission, designed to obtain close-up views of the surface. Ranger was a hard lander and would destroy itself on impacting the Moon at near escape velocity (3.5 km/sec). Later missions were to have carried a crushable, balsa-wood ball that would allow the safe delivery of instruments to the lunar surface,

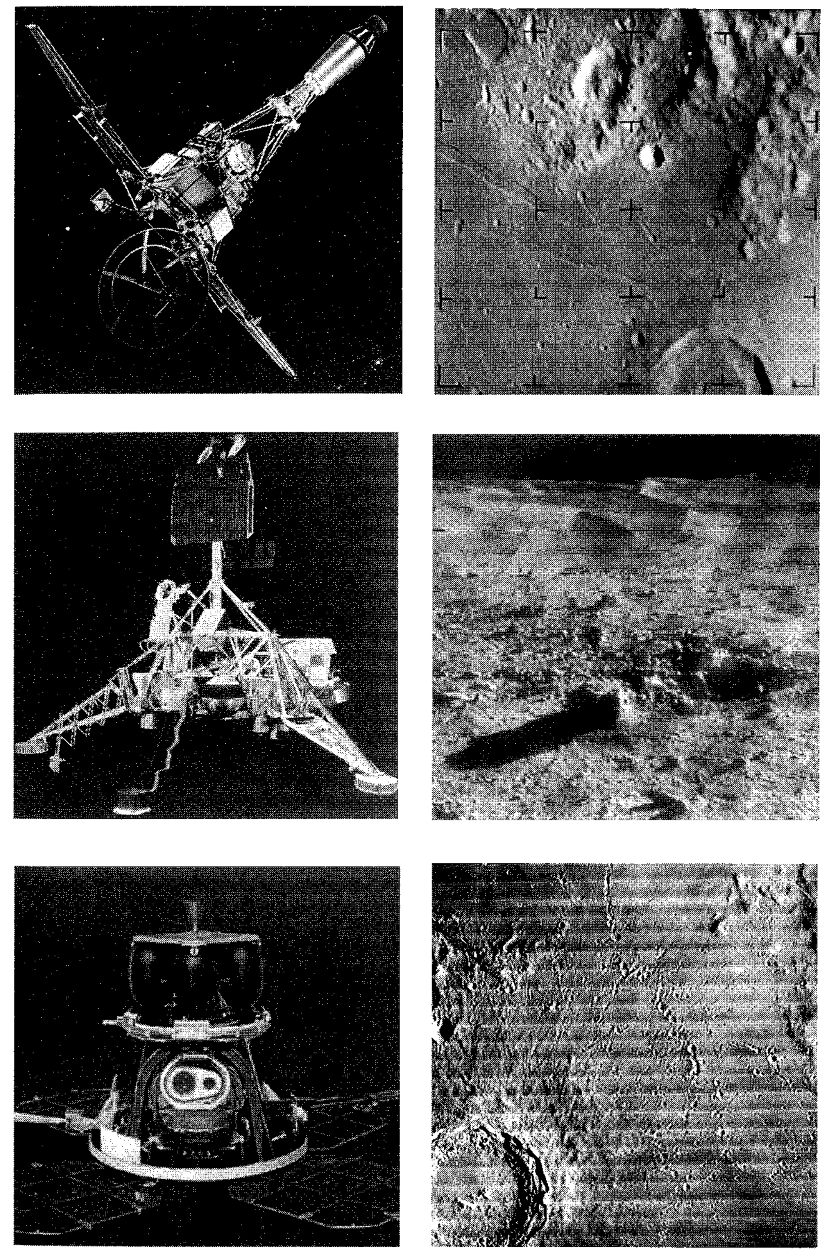

Figure 3.1 (opposite): The three principal robotic precursor missions that paved the way for the manned Apollo missions to follow. At top, the crash-landed Ranger spacecraft, designed to take pictures of increasing detail before impact on the Moon. At middle, the soft-landing Surveyor series, which certified that the surface could support machines and people and told us much about the processes of surface evolution. At bottom, the Lunar Orbiter spacecraft, which mapped the whole Moon and took extremely detailed pictures of proposed Apollo landing sites.

including a seismometer to measure *moonquakes.* These enhancements were dropped when the high-gear schedule of Apollo demanded immediate results. Such results were not instantly forthcoming from Ranger. Several Ranger flights either blew up on launch, missed the Moon completely, or silently crashed into the lunar surface without transmitting a single picture. Finally, on July 31, 1964, the *Ranger 7* spacecraft returned a spectacular series of close-up photographs of a portion of Oceanus Procellarum (Fig. 3.1), the largest expanse of maria on the Moon, each image showing a smaller and smaller area at greater resolutions than ever before.

From the *Ranger 7* mission, we discovered that the ubiquitous craters on the surface continue downward in size to the limits of resolution (even occurring on the surfaces of the returned rock samples). The Ranger photographs allowed us to decipher the nature and dynamics of the ground-up, powdery surface layer that everywhere covers the Moon. From the numbers of small craters, we learned about the effects of bombardment of the surface by micrometeorites and discovered the concept of crater *equilibrium,* in which the rate of crater production by impact equals the rate of crater destruction by erosion. All lunar surfaces are in cratering equilibrium at some diameter. The larger this equilibrium crater diameter, the older the surface. The oldest surfaces of the highlands have equilibrium crater diameters of tens of kilometers, indicating that they are saturated with very large impact craters and that the crust is crushed and broken by impacts for depths of many kilometers.

The next mission, *Ranger 8,* was sent in early 1965 to the western edge of Mare Tranquillitatis. Once again, we saw the crater-upon-crater texture typical of the lunar surface at close ranges. The *Ranger 8* mission also photographed two unusual craters, Ritter and Sabine, thought at the time possibly to be large volcanic craters. With earlier missions having scouted two different regions of the maria, the last Ranger mission (*Ranger 9,* March 1965) was sent to an area in the highlands, the spectacular ancient crater Alphonsus (Fig. 5.4), on the eastern edge of Mare Nubium. Alphonsus represents a class of feature called a *floor-fractured crater;* cracks found on the floor of the crater, in addition to small, dark-rimmed craters that might be cinder

cones, are thought to be manifestations of volcanism. Indeed, Alphonsus had long been one of the sites of the famous *lunar transient phenomena*—reddish, glowing clouds had been reported emanating from the crater. *Ranger 9* saw no evidence for gas venting from the Moon but did return spectacular images of Alphonsus at ever higher resolutions. Another remarkable facet of the *Ranger 9* mission was the return of its pictures via real-time, live television from the Moon, watched by fascinated people across the nation (including me, age 12) as the probe struck the Moon at high velocity.

As Ranger finished giving us our first close look at the Moon, we prepared to soft-land and touch its surface for the first time. Surveyor was originally a spacecraft with orbiter and lander elements, but faced with a choice imposed by delays, the program dropped the orbiter portion and concentrated work on the lander to best support Apollo (Fig. 3.1). Initial Soviet attempts to soft-land on the Moon failed repeatedly, raising questions about the surface conditions. One lurid and widely reported model suggested that the maria were gigantic bowls of dust, cauldrons that would act like quicksand to swallow up any equipment landed on the Moon. Geologists mapping the Moon with telescopic pictures considered such models nonsense but would have to wait for the first successful landing to put such fears permanently to rest.

After much effort, the Soviets beat the United States to the punch once again (for the last time, as it later turned out) and succeeded at a soft landing on the Moon in February 1966 with their *Luna 9* spacecraft. Television pictures showed a surface similar to hard-packed sand covered with a thin layer of dust. The first American landing, *Surveyor 1* in early June 1966, returned hundreds of detailed pictures of the surface, showing us the Moon as it would appear to an astronaut standing on the surface. The Surveyor pictures showed the ground-up surface layer, documenting that it was strong enough to support the weight of the people and machines that would soon be visiting. We could see in the Surveyor pictures evidence for the mixing and crushing of the bedrock into the rock-laden, dusty layer of dirt that makes up the surface.

Five Surveyor spacecraft (*1, 3, 5, 6,* and *7*) successfully landed on the Moon; radio contact with *Surveyors 2* and *4* was lost shortly before landing, and they are presumed to have crashed. *Surveyor 3* carried a trenching tool, designed to dig into the surface and study its properties and strength at depth. This trenching scoop and a television camera were returned to the Earth nearly three years later by the *Apollo 12* astronauts and showed that hardware could withstand long exposure to the lunar environment (the camera is now on display at the Smithsonian Air and Space Museum). *Surveyor 5* carried the first experiment designed to measure the Moon's composition, an instrument for determining the chemistry of the surface. From these data, we found that the maria were rich in magnesium and poor in aluminum, results consistent with a composition of basalt, a very common type of lava on Earth. Having landed *Surveyor 6* at another mare site (Sinus Medii), the program sent the last mission, *Surveyor 7,* to one of the most spectacular locales on the Moon: the rough, hazardous rim of the crater Tycho (Fig. 2.4), deep in the southern highlands. *Surveyor 7* beat the odds by safely landing at Tycho in January 1968.

Although *Surveyor 7* returned fascinating views of the rim of a complex crater (Fig. 3.1), its most significant experiment was the first determination of the chemistry of the highlands. The data showed a surface relatively rich in aluminum and depleted in magnesium, the reversal of the trends seen in the data from the maria. The team analyzing this information suggested that unusual rock types, including one called *anorthosite,* might be the main components of the highlands. Anorthosite and related rocks are made up mostly of a single type of mineral, plagioclase (a calcium-and aluminum-rich silicate). If this supposition was correct, it would have significant implications about the history of the Moon. This chemical composition was anything but primitive, contradicting the concept that the Moon was a cold, undifferentiated object, as Harold Urey believed (see Chapter 1).

The last major task for the robotic precursors to Apollo was the making of detailed maps of the Moon. Such maps were needed to choose and to certify safe landing sites and to aid the astronauts in exploring the new world. If the missions were completely successful, a significant by-product of this effort would be the global, scientific mapping of the Moon. Five of the unimaginatively named Lunar Orbiter spacecraft (Fig. 3.1) flew between August 1966 and August 1967, and each one was an overwhelming success. Unlike the design of the other precursor missions, the plans for the Lunar Orbiter camera were based on the design of classified, espionage spacecraft, intended to photograph features at high resolution from space. The first three Orbiter spacecraft were placed in near-equatorial orbits, similar to those to be used by the upcoming Apollo missions, and returned dozens of very high resolution pictures of the proposed landing sites (Fig. 3.1). Features as small as one-half of a meter in size were recognized, classified, and mapped. Detailed mosaics were made to aid in plotting the landing paths of the Apollo LM spacecraft as well as to depict the boulders, lineaments, and geological features that the astronauts might explore.

With the scouting of the landing sites accomplished, the last two Orbiter spacecraft were sent into near-polar orbits so that the entire surface would come into the view of their cameras. *Lunar Orbiter 4* mapped the entire near side at a resolution 10 times better than the very best views from Earth. It also took detailed and spectacular images of the Orientale impact basin (Fig. 2.8), images from which we first learned details about the process of large impact and the creation of the strange landforms in the highlands. *Lunar Orbiter 5* made detailed, very high resolution mosaics of sites of high scientific interest, including the fresh craters Copernicus, Tycho, and Aristarchus and volcanic regions such as the Marius Hills, the Rima Bode area, and Hadley Rille, a future Apollo landing site. The pictures returned by the Lunar Orbiter series not only paved the way for the Apollo missions but also gave us images of the Moon that are still used extensively by scientists today (as the reader will note through the use of these photographs for many of the illustrations of this book).

The Lunar Orbiter missions also revealed an unexpected hazard for voyagers to the Moon. The orbits of the spacecraft changed with time because subsurface zones of high-density material would tug at the spacecraft, gradually pulling them toward the Moon. The effect of these zones could be sudden and catastrophic: A small satellite released into lunar orbit by the *Apollo 16* mission lasted only two weeks before crashing into the

Moon. These regions, called *mascons* for "mass concentrations," are associated with the large, circular maria and were our first unintended "probe" of subsurface conditions—the Orbiter missions made our first *gravity map* of the Moon. Several models for the formation of the mascons were proposed. The two principal ones involved a thick fill of the basins by flows of high-density lava or the uplift of dense rocks from the mantle by the unloading of the crust during excavation of an impact basin. We now think that the uplift of mantle rocks is the dominant cause of the mascons, but some contribution from lava flooding is probable. More important for lunar exploration, the mascons were a potential hazard for the upcoming Apollo missions, and their effects on the orbits of spacecraft around the Moon had to be comprehended before the missions could be successful.

These precursor missions successfully paved the way for the Apollo missions. We had achieved a broad understanding of lunar history and processes through geological mapping at a variety of scales. We had carefully measured the physical properties of the surface and assured ourselves that it would not swallow up the people and equipment we would soon be sending. Almost as important, we had acquired real operational experience with the flying and operating of spacecraft at lunar distances. Coupled with the human spaceflight experience of rendezvous, docking, and *extravehicular activity* (EVA, or "spacewalking") in Earth orbit during the Gemini program, we were ready to send men to the Moon.

Man Orbits the Moon: *Apollos 8 and 10*

The first humans to look at the Moon close-up were the crew of *Apollo 8*—Frank Borman, Jim Lovell, and Bill Anders—who orbited the Moon in December 1968. *Apollo 8* was only the second manned Apollo flight (*Apollo 7* had conducted an Earth-orbiting mission in October 1968) and the first manned flight of the mighty *Saturn 5* rocket (Plate 4). Sending this mission all the way to the Moon after one Earth orbital flight of the Apollo spacecraft was a bold step. *Apollo 8* made ten orbits of the Moon, taking photographs of the far side and of the far eastern Apollo landing site, finding it to be unexpectedly rough, and making

detailed visual observations of the surface. As had been feared from the Lunar Orbiter data, the spacecraft orbit was indeed disturbed by the presence of the high-density, subsurface mascons, and this hazard would have to be understood and dealt with during the upcoming landing attempts. One of the most significant emotional effects of the *Apollo 8* mission was its famous photograph of a beautiful, blue-green Earth appearing to rise slowly above the stark, gray "wasteland" of the Moon.

After the *Apollo 9* mission tested the LM in Earth orbit in March 1969, the *Apollo 10* mission in May 1969 conducted a full-up dress rehearsal for the lunar landing. Both the CSM (flown by John Young) and the LM (flown by Tom Stafford and Gene Cernan) orbited the Moon, the LM descending to within 15 km of the surface. *Apollo 10* made detailed observations of "Apollo site 2" in Mare Tranquillitatis and confirmed that its smooth appearance on the Lunar Orbiter mosaics was real and that the site seemed to be an appropriate place to attempt a landing. A nearly complete moon-landing mission profile was flown, with the LM firing both its descent and its ascent engines in a test of the Apollo spacecraft in real lunar flight. After several separate orbits, the LM returned to the CSM to rendezvous and dock, just as would the lander returning from the surface. Another day was spent orbiting the Moon and taking additional photographs of the area near Sinus Medii, where *Surveyor 6* had landed just two years earlier. Both the *Apollo 8* and the *Apollo 10* orbital missions paved the way for the grand act to follow: the completion of the decade-long challenge laid down a mere eight years previously.

Man on the Moon: *Apollo 11*

The first lunar landing, on July 20, 1969, was a real cliffhanger—almost literally. As the *Apollo 11* LM *Eagle* swooped in for its landing, Commander Neil Armstrong noted that his spacecraft was headed for the center of a crater, several hundred meters across and strewn with blocks, some the size of small automobiles. Armstrong took manual control, carefully flying *Eagle* around the obstacle, and set the craft on the Moon with less than a few seconds of hovering fuel left in its tanks. Neither Armstrong nor his LM pilot, Buzz Aldrin, recognized exactly where they were on the Moon. Once again, the mascons were to blame; they had pulled *Eagle* downrange, off course by several kilometers (in fact, completely outside of the designated landing area). Even the orbiting CSM pilot, Mike Collins, could not see the LM on the surface; it was not until the astronauts returned home and the onboard film was reviewed that their landing site was located precisely. At the time of the landing the astronauts knew only that they had successfully pulled off the greatest feat in the history of flying since Orville Wright's 10 seconds of immortality. A few hours later Armstrong took his "one giant leap" and became the first human to walk on another world.

In addition to fulfilling the dreams of millennia (Fig. 3.2), the first landing on the Moon accomplished quite a bit of science as well. The astronauts set out a small seismometer, which documented that the Moon is extremely quiet and that moonquakes are small and rare. They also deployed a laser reflector, with which we could measure, to within a few centimeters, the distance between Earth and the Moon. Such precision measurements would allow us to carefully track the Moon's orbital motion and, in addition, the drift of the continents on Earth. The astronauts collected about 40 kg of rock and soil samples from the immediate vicinity of the LM, and the return of this material to Earth answered some of the most important scientific questions that had accumulated over the years.

The lunar samples were extremely dry; no evidence was found for any water whatsoever, with a complete absence of water-bearing minerals in the rocks. The rocks were samples of either basalt, a common lava type on Earth, or breccia, a rock made up of many fragments of older rock and minerals. The basalts from the *Apollo 11* site contained relatively high concentrations of titanium, an unexpected enrichment. It was found that the lunar soil is composed of ground-up lava bedrock and includes abundant tiny fragments of glass, created by the shock melting of small mineral grains during high-velocity impact. The ages of the rocks, determined by measuring the amounts of radioactive isotopes in the materials, were found to be very great; the lavas of Tranquillity Base flowed 3.7 billion years ago, long before virtually all of the surface rocks of Earth had been created. Strangely, the soil (which was created from and lay on

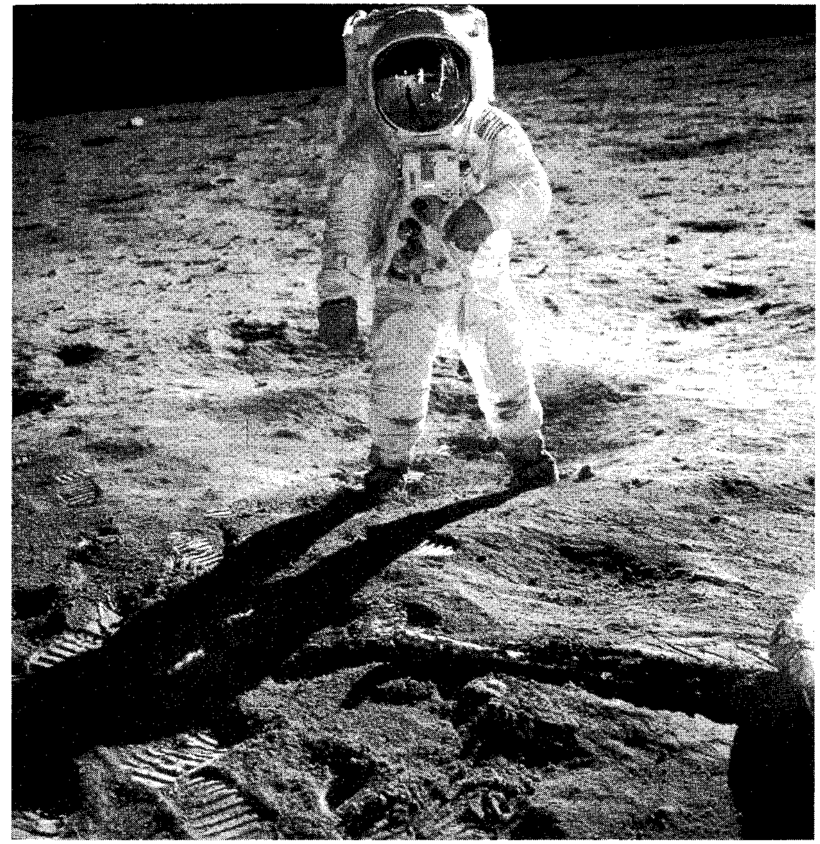

Figure 3.2. An age-old dream achieved. *Apollo 11* Lunar Module pilot, Buzz Aldrin, on the Moon, July 20, 1969. The mission commander, Neil Armstrong, is visible, reflected in Aldrin's faceplate.

top of the 3.7-billion-year-old rocks) appeared to be even *older*, dating 4.6 billion years, back to the age of the Moon itself. It took another mission to the Moon to explain this puzzling fact: The soil is relatively enriched in a radiogenic isotope of lead, resulting in ages that are only apparently older.

The results of the *Apollo 11* mission placed some broad constraints on lunar history. The maria are made of volcanic rock and are very old. Because basalt lava forms by partial melting of a certain type of rock, the *Apollo 11* basalts showed that the interior of the Moon was not primitive in composition but had been created in an earlier melting episode. The surface layer (regolith) is made of ground-up bedrock, partly crushed into powder and partly fused by impact melting. One finding yielded a major insight into lunar evolution: Tiny, white fragments found in the soil are clearly different from the local bedrock. It was postulated that these fragments are pieces of the highlands, thrown to the *Apollo 11* site by distant impacts. This supposition was supported by the chemical analysisthat the *Surveyor 7* spacecraft made of Tycho ejecta, which showed the unusual aluminous composition described earlier. If the highlands were really made of this unusual rock type, anorthosite, the early Moon may have been nearly completely molten, an astonishing idea for a planet as small as the Moon. This concept, called the *magma ocean*, was reinforced by subsequent mission results and will be described in Chapter 6.

Deepening Mysteries: *Apollos 12* and *14*

The second landing, in November 1969, was considerably more lighthearted than the first. Leaving their colleague, Dick Gordon, in lunar orbit, astronauts Pete Conrad and Alan Bean demonstrated a new technique for pinpoint landing. Correcting for the effects of the dreaded mascons, they landed only a few tens of meters from where the *Surveyor 3* spacecraft had landed in eastern Oceanus Procellarum. This landing site, like that of *Apollo 11*, was in the maria and featured deposits that were slightly less cratered (and therefore younger) than those sampled at Tranquillity Base. We did not know how much younger the flows were. This mission featured two moonwalks, each over three hours long, and the emplacement of a nuclear-powered geophysical network station (Fig. 3.3), the ALSEP (Apollo Lunar Surface Experiment Package—the Apollo engineers loved acronyms). The crew collected more rock samples than the *Apollo 11* crew and visited the rims of several impact craters at their landing site. The *Surveyor 3* spacecraft (Fig. 3.1) was visited and sampled to assess the effects of long-term exposure on the surface of the Moon (the effects were not very noticeable—a few microcraters).

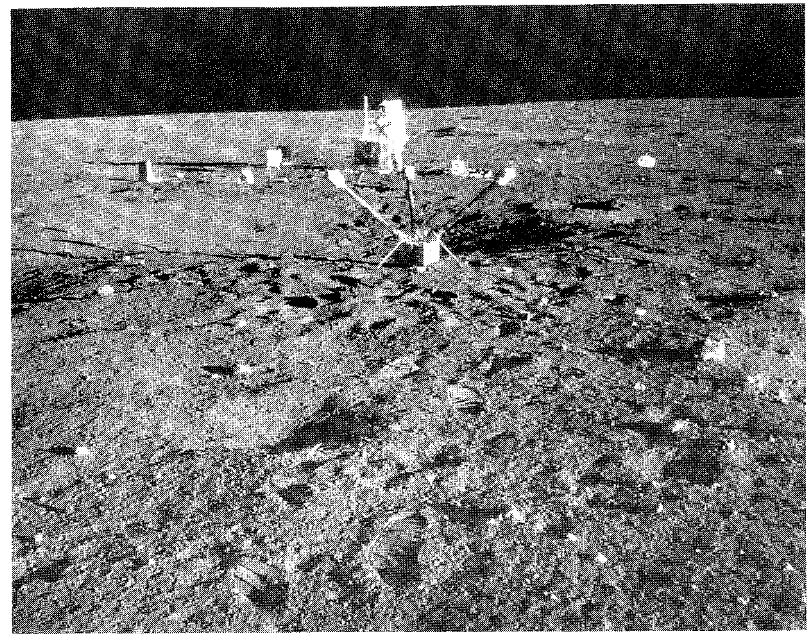

Figure 3.3. An *Apollo 12* astronaut adjusting the antenna of the central station of the Apollo Lunar Surface Experiment Package (ALSEP), the network of geophysical stations set up by five of the six Apollo landing crews. The three-prong instrument in the foreground measures the magnetic field.

The *Apollo 12* basalts showed the same extreme age and lack of water as the other lavas but with some important differences. First, the basalts of the *Apollo 12* site were lower in titanium than those from Tranquillity Base, demonstrating that different regions of the interior had melted to make the two types of lava. Second, these lavas, themselves representing several different lava flows, were "only" 3.1 billion years old, almost 500 million years younger than the lavas from the other site. These results showed that the maria did not all result from a single, massive volcanic eruption but represented a complex series of lava flows poured out over at least a half a billion years. Rare fragments of highland rocks from the *Apollo 12* site included some that were quite different from those found at the *Apollo 11* site, demonstrating that the highlands similarly varied from place to place. An impact breccia from this site is an extremely complex mixture of unusual rock types, foreshadowing similarly complex breccias to be returned by future missions to the highlands. A strange enrichment in certain elements—including potassium, phosphorous, and some radioactive elements—was first recognized in soils and rocks from this site. This material, given the name KREEP, is an important clue to the origin of the crust.

The *Apollo 13* mission in April 1970 was to be sent to the Fra Mauro highlands, just east of the *Apollo 12* landing site (Fig. 3.4). Unfortunately, an oxygen tank in the CSM of the spacecraft exploded on its way to the Moon, and after a truly heroic emergency effort, including the use of the LM as a "lifeboat" to sup-

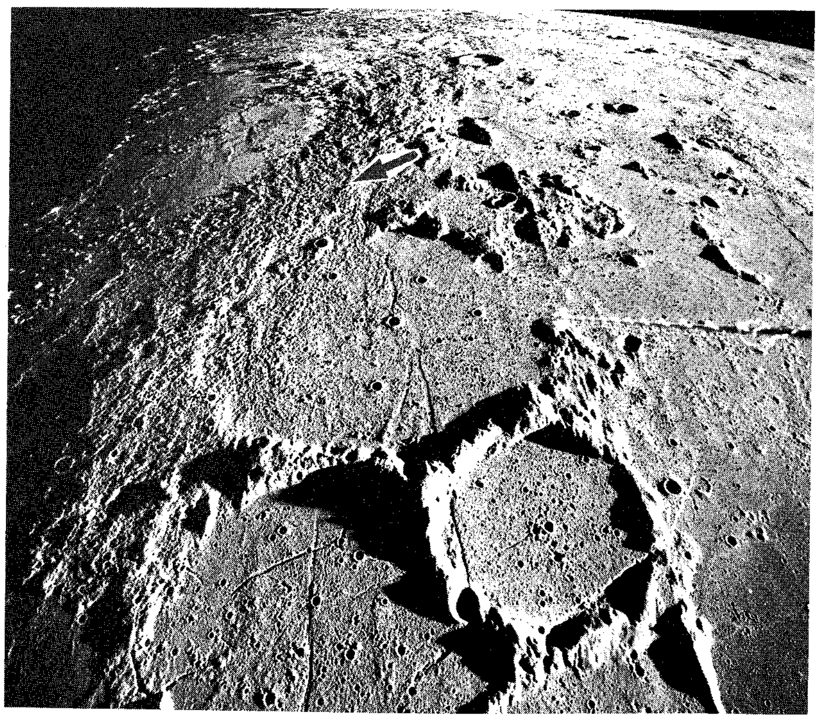

Figure 3.4. The crater Fra Mauro (center), which is overlaid by a rough blanket of debris called the Fra Mauro Formation. The *Apollo 14* landing site (arrow) was sent here to sample rocks thrown out of the Imbrium impact basin.

port the crew, Jim Lovell, Fred Haise, and Jack Swigert returned to Earth safely after looping around the Moon. When lunar spaceflight was resumed in January 1971, the *Apollo 14* mission was redirected to the unvisited site. Fra Mauro was considered to be important because the site was on the regional blanket of debris (Fig. 3.4) thought to be thrown out of the Moon by the impact that created the huge Imbrium basin, a crater over 1,000 km in diameter. Alan Shepard, the nation's first spaceman, and Edgar Mitchell directed their LM *Antares* to a pinpoint landing on the Fra Mauro ejecta blanket. The CSM was piloted by Stu Roosa, who conducted an extensive program of observations from orbit. During two moonwalks, Shepard and Mitchell set up another ALSEP station and fired small explosive charges to "profile" the subsurface with seismic lines (much as is done on Earth during oil prospecting). After trekking up the slopes of a hill 3 km distant and 100 m high to explore the ejecta from Cone crater (1 km diameter), which excavated the Fra Mauro debris blanket, the crew brought up deep rocks for our examination and collection.

The astronauts became disoriented and lost during their moonwalks. The crystal clarity of pure vacuum and the lack of recognizable landmarks confuse the mind and make it very difficult to judge distances on the Moon. Features that appear nearby may be many kilometers away. The smooth, rolling nature of the highlands means that even when one stands on high ground, areas that are physically close may be unseen while distant craters may be clearly visible. Apparently, the astronauts literally walked right by the rim of Cone crater without seeing it. Even so, Shepard and Mitchell did succeed in returning samples of the ejecta of Cone crater, and these rocks both confused and enlightened scientists. The problem of navigating on the lunar surface was solved on the next mission by letting a computer on the Lunar Roving Vehicle (LRV), or *rover*, keep track of where the astronauts were at any given time.

The materials returned by the *Apollo 14* mission are some of the most complex rocks in the sample collection. They are all breccias, complex mixtures of older rocks, including breccias containing breccias from previous events. Nearly all are enriched in the strange KREEP chemical component first identified at the *Apollo*

12 site, and in bulk composition they are considerably different from what was expected. It had been thought that highland rocks would be extremely rich in aluminum, made of anorthosite, as found at the *Apollo 11* site. In fact the bulk composition of the *Apollo 14* breccias is basaltic, not as iron-rich as the mare samples but still much less aluminous than anorthosite. This unusual composition told us that the highlands are composed of different provinces, possibly reflecting different geological histories and evolution. In this case the composition of the Fra Mauro breccias is related to their origin as ejected debris from the giant Imbrium impact basin.

The breccias from this site also showed us that mare volcanism began very early in lunar history. Basalts that were found as small fragments embedded in these breccias are 4.2 billion years old, nearly as old as the crust itself. From this site, we also recognized another important rock type, the *impact-melt breccia,* a rock that strongly resembles volcanic lava but that was created from the intense shock pressures of impact rather than from a volcanic eruption. Impact melts are important components of the highlands because they are the impact products most suitable for radiometric dating. Thus they can tell us much about the geological history of the Moon, provided they can be related to the crater that formed them.

The Great Explorations: *Apollo 15, 16, and 17*

The last three Apollo missions, in 1971 and 1972, introduced a new and exciting scale of exploration, a scale not surpassed (or even equaled) today. Each mission consisted of an upgraded, expanded spacecraft, allowing more experiments and more sophisticated equipment to be carried to the Moon. The orbiting CSM carried a special package of cameras and sensors to study the Moon from orbit. Each mission carried an electric cart, the rover (Fig. 3.5), to the surface. This innovation was not a gimmick but was a valuable exploration tool that permitted the astronauts to venture farther from the LM (by navigating across the surface) and to stay longer at scientifically important sites (by permitting the crew to rest and conserve their air and water while traveling to distant sites). In addition a drill and coring rig allowed deep samples of the regolith to be obtained. All three missions deployed an advanced ALSEP package, creating a long-lived geophysical network that would continue to send data from the Moon back to Earth until the network was turned off six years later. Each LM could stay on the Moon for up to 72 hours, almost doubling the exploration time. This new exploratory capability was exploited by sending these last three missions to complex, multiple-objective landing sites.

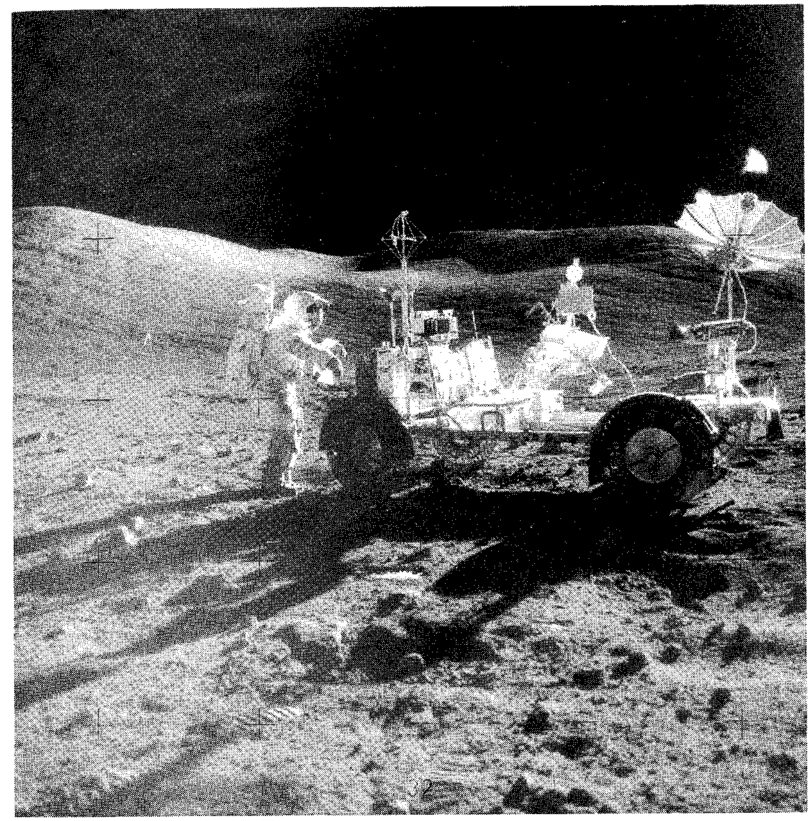

Figure 3.5. An image from the *Apollo 17* mission. On the last three missions to the Moon, an electric cart, the Lunar Roving Vehicle (LRV), allowed the astronauts to travel farther and explore more territory. The large dish at right allowed the LRV to transmit television pictures, even when the rover was far away from the Lunar Module.

Figure 3.6. The magnificent *Apollo 15* Hadley-Apennine landing site (arrow). The site was picked to allow the astronauts to examine both the snakelike Hadley Rille, an ancient lava channel, and the towering Apennine Mountains (right), which make up the rim of the Imbrium impact basin.

The *Apollo 15* mission was sent to the rim of the Imbrium basin at the spectacularly beautiful Hadley-Apennine landing site in July 1971. The huge chasm of the sinuous Hadley Rille (over 2 km wide and 900 m deep) winds across the mare plain, surrounded by one of the steepest, highest (7 km) mountain ranges on the Moon (Fig. 3.6). It provided viewers on Earth with their most memorable lunar scenes. This site was the first multiple-objective site, with the crew being able to sample and

explore both mare terrain and the highlands bordering the Imbrium basin. The three astronauts—Dave Scott, Jim Irwin, and Al Worden—received extensive training in geology, hard work that paid off magnificently as they explored this corner of the Moon for three days. Time outside the LM more than doubled, and traverse distance increased by a factor of five over the previous mission as the astronauts drove the rover across the dusty plains at Hadley.

Apollo 15 returned a variety of impact breccias from the highlands and mare basalts from the plains, but there were also a few surprises in the sample box. A transparent, emerald-green glass was discovered scattered about the site. Analysis showed that this glass is a form of ash deposit from a volcanic eruption over 3 billion years ago. Small fragments of lava rock with aluminum-rich composition were our first sample of "nonmare" or highland volcanism. Detailed photographs showed unusual benches in the mountains of the surrounding highlands (Fig. 3.7), possibly exposing layered rocks from the period of early bombardment. Similarly, Scott and Irwin visited the rim of Hadley Rille, which exposed layered rocks in its walls, mute testimony to a prolonged filling of the Imbrium basin by separate lava flows over a period of many years. The *Apollo 15* mission was the most extensive exploration of the Moon yet, a tribute to the scientists and engineers who were determined to make Apollo a genuine tool of exploration.

The *Apollo 16* mission, in April 1972, is often referred to as the only mission to the highlands, but this is incorrect: *Apollo 14* was also sent to a highland site (Fig. 3.4). *Apollo 16* was, however, the only Apollo mission whose site was distant from the maria; the landing site was located in the central highlands, near the ancient crater Descartes (Fig. 3.8). This mission is most renowned for having disproved its preflight predictions: Planners had believed that the Descartes site was composed of light-toned, highland volcanic rocks, including ancient ash flows and silica-rich dome volcanoes. The LM crew—veteran pilot John Young and newcomer Charles Duke—and the CSM pilot, Ken Mattingly, were given extensive training in volcanic terrains on Earth to prepare them for the exploration of Descartes. The skilled crew members were surprised during their moonwalks—

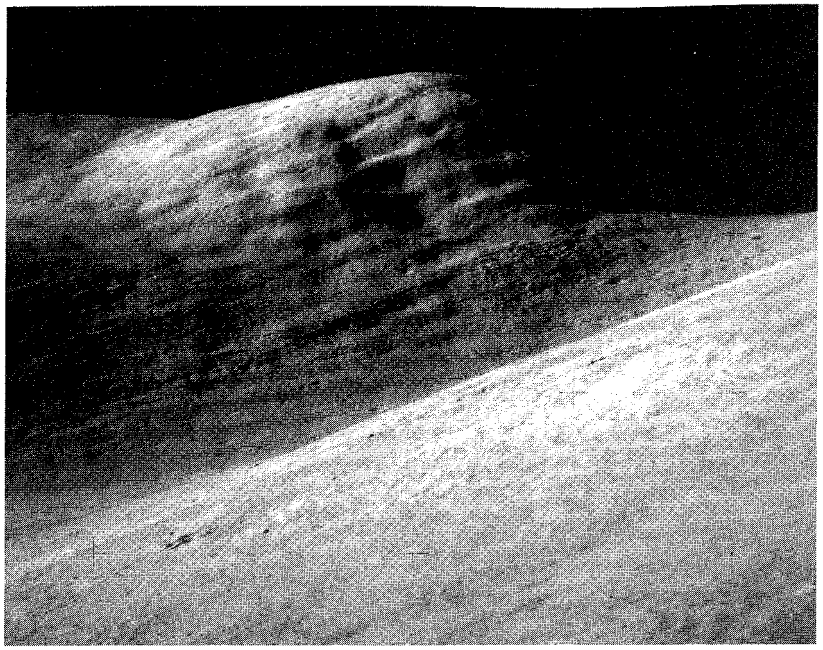

Figure 3.7. A telephoto view of the mountains at the *Apollo 15* landing site. The large ridge is called Silver Spur and may have resulted from the exposure by impact of ancient, deeply buried layers of rock. This cliff is over 600 m high.

where were all the volcanic rocks they expected? Instead almost every variety of impact breccia imaginable was found at every sampling site (Fig. 3.9).

Essentially two geological units were sampled during the *Apollo 16* mission: the wormy-textured Descartes mountains and the smooth, light-toned Cayley plains (Fig. 3.8). Each unit is made up of impact breccia, and scientists still debate whether there is any compositional difference between the two units. The rocks are made up of regolith breccias (found at all sites), fragmental breccias (made up of fragments of older rock), and impact-melt breccias (comparable to those returned previously by the *Apollo 14* and *15* missions). The melt rocks are of particular interest. These breccias have a composition distinct from the upper crust in this region; in fact, their composition more closely resembles

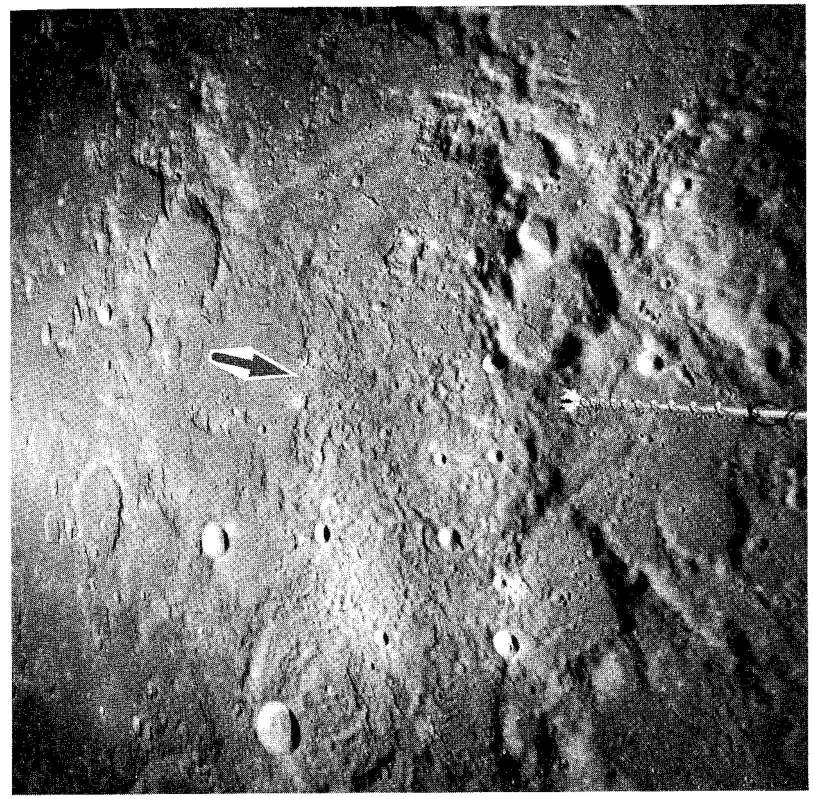

Figure 3.8. The highland area around the crater Descartes, the location of the *Apollo 16* landing site (arrow). Although ancient volcanic rocks were expected, the mission returned impact-processed rocks instead. This finding led to a major revision of our understanding of the Moon.

melts believed to be ejecta from the huge Imbrium basin, sampled earlier. How can this be, considering the great distance of the *Apollo 16* site from Imbrium? Perhaps this composition is common to many different basins, the Descartes site being rather close to the older Nectaris basin, about 300 km to the east. In any event the first Apollo mission to a "pure" highland site completely changed the way we look at the highlands. We now think that impact processes of various types, usually associated with basins, are responsible for the units that make the terrae look like a

Figure 3.9. *Apollo 16* Mission Commander John Young on the rim of North Ray crater, a large impact feature in the Descartes highlands. It is very difficult to judge distances on the Moon. The large boulder behind Young is farther away than it looks and is as big as a house.

patchwork quilt, and the role of volcanism in shaping the geology of the highlands is believed to be minor.

The final Apollo mission to the Moon was sent to the rim of the ancient Serenitatis basin, where mare lavas partly flood an ancient mountain valley. Dark mantle material coats the nearby hills; this unit was thought to be a young volcanic deposit, and it was believed that cinder cones might be found near the landing site. Astronauts Gene Cernan and Jack Schmitt (Schmitt was the first and, so far, the last professional geologist to explore the

surface) landed in the Taurus-Littrow valley in December 1972; the orbiting CSM pilot was Ron Evans. The *Apollo 17* crew traveled the farthest (almost 30 km), explored the longest (over 25 hours), and collected the most samples (more than 120 kg) of all the Apollo missions. While exploring the Moon, the astronauts found and sampled giant boulders that had rolled down the mountains—a bright "landslide" triggered by the formation of the crater Tycho, over 2,200 km away—and beautiful orange soil that glistened in the bright sunlight of the surface (Plate 5). This spectacular flight was indeed a fitting finale to man's first round of lunar exploration.

As at the *Apollo 15* site, two major terrains were explored during the *Apollo 17* mission: the mare fill of the valley and the highlands of the surrounding Taurus Mountains. The mare lavas of the valley, basalts from many different flows, are very rich in titanium, similar to the lavas sampled by the first landing, *Apollo 11*. Photographs and remote-sensing data show that these high-titanium lavas may be continuous parts of the same series of lava flows in this region. The orange soil discovered at Shorty crater (Plate 5) turned out to be an unusual black-and-orange glass (Plate 6). Like the green glass from *Apollo 15*, these glasses are volcanic ash, the product of a huge fountain of liquid rock sprayed out onto the surface. However, this ash is old, not young as had been thought by the premission analysis, having erupted about 3.6 billion years ago, just after the eruption of the lava flows. Study of samples from the bright landslide across the valley (Plate 5) indicates that the crater Tycho formed 108 million years ago, providing an important time marker to the lunar geological column. The highlands, sampled at two different mountains (or *massifs*) at different ends of the valley, are made up of a complex mixture of rocks cooled slowly at depth and excavated from the deep crust by the giant impact that created the Serenitatis basin. Various impact-melt breccias were collected and found to be grossly similar to, but different in detail from, the melt breccias collected at the other Apollo sites. The most populous group of impact melts from the *Apollo 17* site may represent the melt sheet created during the impact that formed the Serenitatis basin, as is seen in the center of the Orientale basin (Fig. 2.9).

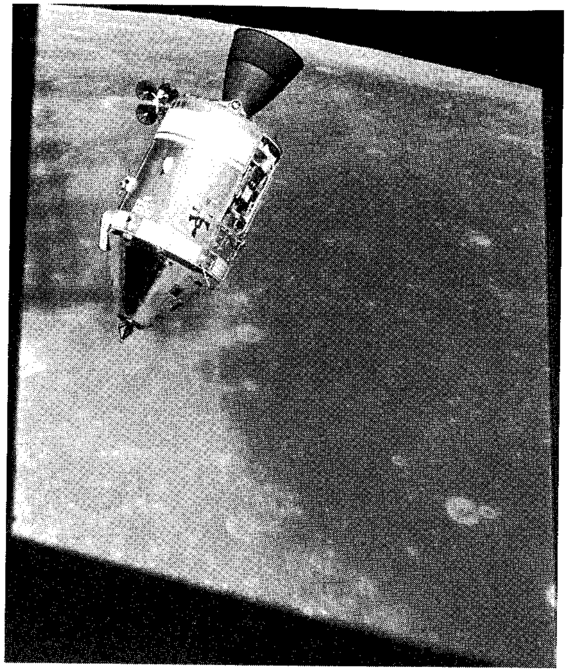

Figure 3.10. The Command-Service Modules of the Apollo spacecraft. The cylindrical module contained a bay of scientific sensors on the last three missions, allowing scientists to map the composition of the surface from orbit. The conical module (at bottom) is the only part of the Apollo spacecraft that returned to Earth.

These advanced Apollo missions carried sophisticated experiment packages in lunar orbit (Fig. 3.10). Two cameras and a laser altimeter measured the topography and shape of the Moon and took high-resolution stereo photographs, permitting detailed geological studies of different regions and processes. Sensors measuring the X-rays and gamma-rays permitted scientists to measure the chemical composition of the lunar surface. From these remotely sensed data, we first learned about regional provinces of different composition in the highlands. Other instruments detected the emission of gas from certain areas on the Moon, suggesting that the deep interior may still contain small pockets of volatile elements. On the *Apollo 15* and *16* flights, a small subsatellite was launched from the CSM, the first extraterrestrial launch of a satellite from another spacecraft. This subsatellite carried a magnetometer to measure the small magnetic field anomalies on the surface. The subsatellites also permitted the detailed gravity structure of the Moon to be mapped by tracking their radio signals. As mentioned earlier, the *Apollo 16* subsatellite lasted only two weeks before its orbit decayed because of the mascons and crashed into the Moon.

The end of the Apollo flights did not end the collection of lunar data. The sample collection, kept in a hurricane-proof vault in Houston, Texas, continues to be dissected, examined, and studied. The network of ALSEP stations on the Moon continued to send back data until it was decided to terminate the network in 1977 because of budgetary pressures. From the seismic experiment, we discovered that the Moon has an aluminum-rich crust about 60 km thick, beneath which is an iron- and magnesium-rich mantle. Probes designed to measure heat flow allowed us to estimate the amount of radioactive elements deep within the Moon and, from this, its bulk composition. We determined that the Moon has a composition similar to the mantle of Earth, and study of the isotopes of oxygen show that Earth and the Moon were made in the same part of the solar system. Both of these facts are significant constraints to models of lunar origin.

Measurements of the magnetic field of the Moon showed that local areas of the crust are magnetized, but the Moon does not possess a global magnetic field like that of Earth. Together with the relatively low bulk density of the Moon (about 3.3 g/cm^3, compared with 5.5 g/cm^3 for Earth), the lack of a global magnetic field suggests that the Moon has no large, liquid iron core, which generates Earth's global magnetic field by a process known as a core dynamo.

The *Apollo 15, 16,* and *17* missions were outstanding successes by any objective measure. The Apollo program as a whole and these missions in particular form the cornerstone of our understanding of the Moon and its history. A nearly constant debate rages in the science community regarding the value of human spaceflight versus the unmanned robotic missions. The Apollo landings demonstrated that the difference, in capability and knowledge returned, between human exploration of the Moon and small robotic missions is comparable to the difference between a nuclear bomb and a firecracker. The manned Apollo missions revolutionized our understanding of the Moon and of planetary science in a way that the unmanned robotic precursors did not and could not. The Apollo missions are lasting testimony to the value of people in the exploration of the solar system.

The Russians Went Too: Soviet Robotic Lunar Landers

In retrospect it is reasonably clear that we were indeed in a race to the Moon with the Soviets in the decade of the sixties. Soviet leaders (especially Nikita Khrushchev but also his successors) considered space spectaculars to have enormous propaganda value, with each decisive "space first" demonstrating the superiority of "progressive" Soviet science and technology over the "decadent hedonism" of the capitalist West. Because of the catastrophic explosions of their giant booster rocket (the N-1) on at least two occasions, the Soviet manned landings on the Moon never took place.

Even after the race had been lost, the Soviets made a major effort to steal some of the thunder from the Apollo program. The most notable attempt was the flight of the mysterious *Luna 15* spacecraft in July 1969, at the same time that *Apollo 11* went to the Moon. *Luna 15* was an automated spacecraft that crashed into the surface while the *Apollo 11* crew was still orbiting the Moon. Soviet news releases clumsily issued reports that their "automated moon craft completed its historic mission," but at the time there was much speculation that *Luna 15* had been designed to land and to return a scoop of lunar soil to Earth before the *Apollo 11* astronauts could bring back their samples. After the *Apollo 11* crew returned successfully, the Soviets claimed that there had never been any race to the Moon with the Americans, a ludicrous claim then and now yet one believed and repeated by many in the credulous American media.

That the mission of *Luna 15* was indeed to return a sample is suggested by the flight of *Luna 16* in September 1970. This small spacecraft (Fig. 3.11) successfully landed on Mare Fecunditatis, on the eastern edge of the near side, and returned about 100 g of soil with an ingenious drill core that was wound into a ball-shaped return capsule. The soil from this site consists of mare

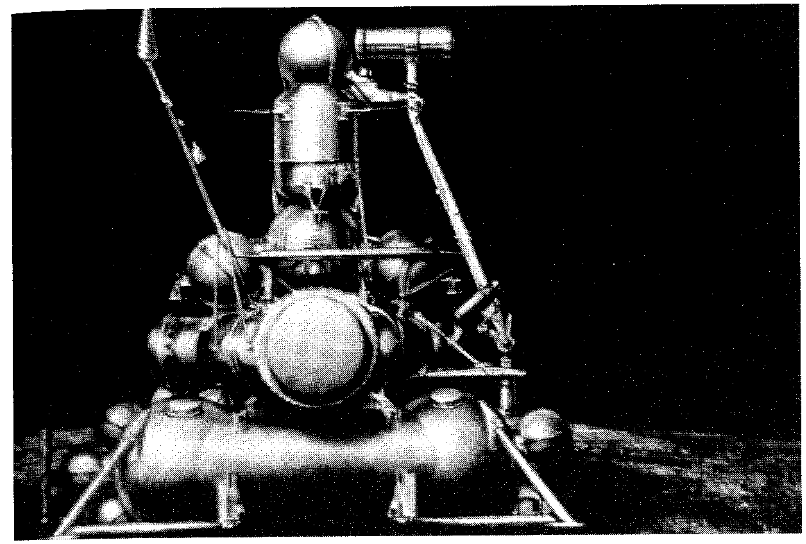

Figure 3.11. The Soviet *Luna 16* spacecraft, which returned a soil sample to Earth. Although conducted largely to steal some of the thunder from the Apollo program, these missions demonstrated that robotic return of planetary surface samples is technically feasible.

regolith, including several fragments of lava that were large enough to measure their ages. The *Luna 16* samples, mare basalts with relatively high aluminum content, erupted onto the surface 3.4 billion years ago. Abundant fragments of impact glass are also present, giving us clues to the existence of other, unsampled rock types on the Moon. The *Luna 20* mission landed on the Moon in February 1972 and was an identical copy of the *Luna 16* mission. It returned soil samples from the highlands surrounding the Crisium impact basin. The small samples are made up of tiny rock fragments of the highland crust, as at the *Apollo 16* site, and impact breccias. The final Soviet sample-return mission, *Luna 24* in August 1976, returned the largest sample to date: a 2-m core sample from the interior of Mare Crisium. These basalts are also a high aluminum variety but contain much less titanium than any Apollo sample (similar, very low titanium basalts were subsequently discovered in the soil from the *Apollo 17* landing site). The *Luna 24* basalts show that the lava flows in Mare Crisium erupted between 3.6 and 3.4 billion years ago.

The three Soviet samplers demonstrated that the robotic return of surface samples is a technically practicable tool to explore the Moon. Because of launch, flight-control, and landing constraints, these missions unfortunately were confined to landing sites on the eastern limb. It is highly desirable to be able to return samples from anywhere on the Moon. The Luna missions also show that there is not only a quantitative difference between human and robotic missions but a qualitative difference as well. We learned more about the Moon from any single Apollo mission than we did from the totality of the three Luna missions. This difference not only is related to the small mass of the returned sample from the Luna missions but also is caused by the geologically guided sampling that people can do. We understand the context of the Apollo samples much better than we do that of the Luna mission samples.

A variety of flybys, orbiters, hard landers, and rovers was also sent to the Moon by the Soviet Union. The two *Lunakhod* spacecraft were small rovers, remotely controlled from Earth. They had crude instruments and returned mostly television pictures and some data on the physical properties of the soil. However, they demonstrated that remote control of machines on the Moon is feasible. Future robotic sample-return missions should include the ability to operate the spacecraft remotely (teleoperation) so that the most significant samples can be obtained (see Chapter 10). Because the surface of the Moon is complex and varies from place to place, the ability to rove across its surface will be highly beneficial in future sample-return missions.

The Soviet lunar program, though not successful in its political objective to technically embarrass the United States, nevertheless achieved some significant scientific accomplishments that add to and enhance our understanding of the Moon. These small missions also foreshadowed the rich possibilities of small robotic spacecraft as tools for the exploration of the solar system. We will examine a variety of possible missions and their relative strengths and weaknesses when we consider future strategies for exploring the Moon (see Chapter 10).

Chapter 4

A Fall of Moondust

The Regolith

We have known for a long time that the surface of the Moon is covered with fine dust. If its surface were bare rock, we would see a bright reflection (a *specular* reflection) at the point on the Moon directly under the Sun (subsolar point) as it rotates on its axis. Such an effect is similar to the bright glare one sees when looking toward the Sun in late afternoon on a lake, ocean, or smooth body of water. Bare rock would also show this effect, although not as mirror-like as water because a rock surface would be much rougher at fine scales.

The surface of the Moon does not display this type of bright, specular reflection. In fact by carefully studying the exact way light is reflected from the surface, scientists determined that the Moon was covered everywhere by dust—very fine dust. What was not known in the pre-Apollo days was how deep such a dust layer might be. Some scientists thought that it might be hundreds of meters (if not kilometers) thick and so unconsolidated that the dust would instantly swallow up any craft landing there. Geologists looking at the Moon suspected instead that the dust layer was at most only a few meters thick. They speculated that over geological time, the rock layers postulated to make up the crust had been ground up into a powder-like dust layer by the incessant micrometeorite bombardment.

Before taking the risk of landing men on the Moon, we had to understand the nature and extent of the lunar dust layer. Thus one of the prime scientific objectives of the robotic missions flown before Apollo was to understand the surface layer—how it formed and evolved over time—and to assess its potential risk to human missions. Giving this issue priority ensured that much