15

Golden Apennine-Hadley

1971

H TO J

The Vietnam War had first call on the taxpayers' dollars, and by the time the *Eagle* landed, Apollo exploration felt the squeeze. The hopeful plans tendered at Falmouth and Santa Cruz for AAP missions, not to mention post-AAP, had already shriveled. In better years President Johnson had led the drive toward the Moon, but now he was obsessed by the war, and his last proposed budget, the one for fiscal year 1969–1970, included funds for only three landings after Apollo 11. Complex negotiations in Congress and the incoming Nixon administration, however, led to restoration of enough funds to keep NASA exploring the Moon after Apollo 14.[1]

So three more Apollos would fly before Project Apollo and the U.S. presence on the Moon came to their early ends, and the three would be dedicated grandly to solving the Moon's remaining mysteries.[2] Scientists had long set their hearts on really scientific lunar missions, on which the astronauts would perform as explorers of a new world and not just as test pilots of a new kind of experimental flying machine. The design of such missions began to take concrete form in early 1968.

In the lettered sequence of increasingly complex missions, these dream fulfillers were the J missions. A J mission could double the total stay time on the surface to almost three Earth days thanks to an "extended" lunar module with more than double the carrying capacity of an H-type LM. The astronauts would be setting up field quarters rather than dropping in for a quick visit. They would perform three EVAs rather than the two of Apollos 12 and 14, and improved backpacks could extend each EVA to the duration of an Earth day at the office minus the coffee breaks. Improved space suits allowed more flexible movement including limited knee bends. More scientific instruments could be carried to the Moon and more rocks could be brought back. There was more oxygen, power, water, and waste-disposal capacity, and more fuel in the LM descent stage to ease the extra mass down onto the surface. To send all this extra mass on the way in the first place, the already powerful Saturn 5s were upgraded and seemingly minor adjustments were made in such operational variables as launch azimuth and parking-orbit altitude.

To spectators and scientists alike, the biggest innovation was the battery-powered *lunar roving vehicle* (LRV, or rover), chosen in May 1969 by George Mueller over the flyer as the means of transporting the astronauts farther and faster than kangaroo hops could. The Marshall Space Flight Center studied the various proposals from industry and awarded the contract to Boeing in October 1969.[3] Trafficability and terrain studies for the rover involved some of the SPE geologists and recent (1968) Astrogeology Branch hire Richard Joseph Pike (b. 1937), whose Ph.D. committee at the University of Michigan had included Ralph Baldwin. The rover had independent drive and steering on all four wheels, could negotiate rugged terrain, and cruised over level ground on the order of 15 km per hour, about as fast as a San Francisco cable car. Each LRV weighed about 210 kg (on Earth) and could carry another 500 kg, yet could be folded into an incredibly small space in the LM and could be deployed in only seven minutes.

Science would also be served from orbit in new ways that had been discussed since some of the earliest proposals for manned lunar spaceflight. Thought had been given to flying the orbital instruments on Apollo 14, but in May 1969 George Mueller opted for the mission that became Apollo 15.[4] A *scientific instrument module* (SIM) with half a dozen new instruments would occupy a bay (SIM bay) of the service module that was larger than the habitable space inside the command module.[5] Metric (or mapping) and panoramic cameras would provide unequaled photographs of the strips beneath the spacecraft.[6] A laser altimeter coordinated with the metric cameras would systematically spot-check the distance between spacecraft and ground and so could roughly characterize the Moon's figure. Three chemical sensors hatched by a close-knit group of investigators mainly from JPL, Goddard, and Urey's department at UCSD would analyze the same, unfortunately narrow, strips.[7] One of the sensors was the gamma-ray spectrometer that Jim Arnold (UCSD) had long advocated, which would measure the Moon's natural radioactivity and particles that are created when cosmic rays hit the surface. It would be particularly good at detecting KREEP, and so could check whether KREEP was indigenous to the Imbrium-Procellarum region as the Apollo 12 and 14 samples suggested. An X-ray-fluorescence spectrometer from Goddard with Isidore ("Izzy") Adler as principal investigator would detect some of the most important elements in both mare and terra rocks (magnesium, aluminum, and silicon) from the interactions of solar X-rays with the surface. With luck it could map the Moon's major compositional provinces, including the suspected anorthositic terrae. An alpha-particle spectrometer would detect radioactively created radon in the Moon's upper atmosphere. After the rest of the mission was over, the astronauts would launch from the SIM bay a 38-kg subsatellite carrying a particles-and-fields detector and magnetometer; this would be tracked from Earth as it was tugged by small gravity anomalies à la Lunar Orbiter. Because the service module was destined to burn up in Earth's atmosphere, the CMP would retrieve the mapping and panoramic film magazines from the SIM bay by space walking during the coast through interplanetary space back to Earth.

Apollo 15 turned out to be the first J mission. Originally it was to have been an H mission whose most likely landing sites were Censorinus, the small young drill hole in the Nectaris basin rim; Littrow, which had been the Apollo 14 prime site before the Apollo 13 abort; or the linear Davy chain of craters, the favorite of a large faction of GLEP as a likely source of deep lunar material. Astronauts conducting an H mission on foot might sample Imbrium basin ejecta, "upland fill" (light plains or mantles thought to be volcanic), and possibly other terra rocks in addition to the putative deep material, all within a relatively small area somewhere along the chain.

A prime crew of Dave Scott, Jim Irwin (LMP), and Al Worden (CMP), who had been together before as the backup crew for Apollo 12, was named for Apollo 15 on 26 March 1970. Scott had flown with Neil Armstrong in the nearly disastrous Gemini 8 mission in March 1966 and was CMP of Apollo 9 in March 1968. Irwin and Worden had not flown in space. Dick Gordon, CMP of Apollo 12, was the backup commander, and rookie Vance Brand was the backup CMP. The backup LMP, also making his debut on a crew, was geologist-astronaut Jack Schmitt.

Three weeks later the Apollo 13 accident sent the planners back to square one. Subsequent missions had to be postponed until the hardware was checked and put back in order. There was now extra time to fabricate the J-type extended LM and the rover, raising the possibility that the next flight after Apollo 14 might be a J mission.

THE GEOLOGIC CREW

The commander of Apollo 15, David Randolph Scott (b. 1932), occupies a special place among the explorers of the rocky Moon. His academic work was in aeronautical engineering (MIT), and he was very much a pilot and air force man (his father was a general). However, geologists who worked with him are unstinting in their praise of his interest and ability in their subject. Like many geologists, including me, he had long been interested in history and archaeology, and had shown his interest and understanding of geologic and other scientific matters during his training in 1964. When the enthusiastic Lee Silver got hold of him, his interest blossomed into excitement and total commitment. Several members of the geology team believe that Scott transmitted his enthusiasm to Irwin and the later J-mission crews, and the record shows that Apollo 15 represented the beginning of a short but sweet era of immersion in geology that also characterized Young, Duke, Cernan, and Schmitt. Scott has said that after an early stage of learning geologic terms by rote, he soon began to think with them as with a natural language. Two anecdotes from later years confirm his interest: he collects rocks during all his earthly travels and built a fancy rock cabinet to hold his collection; and his wife had to take a geology course to be able to communicate with him.

Apollo 15 was also fortunate in the other two crew members, LMP James Benson Irwin (1930–1991) and CMP Alfred Merrill Worden (b. 1932). Irwin geologized well, and so devotedly that he apparently damaged himself physically, as we shall see. Worden was an enthusiastic and staunch observer from orbit, and he affected the site of a future landing when he commented on the small, dark cones and patches on the massifs of the Taurus Mountains on the eastern rim of Mare Serenitatis. Irwin also authored one of the few autobiographies by an astronaut (1973), and Worden the only book of poetry (1974).

The geologic conduct of Apollo 15 also was fortunate in the people who stayed on the ground. Gordon Swann continued as geology team leader. He was an excellent consensus man who could mediate between the rival USGS and MSC factions despite being clearly wedded to one of them, and he was adept at establishing ties with the local Texans in the operational end of MSC because he spoke their language and drank their beer. There was still no official geology training program when preparation for Apollo 15 began; training for Apollo 14 had been ad hoc, as the results demonstrate. Jim Lovell, who had experienced Lee Silver's effectiveness during the Apollo 13 training, advised Scott that Silver was the man to lead the Apollo 15 crew's training. Silver had been too pressed for time to take on the Apollo 14 training, but (on the weekend of the Apollo 13 launch) willingly accepted the challenge of the later Apollo 15. Silver started Scott and Irwin in the Orocopia Mountains, where he had first tasted astronaut training with the Apollo 13 crews, an ideal place for reviewing the basic principles of field geology—"review" because all had been immersed in geology before. Shuttling constantly back and forth between Caltech and the field areas, Silver supervised most of the Apollo 15 training trips and also translated other geologists' comments into a form understandable to NASA and the astronauts.

Paul Gast, always determined to carve a larger piece of the action for Calio's

Science and Applications Directorate, named a mission science trainer as the MSC counterpart to Swann. The first such position, for Apollo 15, was held by geologist Gary Lofgren. Gary had come to MSC in August 1968 and got his feet wet with Apollo 13, but did nothing with Apollo 14 because the Apollo 15 training was already under way. Gary and others among Gast's geologists and petrologists, like Bill Phinney and Grant Heiken, got along well as individuals with the USGS team and contributed much to the enormous training work load.[8] Nevertheless, the USGS played the greater role in the Apollo 15 training and an almost exclusive role in the back-room operations.[9]

The Apollo 15 crew went on at least 16 geologic field trips between May 1970 and May 1971, no small bite out of their total mission preparation. The pace of the training became brutal for the geologists of SPE and MSC because the Apollo 15 exercises overlapped with exercises for Apollo 14 at the beginning and a one-per-month series for Apollo 16 at the end. These were no reconnaissance tours or abstract exercises like those we conducted in 1964 and 1965, but intensive, down-to-earth simulations of lunar observing and reporting. For Apollo 15 alone some 30 EVAS, of about the length they would be on the Moon, were simulated either on foot or with a rover mock-up named Grover (essentially, geologic rover), built in the summer of 1970 at Flagstaff for a few thousand dollars. Silver sometimes ran along behind Grover to see what the astronauts were seeing so he could judge their observations. In addition to the field teams, Lofgren, and one or two other MSC geologists, each drill was accompanied by the astronaut mission scientist who would serve as the capcom for the EVAS of the mission. For Apollo 15 this was Joseph Percival Allen IV (b. 1937; Yale physics Ph.D.), a member of the sixth group of astronauts and universally known as Little Joe. Silver and Swann described Allen as a smart, talented, and smooth intermediary between themselves, on the one hand, and MSC and the astronauts, on the other.

In June 1970 the Apollo 15 crew revisited Meteor Crater and later the Nevada Test Site, this time under the guidance not of Shoemaker or Silver but of U.S. Air Force Reserve Colonel David J. Roddy, Astrogeology's Dr. Strangelove, who worked for many years with the "Defense community" interpreting large explosions. Roddy also took the Apollo 15 and 16 crews to the Canadian-U.S. test ground at Suffield, Alberta, to watch a large TNT explosion make an 86-m-wide crater (Dial Pack). During a busy July, Swann and Tim Hait briefed the Apollo 15 crew on the lessons learned from the Apollo 11 and 12 photography; Hait and small-plane pilot Don Elston conducted a two-day exercise in aerial observations over the many volcanic features near Flagstaff for CMPS Worden and Brand; and Silver, Swann, and George Ulrich led Scott, Irwin, Gordon, and Schmitt in the first EVA exercise with equipment in some of the same terrain. In the same month the tireless Silver and Hait took the future Apollo 16 crew of John Young and Charlie Duke on an extensive tour that included a fly-around in northern New Mexico and fieldwork in one of Silver's former field areas, the San Juan Mountains of Colorado, which feature blocks of rubble fallen from the mountains (talus) and consisting of volcanic tuff breccias that could simulate lunar breccia-in-breccia textures of impact origin. They repeated the San Juan trip in August for the Apollo 15 crew.

September 1970 was a big month for Apollo 15. The crew and their instructors examined a deep-penetrating volcanic vent (diatreme) with a breccia-filled neck at Buell Park, Arizona, where Schmitt and Silver had both worked. Diatremes had been important in Gene Shoemaker's lunar self-education and were still thought to be a Davy analogue. Two of MSC's extraordinarily competent flight directors, Glynn Lunney and Gerald Griffen, observed the proceedings to find out whether the field exercises were realistic preparation for the Moon. They were. But Davy analogues went out of style during the month when, on 2 September, two Apollo missions were axed. One victim was Apollo 20, and the other was the Apollo 15 H mission. The J slot that had been assigned to Apollo 16 went to Apollo 15. Apollo 16 astronauts Young and Duke got the news while in Flagstaff for a training exercise on more diatremes and the local volcanics and were temporarily depressed at losing the chance to fly the first J mission.[10] A J mission had been designed for Davy, but whether it would exhibit deep material or fulfill any other miscellaneous desires of its supporters was too uncertain to justify sending one of the three remaining Apollos there.

When they submitted their proposals to become leaders of the Apollo field geology teams, Gordon Swann had proposed for the H missions and Bill Muehlberger for the J missions. In accord with the distribution plan for H and J missions at the time, Gordon's proposal had been accepted for Apollos 14 and 15. Apollo 15's conversion to a J mission thus placed them in a dilemma. If one of them had been a NASA geologist, a furious squabble would probably have ensued. But they easily came to a gentlemen's agreement whereby they split the remaining missions and Gordon continued to lead the Apollo 15 team.

A SPECIAL SITE

The landing site of Apollo 15 was also finally decided in September 1970. J missions could explore more complex sites than simple point targets like Censorinus, Littrow, and Davy. They could even go outside the equatorial belt because ways had been found to reduce SPS propellant consumption without giving up the trajectories that permitted a safe return to Earth in an emergency.

One nonequatorial site that had always attracted scientists and laymen alike was the western foot of the Apennine Mountains (Montes Apenninus), which are part of the Imbrium basin rim. The steep western scarp of the Apennines faces the basin, and the gentler eastern flank slopes away from it. Here, within reach of an LRV and possibly even a man on foot, were not only a vertical stratigraphic section of rock beds ripe for sampling but also one of the largest sinuous rilles, Rima Hadley, and a patch of mare whose unfortunate name, Swamp of Decay, could hide in the original Latin, Palus Putredinis. To cover its many features, we Lunar Orbiter targeters had Orbiter 5 photograph Apennine-Hadley in a "slow-4" mode that stretched out the length of the photographic footprint while putting space between the high-resolution frames. In 1967 GLEP listed Apennine-Hadley as an AAP mission because it seemed both rich in objectives and hard to reach.

The region happened to be covered by one of the best telescopic photographs ever made, taken by astronomer George Herbig in 1962 with a primitive camera attached to the 3-m reflecting telescope at Lick Observatory while he was waiting for the Moon to set so he could turn to more interesting objects. The rille, a special feature par excellence, had drawn all eyes ever since that photograph was published. I saw it in a newspaper in November 1962 and remember making some dumb remark about a Russian bulldozer track—recall who was leading the space race then. So originally it was the rille rather than the Apennines that attracted attention to the site. Knowing the process of rille cutting was considered important for understanding lunar processes and materials. The most respectable theory was origin as a lava channel or tube, as Kuiper and Strom proposed. Other ideas included a pull-apart crack due to shrinkage (I think Jack Schmitt liked this one); a channel eroded by hot ash flows, as the tektites-from-the-Moon people believed; or a river channel, as Harold Urey and an otherwise enlightened group of physicists at UCLA had fantasized before Apollo 11 and as John Gilvarry still did afterward.[11] Some Lunar Orbiter and GLEP targeters imagined that the arrowhead-shaped south end of the rille that seems to be its source might be an active source of volatiles, or at least a trap for them. Other conspicuous rilles (Rima Prinz I, Schröter's Valley, two in the Marius Hills) had therefore been major competitors for the Hadley mission in the late 1960s.

Although the likelihood of volatile eruptions seemed lessened by earlier findings of the Moon's antiquity and quiescence, interest in the Apennines persisted because they were thought to be likely sources of Imbrium basin ejecta and samples from deep within the crust. Shoemaker's study of Meteor Crater and nuclear craters had led to a model of overturned ejecta "flaps" whereby the Imbrium ejecta at the top of the Apennines would have come from greater depths than did the Fra Mauro Formation at the Apollo 14 site. Other deep samples might be exposed along the Apennine Front beneath the Imbrium ejecta. Some of these might have come from ejecta of the Serenitatis basin, which is cut off by the Apennines (see frontispiece) and so probably became incorporated in them when they were created. There was even hope that undisturbed primitive crustal rock might underlie the Serenitatis ejecta along the front.

Davy finally expired when MSC engineers eased the operational difficulties at Apennine-Hadley and changed the requirements for photographic site certification. They found a way for the LM to clear the Apennine crest, which towers 4,000 m above Palus Putredinis, and then descend in a new steep (25°) trajectory to the landing site. Although this change would also have benefited Davy, which lies west of (down track from) large crater rims, it gave Apennine-Hadley the critical boost it needed to vanquish Davy. Also, landing safety could now be certified by extrapolating terrain information into the Orbiter M-frame coverage from nearby H frames, so gaps between the H frames were no longer a cause for rejecting a site for landing. On the other hand, some stereoscopic coverage was still required, but none would be available soon enough to plan a Davy mission because Apollo 13 never got around to the near side and Apollo 14 would come too late. The same obstacle excluded Descartes as the Apollo 15 site.

Its northern position put Apennine-Hadley on one corner of long-legged triangles with the Apollo 12 and 14 ALSEPs for establishing a seismic network, and with the Apollo 11 and 14 laser reflectors for establishing a triangulation network. The inclined orbits of the CSM that overflew it would carry the geochemical and geophysical experiments and cameras over new, nonequatorial parts of the Moon not reached before and not reachable from Davy, including the mascon basins Serenitatis and Imbrium. The allegedly rare volcanic rocks of the Marius Hills remained in competition for the J-1 slot until quite late, but geophysicists, some geochemists, and mission commander Dave Scott all favored Apennine-Hadley.[12] Jack McCauley has told me that it is his least favorite site (as Apollo 12 is mine) because the importance of the rille was overblown, and he has a point. Nevertheless, Apennine-Hadley was approved as the Apollo 15 landing site by the ASSB on 24 September 1970, a week after the Saturn 5 was erected in the Vehicle Assembly Building. The landing point was fine-tuned by Bellcomm and the USGS. Jim Head favored one within range of the 350-m Elbow crater, named for a 90° bend in Hadley Rille, because it looked like a good drill hole in the adjacent Apennine Front. Hal Masursky argued for the arrowhead. Noel Hinners was the man to convince, and Head succeeded. I am glad he did; the arrowhead would have been a difficult landing site, and if anything unusual is there, it is probably out of reach.

Subsequent geologic training included rocks and landforms like those expectable in the lunar mountains, maria, and sinuous rilles. Anorthosites had held special fascination for petrologists as likely components of the terrae ever since

Armstrong and Aldrin had brought back some grains given this name, so in October 1970 MSC petrologist Bill Phinney led a tour of the Duluth Complex of gabbro and anorthosite at Ely, Minnesota. In November, Silver led a trip to the thrice-deformed or brecciated anorthosites in the San Gabriel Mountains above Caltech.

The training, of course, also stressed basalt flows and constructional landforms. The young examples of the old training standby near Flagstaff were visited in that same November 1970 — a busy month, with Shepard and Mitchell training farther south at the artificial crater field in the Verde Valley and the Apollo 16 crew at the NTS with Dave Roddy. Dale Jackson had passed through MSC's anti-Jackson filter with the full support of Silver, Muehlberger, Swann, Shoemaker, and the J-mission crews, and in December 1970 he reappeared in the thick of a training program in another old volcanic standby, Hawaii. Also participating was Dallas Peck (since 1981 the director of the USGS), a Caltech graduate who had worked extensively in Hawaii and who continued as an active member of the geology team. The geologists led the Apollo 15 crew through five EVA exercises, including one at Kapoho, an unvegetated 1960 eruption site the Apollo 12 crew had considered the most moonlike of all their training sites, which comes complete with secondary-impact craters from volcanic bombs and a regolith-like cover of tuff (created by contact of lava with water).

The training pace continued through the winter. In January and February 1971 (the month of Apollo 14) Gary Lofgren ran exercises at the maars of Kilbourne Hole in New Mexico and the Ubehebe group near Death Valley. In March the crews walked and drove Grover along the edge of the gorge of the Rio Grande to anticipate what could be done along the edge of Hadley Rille, and explored the flank of the nearby Picuris Range as they would the Apennines.

Every new mission sent USGS geologists into action making maps. The field geology teams, who came from the SPE Branch in Flagstaff and from academia, prepared the detailed mission maps. But the regional maps were made by the Astrogeologic Studies Branch, in the case of Apollo 15 by Mike Carr and Keith Howard at Menlo Park, with some help on Mike's 1:250,000-scale map from Farouk El-Baz of Bellcomm.[13] As is true for all the earlier landing sites, their mapping and interpretations remain mostly valid today. Being right can be a nice feeling, and we all enjoyed it while we could.

In April 1971 Silver and a crowd of 11 geologists from the USGS, MSC, and Bellcomm (namely, Jim Head) took the six astronauts of the prime and backup crews plus future capcoms Joe Allen, Bob Parker, and Karl Henize to the Coso Hills in the China Lake Naval Weapons Center in the California desert. The Cosos are an attractive place if you are a geologist or astronaut-geologist and want to see what rocks look like without such things as trees or grass to obscure e view. Several kinds of volcanic rock and volcanic landforms lie near hills onsisting of older rock, just as the basalts of Palus Putredinis lie near the Apennine Front. Emphasis was on sampling and geologically characterizing the inaccessible mountains by selective sampling of the debris at their bases, an unsurpassable bit of preparation for the Moon. Special-feature lovers thought the obsidian domes at the Cosos might serve as analogues for an Apollo 15 mission objective added by the geology team: a group of dark, irregular hills north of the site that Gerry Schaber named North Complex. NASA and the MSC engineers wondered why so much training was needed, so the Coso exercise was observed by a high-level delegation from the headquarters Apollo Program Office, including no less than the program director, Rocco Petrone, the exploration director, Lee Scherer, the mission director, Chester Lee, the surface-experiments program manager, Don Beattie, and, briefly, from MSC, George Low. The whole interplay among astronaut observers, geologist monitors, and flight controller and capcom intermediaries was practiced. The geologists who had been on the team in December 1967 had attended flight controllers' school, so everyone would know what everyone else was doing during a mission. The CMPs overflew the Coso region as they would Apennine-Hadley. A subsequent trip to the NTS in May 1971 was similarly observed by the masterful flight director who had talked Apollo 11 down and Apollo 13 through its most dangerous period, Gene Kranz. Anything that was going to consume as much time and effort as all this geology had better be workable through the system of flight directors and controllers who ran the mission.

In addition to fieldwork, the Apollo 15 crew received 80 hours of classroom lectures from 15 different scientists, including Silver, Swann, Schaber, El-Baz, Head, and others brought in from outside MSC for the purpose. MSC petrologists conducted rock identification courses and took the astronauts into the Lunar Receiving Laboratory to see actual samples of Moon rocks. Photogeologists devoted another 80 hours in Menlo Park, Flagstaff, Houston, and the Cape to briefing the crews, especially CMPs Worden and Brand, about what could be seen from orbit. Bill Muehlberger estimates that each J-mission astronaut earned the equivalent of a master's degree in geology; in fact, they probably saw more geology than the average master's recipient.

The rover was completed by a hustling Boeing in February 1971 and handed over to Marshall in March. After checkout it was stowed in the extended lunar module *Falcon* in May. The scientific exploration of the Moon by Americans was in full flower, and the Soviet program was almost forgotten here until cosmonauts Georgi Dobrovolsky, Vladislav Volkov, and Viktor Patsayev died on 30 June (Moscow time) when the atmosphere of their Soyuz 11 escaped into space during reentry after 24 days in orbit.[14]

The last full-blown exercise before Apollo 15 lifted off was a remote simulation between George Ulrich and the crew on the south rim of the Little Colorado River gorge and Grey Mountain near Cameron, Arizona, and Swann's team in a back room in Houston in June. Silver, Muehlberger, and SPE also organized the shipment to Cape Kennedy of railcars full of every type of rock expectable at Apennine-Hadley from the San Gabriels, Flagstaff, Texas, and North Carolina. These rocks were dumped on the Florida sand and prepared for last-minute training exercises by Ulrich and volcanologist Edward Wolfe. One minor hitch arose when a bulldozer operator turned Hadley Rille into a ridge because he saw the lunar photograph he was given in reversed relief, a common problem for novices. The local rattlesnakes caused another hitch because for the first time in their lives they had rocks to hide in. They had to be chased out by shovel crews before each exercise, avoiding the absurd headline, "Moon Shot Scrubbed by Snakebite." Finally, the crew invited Silver, Swann, Schaber, Head, and Jack Sevier to the Cape four days before the launch for one last review of the problems they might expect.

ON THE PLAIN AT HADLEY

The three explorers lifted off at 1334 GMT (9:34 A.M. EDT) on 26 July 1971. Three days later the CSM and the S4-B got to the Moon on separate paths, and the S4-B struck the surface at 2059 GMT on 29 July, 185 km east-northeast of the Apollo 14 ALSEP. Just after orbital insertion, Dave Scott waxed ecstatic about his first view of the Moon from orbit, eliciting a grumble from Alan Shepard, listening to the air-to-ground communication while preparing for a television interview, "To hell with that shit, give us details of the burn."[15]

Falcon (named for the air force mascot) landed on Palus Putredinus at 2216 GMT on 30 July 1971 at 26.10° N, 3.65° E, settling at a 10° angle that caused the flight controllers in Houston to compare it sarcastically with the Leaning Tower of Pisa. Scott's equivalent of "Houston, Tranquillity Base here. The *Eagle* has landed" was "Okay, Houston. The *Falcon* is on the plain at Hadley." As with Apollo 11, the problem was exactly *where* on the plain at Hadley. On the way down Scott had had a good view of the general landing site, including Hadley Rille, but not of the landing point, which did not stand out as distinctly as it had during the simulations. Once on the ground, Scott told Ed Mitchell that "the general terrain looks exactly like what you had on 14," and added poignantly, "It's very hummocky, and, as you know, in this kind of terrain you can hardly see over your eyebrows. There's very little to tell us exactly where we are." Not until Al Worden passing overhead in the command module *Endeavour* (for Captain

Cook's ship) spotted *Falcon* two hours after landing did their approximate location become known.

Most of the next two hours were consumed with interchanges of numerical data with Houston, putting the already fatigued geologists in the back rooms (now three in number) to sleep. The surface EVAs would not begin until after a rest period. Because of the uncertain location and nature of the terrain that the LRV would have to traverse, and to relieve his excitement, Scott had the idea of performing a "stand-up EVA" (SEVA) from the open hatch on top of the LM, reminding Irwin of the Desert Fox in his Panzer.[16] Four and a half minutes into the SEVA Scott woke up the back rooms with, "Oh boy, what a view." In his book Irwin compares the scene to a beautiful little valley in the mountains of Colorado high above timberline, with the Apennines glowing gold and brown—the Moon's typical color—in the early morning sunshine. Scott took panoramas with the 60- and 500-mm lenses of the Hasselblad, the only time this was done from an open LM. Then he began what many who heard it rank as the best geological description by an astronaut on the Moon. He described in detail the terrain in all directions from the LM relative to landmarks with which he was already thoroughly familiar. In the mountains, he noted the smoothing of the peaks and the absence of large boulders, caused by the steady assault of lunar erosion. He aimed the 500-mm lens at a part of the Apennines named Silver Spur in honor of his mentor, observing distinct benches that may represent distinct rock layers. Scott also photographed and described intersecting sets of striations on all the mountain slopes and commented that Mount Hadley was the best-organized mountain he had ever seen.[17] But not all structures that seem like beds of rock are real. They are the surface equivalent of the telescopic lunar grid: they change with changing Sun illumination. Norman ("Red") Bailey, George Ulrich, and Keith Howard later reproduced them on piles of powder.[18] Every close observer of Earth's outdoors has noted the same thing on grassy hillsides.

After three quarters of an hour Scott closed the hatch, then resumed his reconnaissance preview of Apennine-Hadley through the LM window. He and the capcom (Joe Allen during the SEVA and now) worked on refining the position of *Falcon,* and Scott described the size distribution of craters and the white, light gray, and black debris on the Hadley plain. After an hour and a quarter he closed out his narrative, and he and his roommate buttoned down the LM and went to sleep despite the noises of pumps and fans that made Irwin compare the LM to a boiler room.

After their wake-up call the next day Scott, Irwin, and capcom Bob Parker reviewed the plan for the first EVA, which had to be slightly altered because *Falcon* was a little north of the nominal starting point. Parker suggested that the rover might make up some time because the plain was so nice and flat, but Scott reminded him about all those 3–4-m craters he had seen and described. Parker forwarded the fairly obvious "motherhood" (his term) suggestion from the geologists in the back room to take "selected samples at the crew's convenience at the end of the EVA."

After three and a half hours of talk and preparation, Scott descended and saw that the rough topography not only caused the lean of the LM but also had damaged the descent engine bell. After Irwin descended, they unpacked the LRV and headed south toward the 2.25-km-diameter St. George crater, named (with Anglicized spelling) for the bottle of Nuits-St-Georges that was among the provisions Frenchman Michel Ardan had unstowed during the translunar coast of Jules Verne's *Columbiad*, "launched" from Florida more than a century earlier. Geologists had assumed that St. George had brought Apennine material to the surface because it punches into a 3,400-m-high peaklike massif of the Apennine Front known as Hadley Delta. The astronauts' immediate objective was Elbow crater, where the bend in Hadley Rille touches Hadley Delta. They bounced around bucking-bronco style, commenting that they could not do without their seat belts, and had some trouble driving toward the zero-phase point directly away from the Sun. The steering mechanism of the front wheels did not work, but driver Scott managed to steer with the rear wheels. His only trouble was keeping his eyes on the road amidst the fascinating moonscape. They looked east along the front and confirmed the near absence of blocks so disturbing to a geologist, although Irwin reported seeing one large one about a quarter of the way up the front. The edge of the rille was another matter; Irwin commented that its large rocks looked like the ones on the rim of Apollo 14's Cone crater. They drove a little farther, looked into and photographed the rille from a scenic vista point, and commented that the far side of the rille was much blockier than the near side next to St. George. So they were establishing once again that lunar mare basalt is more nearly intact than lunar terra rock. Sun illumination had led inexperienced observers to think that the east-west leg of Hadley Rille is shallower than the north-south legs, but Scott and Irwin disabused them of this astronomical-era illusion. Nevertheless, Scott toyed with the idea of driving down into it. This was not widely regarded as a good idea, though I am told Scott still thinks it could have been done.

Finally, after some disagreement about which crater was Elbow, they found it, and its east rim became Apollo 15 Station 1. As would be the usual practice at a new station, Irwin took a panorama with his Hasselblad while a competent and well-liked flight controller in Houston called "Captain Video" (Edward Fendell) panned around the television camera, now mounted on the rover. The television ratings for Moon landings would never again be at the Apollo 11 or Apollo 13 levels, despite the employment of a superb new high-resolution color TV camera specially designed for Apollo by NASA, RCA, and CBS that was worlds ahead of the cheap black-and-white job of Apollo 11 or the Sun-sensitive one of Apollo 12. However, the transmissions changed the career plans of at least one young student, Paul Dee Spudis (b. 1952), who was watching with fascination in Scottsdale, Arizona. Paul had been training to be an electrical engineer (the leading profession in Apollo), but he switched to geology because of Apollo 15 and is my heir apparent in the Moon business.

After 25 minutes at Elbow, Scott and Irwin proceeded up the front on the flank of St. George crater to Station 2, commenting on the beauty of the view, the (false) lineaments, and finally spotting some good boulders, one of which (a KREEP-rich regolith breccia) they sampled and described in detail. Scott reminded anyone who might have forgotten where they were that these rocks had been sitting there since before creatures swam the seas of Earth — though that particular breccia turned out to have been in position "only" a few million years. They observed the splattering of rocks by impact glass that would prove to be common on the Moon and turned over the boulder to sample the undisturbed soil beneath it, sharing with capcom Joe Allen their evident excitement at doing real geologic fieldwork. At Station 2 they also made the first use of a small rake suggested by Lee Silver. Since the intense and minute examination characteristic of lunar sample analysis could do so much with small samples, Silver thought the J missions should collect many more. Therefore, he designed a rake with tines spaced widely enough to allow fine soil particles to escape collection but close enough together to capture all samples between about 0.5 and 6 cm ("walnut size") within a given volume of regolith, thus giving a systematic, representative, and unbiased sample. But St. George was not really the key to the mountains that had been hoped. Rocks were rare, and the samples turned out to be breccias that included more mare basalt than terra rock. Here again was seen the effect of impacts throwing rock from one bedrock unit to another.

An hour and a quarter after arriving at Elbow, Scott and Irwin left St. George and headed back toward the LM (which they could not see from the front), finding that driving northward, away from the Sun, was easier than going toward it. They saw the tracks their rover had made on the way south, observing that they penetrated only about half an inch and remarking, "Somebody else has been here." En route Irwin suddenly interrupted his description of more false linear patterns with the question, "How come we stopped?" Scott answered for the benefit of Houston, "I got to put my seatbelt on," but in fact he had seen a beautifully vesicular basalt he just had to have and was exercising his prerogative as an on-the-spot explorer to bend the preordained plan a little. The rock has since become known as the seatbelt basalt. Resuming the drive, they watched the LM come in and out of view because of the hills and dales of the cratered mare surface, just as the hummocks of the Fra Mauro Formation and Cone crater had blocked the view of Shepard and Mitchell. There were so many rocks but so little time, and after a total drive of 9 km they arrived back at the LM two and a quarter hours after leaving it.

At the end of the EVA (instead of the beginning, as before), Irwin hung the ALSEP on the barbell and carried it about 100 m from the LM, where he set up the central station after a few tense minutes in which it failed to erect itself when he released what he thought were all its confining bolts.[19] At the same time Scott was having even worse trouble with one of the mission's scientific innovations, a "deep" drill. He was supposed to drill three 3-m holes, one for extracting a long core and the other two to emplace heat-flow probes. A planet's interior heat not only determines how much differentiation and volcanism will occur but also how dynamically its surface is deformed by internal forces. Measurements of the lunar heat flow were therefore given high priority on the J missions, especially since the only H-mission heat-flow experiment, carried on Apollo 13, did not make it to the Moon's surface. Scott could get the drill to penetrate only about a meter before he had to give up temporarily and deploy the solar wind foil and a new, larger LR^3. As at the Apollo 12 and 14 sites, the ALSEP included a passive seismometer—a factor, along with the LR^3, in the selection of this northern point for the landing—and a typical set of the other geoscience and sky science instruments (appendix 2).

Back in the LM, Scott and Irwin spent more than two hours talking with Joe Allen about details of the sampling, drilling, visual observations, and, still, their exact location. The work of emplacing the experiments and gripping rocks and tools had caused great pain in their fingers. In the LM they found the reason was pressure exerted by their tight-fitting gloves—partly because their fingernails had grown during the trip and partly because they had perspired copiously. That perspiration, combined with the nonfunctioning of Irwin's drinking-water bag in his spacesuit on all three EVAs, was ominous. When you lose your bodily fluids you also flush out potassium, and without potassium your heart muscles can be damaged. On returning to the LM they gulped down water, but Irwin suffered several heart attacks between 1973[20] and a fatal one in 1991.

A GREAT DAY IN THE FIELD

The second EVA was devoted to a prime geological traverse that finally gave Scott the freedom to explore that he had wanted.[21] Joe Allen and a new subdivision of the geology team, known as the planning team and housed in a separate room from the larger EVA team, had reviewed what happened the day before and sent up some modifications to the plan. They were to bypass Station 4 at a secondary crater called Dune on the outbound traverse and proceed directly to the Apennine Front, where they should look for crystalline igneous rocks rather than breccias. While Scott was trying the drill again at the end of the EVA, Irwin could do near the LM what had been planned for Station 8. The object of the changes was to maximize the science while minimizing travel time. When Allen asked if there were questions, Scott replied, "No, no questions Joe. You're really talking our language today." He descended the ladder at 1149 GMT on 1 August 1971 after more than 16 hours in the LM, picked up some more samples, and after an hour bounced off with Irwin 5 km south-southeast across the rough mare surface toward the main mission objective, Hadley Delta. Their first stop was the easternmost of the entire mission, Station 6, almost 3 km east of the stations they had visited the previous day. Irwin pointed out a string of craters on the flank of Hadley Delta — the only craters they could see up there — whose orientation, they both inferred, marked them as secondary-impact craters of a primary crater north of their position. Possibly they are an extension of the cluster that includes Dune (South Cluster), whose source is Autolycus or possibly Aristillus, 150 and 250 km to the north, respectively, but the geology team never identified the craters on a photograph. When the astronauts got to the front they noticed the relative absence of the deep craters they had been seeing on the mare plain.

They were looking for rocks but quickly confirmed what they had observed already: rocks are rare on the slopes of lunar mountains. The succession of superposed beds representing ancient, pre-Imbrian basin and mare deposits that we all hoped to find is not visible, except possibly on the distant Silver Spur. Instead, the slopes are covered by mixed, messy debris of the type seen on all lunar close-up photographs since Ranger 7's and that is responsible for quickly degrading craters on steep slopes. The LRV took them effortlessly a kilometer up the steep slope, an impossible achievement had they been on foot. From a distance, one sample looked pretty much like another at Station 6 because all were covered with dust. But Scott and Irwin knew they were collecting breccias of somewhat differing types. After about an hour at Station 6, they headed west toward a large block that the back room thought was near Spur crater.

En route they stopped at Station 6A, up a very steep slope from Spur crater, where Irwin was surprised to see a change from the usual variations on the standard lunar tan: on top of an otherwise ordinary breccia block was a layer that looked distinctly green. More green appeared where their boots kicked through the surficial soil. Here were weakly cohesive clods of green glass that would later add an important clue about the deep interior of the Moon. Then they eased their way about 200 m down the hill to Spur crater, where they found more green — and gold.

I refer to a famous comment made by Dave Scott at Spur crater (Station 7) that they had found a gold mine of geologic richness. Fifteen minutes after arriving at the station Scott spotted a big boulder with "gray clasts and white clasts, and oh boy — it's a beaut!" But then a white rock sitting on a mound of indurated soil caught their attention. Discussion of how to sample it led Irwin to suggest that Scott simply lift it off its pedestal, which he did. Then, "Guess what we found! Guess what we just found!" Irwin replied, "I think we found what we came for." They had seen the glint of large white crystals with characteristic parallel striations that someone trained in mineralogy could readily identify as plagioclase twinning. Scott ventured the comment, "Almost all plag . . . something close to anorthosite, because it's crystalline and there's just a bunch — it's almost all plag" — as indeed it is, 98%. So here was a 269-g piece of the eagerly sought anorthosite in the mountains of the Moon, exactly where one hoped to find it, and sitting on a pedestal yet. A piece of the original lunar crust! — so it was thought then, and so it still appears. The boys in the back room could not contain their exhilaration any more than could Scott and Irwin, and reporters at a press conference picked up the excitement and named sample 15415 the Genesis rock even before it got back to Earth.

Five minutes later there was more excitement as Scott exclaimed, "Oh, look at this, Jim," and Irwin replied, "Ha, what a contact!" Scott had found

> man, oh man . . . about a 4-incher, Joe . . . on one half of it, we have a very dark-black, fine grained basalt with some . . . very thin laths in it of plag . . . some millimeter-type vesicles along a linear pattern very close to the contact . . . and on the other side of the contact, we have a pure, solid-white, fine-grained frag, which looks not unlike the white clasts in the [Apollo] 14 rock.

He had found sample 15455, the first of two "black-and-white" breccias that turned out to consist not of basalt but mainly of crystalline rocks of the deep lunar crust included within a dark, fragment-laden, KREEP-y, impact-melt matrix. Ignoring capcom Allen's relay of science input from the back room to pass over the large "beaut" rock they had spotted earlier and get "as large a collection of smaller frags as you can get us," Scott and Irwin collected and photographed a piece broken from the rock that proved to be a second black-and-white breccia (15445). These were another thing they had come for: 1.22 kg of the Imbrium basin melt-rich ejecta and the only pieces larger than 25 g of this vital and much-sought unit they found during the whole mission. Irwin collected rake samples, getting fewer walnut-size pieces as he moved away from Spur's rim, as

Allen cautioned that departure time was coming up, but never mind, because "we're making money hand over fist." Scott stuck a glass spherule in bag 173 with other soil material, noting, based on his knowledge of the geology team, that it could be identified because "our friends in the back room are writing that down right now" (it was Bob Sutton's job to keep track of the samples and the photographs and comments that pertained to them). They scooped up the soil that Allen told them was wanted, then piled such a great weight of rock and soil on the LRV that it bounced.

After 49 minutes at the gold mine, it was off for a quick 17-minute sampling and photographic stop at the bypassed Station 4, then back to the LM. The ALSEP picked up the rumble of the rover rolling and bouncing across the plains. They found their outbound tracks and followed them back, easing the frustration of trying to identify features and locate themselves caused by the lack of an atmosphere: "I don't know how large 'large' is anymore"; and "I give up on distances and sizes." They arrived home four hours after leaving it.

The remainder of the EVA was devoted to off-loading their treasures and to unfinished scientific chores. While Scott and Irwin were talking about where things were and where to put them, Allen interrupted with, "Dave the only problem is, if we're able to get the deep samples using the drill stems, we'd like them in the SRC [sample return container]." Scott: "Now, Joe, you didn't say anything about getting deep cores . . ." Irwin: "Yes, that's the first time anybody said anything about that." Also, Houston had changed its collective mind about where Irwin should do the group of chores collectively called Station 8. Near the ALSEP he took photographs, collected "pink" and "black" rocks, and dug a trench sample while Scott went off to drill the deep hole. Dave drilled the hole to the 3-m depth but then could not extract the drill, despite great effort.[22] Finally the strictures imposed by their life-support systems called a halt to the EVA, which at seven hours was already half an hour longer than had been planned at the beginning of the long and rewarding day in the field.

TIME TO LEAVE

The third EVA, beginning at 0852 on 2 August, had been planned to take the Hadley geologists in new directions, west and north; in fact, all the way to North Complex, which Mike Carr and Keith Howard had tentatively interpreted on their geologic maps as basin material with a thin pyroclastic coating, and Gerry Schaber thought was covered with lava. But capcom Allen sent up the message, "We're going to ask you to stop first at the ALSEP site and spend a few minutes recovering the successfully drilled core tube." The struggle resumed, and continued for more than a few minutes. Scott: "I don't think it's worth doing, Jim.

We're not going to get it out." Irwin: "Dave, we're going to do this. We're going to get this drill out." In the back rooms of the planning team, Dale Jackson and Gordon Swann of the EVA team agreed with Scott and groused about the time it was taking. Lee Silver, however, agreed about the importance of the drill core, pointing out as well that the world would have considered a failure to extract it an Apollo failure. Finally the drill popped out of the hole and the astronauts extracted and stowed the core.

An hour and 20 minutes after Scott climbed down the LM ladder, they proceeded west in the rover, "like driving over the big sand dunes in the desert" (Irwin), to Hadley Rille, which is about 1,300 m wide and 400 m deep at the cluster of stations (9, 9A, 10) where they reached it on this EVA. They photographed the far wall, on which outcropping ledges of mare-basalt beds at least 60 m thick are exposed.[23] They collected a rake sample, a double-core sample, the comprehensive sample, and large amounts of basaltic rock, including the 9.6-kg "Great Scott" (sample 15555). The rille rocks are the only exposed noncrater rocks seen in place on any Apollo mission, and some of the almost bare boulders Scott and Irwin sampled were only slightly dislodged from the ledges — the only outcrops sampled on any mission. North Complex — the astronauts called it Schaber Hill — was a victim of the delay extracting the drill core and of squeezing the EVA between a lengthened rest period and the scheduled time of lift-off. Scott had protested, "I'd sort of — would like to get up to the North Complex if we can," and words to the effect that he hoped fooling around with the drill was more important than studying the geology of the area. But the drill core won the battle of the back rooms.

Back at *Falcon* — the Leaning Tower of Pisa in more ways than one — Scott performed Galileo's famous experiment by simultaneously dropping a geologic hammer and a feather from the Air Force Academy's falcon mascot. Galileo was right; they hit the ground at the same time.[24] To Scott's annoyance, Irwin accidentally ground the feather into the regolith, where it might be found someday and appear a bit strange to a human or nonhuman finder. Capcom Allen called up the message, "And, Dave and Jim, I've noticed a very slight smile on the face of the professor [Silver]. I think you very well may have passed your final exam." At 1711 GMT on 2 August 1971, two and a half hours after the end of the four-hour, 50-minute EVA, the television camera showed *Falcon* pop into orbit with two astronauts and 77 kg of samples, surprising viewers by the suddenness of its takeoff.

After rendezvous with Al Worden in *Endeavour,* the ascent stage of *Falcon* was sent on its geophysical mission and hit the Moon 93 km west of the landing site at 0304 GMT. Slayton sent up a seemingly innocent message to take a sleeping pill — but he had been looking at Scott's and Irwin's irregular heartbeats. They exchanged warm evaluations of their geological work with the capcom, who commented, "superfine job . . . remarkable." "Everybody down here is still floating so high, they're having a hard time getting down to all that data you gave us." But then he immediately belied that comment by mentioning that he was looking at a preliminary geologic report of each EVA that was more complete than the 90-day reports from previous missions. Scott replied in kind, "Well, it's because you've got the real professional back room there. Those guys really know how to put it together, especially with the way they were coming up with the new ideas while we were on the surface. That was really neat."

George Abbey, special assistant to flight operations director Chris Kraft, called Lee Silver into the Mission Operations Control Rooms (MOCR) in the predawn hours of 4 August and said that the astronauts wanted to speak to him. This was the only time in the entire Apollo program that a geologist spoke directly to an astronaut in space without the intermediary of a capcom. Silver said, "Hey, Dave, you've done a lovely job. You just don't know how we're jumping up and down, down here." Scott replied, "Well, that's because I happened to have a very good professor." Silver: "A whole bunch of them, Dave." Dave agreed and added, "we sure appreciate all you all did for us in getting ready for this thing . . . there is an awful lot to be seen and done up there." Silver: "Yes. We think you defined the first site to be revisited on the Moon." Scott bowed to the professional geologists by saying, "I hope someday we can get you all up here too. . . ." Professionals might be useful at a lunar base, but Scott and Irwin probably did as well as a professional geologist would with the same time limits and restricted movement.

They lingered in orbit half an Earth day after this exchange and released the subsatellite from the SIM on the last orbit, at 2100 GMT on 4 August, about one and a half hours before transearth injection. On the way home, 320,000 km from Earth, Worden crawled out into black interplanetary space for a 38-minute EVA and retrieved the film cassettes of the metric and panoramic cameras from the SIM bay. These would give us excellent stereoscopic views of the long-studied strip of the near side including the Crisium, Serenitatis, and Imbrium basins, and of a previously poorly known strip extending to the center of the far side. The astronauts also held a press conference during which the capcom passed on a question about the Genesis rock and about the drill, which "seemed to drive you up the crater walls. What was the problem, and was it worth the time?" Scott had already prepared a watered-down answer and had only good things to say about the drilling effort. He and Irwin allowed as how a visit to North Complex would have been nice, but it was an add-on to the mission plan anyway. The vibes from Apollo 15 surely rank with those from Apollo 11 as the best of the entire lunar program. Splashdown of the most complete scientific mission that had ever been performed on another planet came north of Hawaii at 2046 GMT on 7 August, 12 days and seven hours after it left the Cape.

Among the greeters on the recovery carrier was Robert Gilruth, carrying certain documents with green covers. The geology team had been working night and day as usual and had prepared reports of the fieldwork at Apennine-Hadley for Gilruth to present to the men who had performed it. Within two days of splashdown, Bob Sutton and others of the team put together a book of sample information, including photographs, that served as a working document. Follow-up reports benefited from the excellent photographic and verbal documentation by Scott and Irwin, and from their comments as they stood by to watch the rock boxes being opened. I have never spoken with a scientist who did not think the two performed superbly. Even Caltech geochronologist Gerry Wasserburg, who did not always see eye to eye with his Caltech colleague Silver, in a letter to Gilruth praised Apollo 15 as "one of the most brilliant missions in space science ever flown."[25] Tony Calio congratulated Silver personally. Apparently, the achievement of Apollo 15 was, after all, greater than any petty human animosities.

A PROFILE OF THE MOON

Apennine-Hadley had been selected to "shed light" on both the terrae and the maria and on the depths of the Moon as well as its surface skin. Let us imagine that we are examining the core from a science fiction drill hole 500 km deep and see how well this vertical sampling was achieved by the two astronauts and their instruments in about 19 short hours on the Moon's surficial veneer. We start at the top, in the part of our otherwise imaginary core that Scott and Irwin actually brought home.

The painfully won 2.4-m core taught, or retaught, the lesson of the Moon's antiquity and changelessness. Distinct regolith layers had been collected in cores from all sites except those from Apollo 11, but this Apollo 15 core contained an especially impressive 42 layers, the lowest of which seem to have lain undisturbed for 500 million years—about as long as life has occupied Earth's lands.[26]

Ejecta from as far away as Autolycus (150 km) or Aristillus (250 km) ought to have been shocked and possibly geochronologically reset by the impact that sent it flying, so you might be able to date the source crater. On this basis, the 1.29-aeon age of sample 15405, the youngest dated large lunar rock (513 g), is thought to date Autolycus or possibly Aristillus.[27]

The maria are the next lowest stratigraphic horizon below the Copernican craters, there being no noteworthy Eratosthenian craters nearby. Because of the regolith mixing and because it landed on a mare plain, Apollo 15 returned far more mare basalt than any other type of rock — unfortunately, because the maria were and are much better understood than the terrae. Two main types found in Palus Putredinis were extruded at nearly the same time, about 3.3 aeons ago. Hadley Rille is almost certainly a collapsed lava tube or channel. If so, the many layers seen in its walls may indicate reuse of an old structural trench by repeated lava flows.[28]

Stratigraphically and topographically below the mare basalt and Archimedes but stratigraphically above the Apennine massifs is the Apennine Bench Formation. These light plains had played a key role a decade before Apollo 15 in distinguishing Palus Putredinis and Mare Imbrium from the Imbrium basin, and therefore all maria from all basins. Although the plains' stratigraphic relations were obvious once they had been noticed, their origin was not. Throughout the 1960s interpretations vacillated between impact-melt and volcanic origins according to the fashion of the day. The bench was not a mission objective but may have been brought within range of the EVAs by impacts. The probable plains samples are in the form of numerous small KREEP-rich fragments of nonmare basalt that have clean, fragment-free basaltic textures and lack siderophile elements like nickel, iridium, and gold that are abundant in meteorites. These properties led Paul Spudis and most other analysts to conclude that the samples are volcanic, not impact melt. This would mean that the Apennine Bench is a true, erupted, terra-type basalt, as was long proposed for the terra plains. Their determined age of 3.85 ± 0.08 aeons is consistent with origin as Imbrium melt but is too imprecise to help in the origin controversy. So is the debate over? Apparently so; Paul told me that one of the last holdouts for an impact-melt origin, geochemist Ross Taylor, recently caved in. Still, I would like to see larger samples collected from the bench to remove all doubt about this important and long-lived problem.

Next oldest are the Apennines, which were put where they are by the impact that formed the Imbrium basin at the beginning of the Imbrian Period. A dating technique based on argon isotopes that became popular during the Apollo era determined (with some uncertainty) a 3.86 ± 0.04–aeon age for the black-and-white breccias from Spur crater, similar to but overlapping the ages of the Apollo 14 and Apennine Bench samples. So the Apollo 15 samples seem to have straddled the Imbrian Period as I define it, beginning about 3.85 aeons ago with the Imbrium impact and ending about 3.3 aeons ago with the eruption of the basalts of Palus Putredinis — a span of 550 million years, give or take a few tens of millions.

The search for the suspected next oldest geologic unit in the Apennines, the Serenitatis ejecta, has been inconclusive. Too few terra rocks were exposed or sampled. Nor were any pre-Serenitatis rocks found in place. So to go lower in our imaginary drill core, we have to follow the petrologists and geochemists, who are always trying to look through the impact screen at the original composition of the Moon. The oldest samples from Apollo 15 are the (noritic) clasts in the black-and-white breccias and, probably, the Genesis rock (15415). This exciting sample has been dated at "only" 4.15 aeons and reveals textures suggestive of shock and recrystallization. The striations Scott thought were due to an original crystal structure (twinning) are actually due to shock. Therefore some petrologists temporarily rechristened it the Exodus rock—metamorphic; 4.15 aeons dates the shock. However, 15415 has certain properties (a very primitive initial strontium ratio) that suggest it is indeed a part of the earliest lunar crust; that is, it crystallized from its magma about 4.5 aeons ago. The Apollo 11 anorthositic fragments had suggested that the crust originated by flotation of plagioclase in a volume of magma that earned itself the persistent name of magma ocean.[29] Later missions would be needed to collect abundant early terra rocks, but Apollo 15 made a start.

Although the gamma-ray and X-ray instruments in the orbiting CSM can look at only the most surficial skin, their readings probably apply approximately to the underlying material as well because most fragments in a regolith are derived locally. The gamma-ray spectrometer detected the KREEP that was increasingly appearing to be typical of the Imbrium-Procellarum region and accordingly found little of it elsewhere. The X-ray spectrometer detected differences in magnesium and aluminum concentrations that made a start in locating anorthositic and nonanorthositic compositions in the terrae, and it showed a difference in maria and terrae that aided certain number-wedded scientists congenitally unable to distinguish between dark and light on a photograph. Unfortunately, the strips overflown by Apollo 15 and later missions are narrow, and a global compositional survey is still needed.

In looking at the maria as we did above, we were looking not only at the 3.3-aeon-old stratigraphic unit called mare material but at a layer of the Moon that lies beneath even the terra crust. I refer to the Moon's mantle, the source of the mare basalts. Know the compositions of the terra crust and the mantle, and you know pretty well what the whole Moon is made of and how it differentiated. The Apollo 15 basalts, however, were modified during their ascent to the surface and thus cannot tell us details about the mantle sources. The colorful green, red, brown, and yellow pyroclastic glass droplets found by Apollo 15 and less abundantly in other lunar regoliths are more nearly primary (unaltered) and so may tell us more. They may have been erupted from depths greater than 500 km; that is, more than a quarter of the way from the Moon's surface to its center. Like the mare basalts, they are about 3.3 aeons old. They tell us that the mantle probably consists of olivine and pyroxene with local enrichments of ilmenite and local pockets of volatile-rich minerals. If North Complex had been reached, we might have learned more about this enormous depth.

More about the lunar interior was learned from the rulers of the depths, the geophysicists. By the time of the Third Lunar Science Conference in January 1972 they knew the deeper structure of southern Oceanus Procellarum better than any other site on the Moon because of the close placement of the Apollo 12 and 14 ALSEPs and their triangulation with the Apollo 15 ALSEP. A layer about 20 or 25 km thick overlies another layer 40 or 45 km thick, for a total crustal thickness here of about 60 or 65 km. At the time of the conference the experimenters of the passive seismometers thought the 20–25-km layer was mare basalt.[30] Geologists doubted this large figure because many small craters poke through the maria from the mare substrate. Now, most of this layer is known to be breccia even under the maria, whose basalts on the whole Moon amount to very little volumetrically. Sixty or 65 km is commonly cited as "the" near-side thickness, but many more seismic stations would be required to determine the average thickness of a crust whose thickness is different beneath each of the many impact basins that punched into or through it before 3.8 aeons ago. The seismometers from the three ALSEPs showed seismicity only one-billionth as energetic as Earth's.

Readings from the heat-flow probe were interpreted at the time of the conference as indicating the astonishingly high value of half Earth's heat flow. Four years later, however, after the Apollo 17 values were in hand, the experimenters cut this value in half, more in keeping with a cold Moon containing a modest amount of radioactive elements.

The magnetometer left on the surface by Apollo 12 had revealed a surprisingly large local magnetic field originating not in space but in or on the Moon, and one of the two measurements made with the Apollo 14 portable magnetometer yielded an even larger value one five-hundredth as strong as Earth's field. Natural remanent magnetism in the rocks is responsible for the steady field. The plot thickened when during its two-month life the Apollo 15 subsatellite found magnetic spots over much of the Moon's surface, including the far side. The magnetism is minor by terrestrial standards but amazing on a planet thought by most geophysicists not to have a core. Maybe all those impacts you can see on photographs had something to do with it. The geophysicists would have to think about it.

The geologists and geochemists had plenty to think about, too, but their immediate concern was a landing site that would give them even more food for thought.