17

Beautiful Taurus-Littrow

1972

A GEOLOGIST GETS A MOON TRIP

The future of Project Apollo had been starkly clear since September 1970: after Apollo 17, none. The launch teams at the Kennedy Space Center, the flight operations teams at MSC, the geologic support teams, and the geologically expert astronauts would have only one more chance to strut their stuff.

If a professional geologist was ever going to fulfill Gene Shoemaker's quarter-century dream, now was the time. Although originally he gave only fleeting thought to becoming an astronaut, Jack Schmitt had gravitated to the mission-planning aspects of astrogeology ever since his arrival in Flagstaff in July 1964. He headed the field geological methods team and worked with other aspects of the novel enterprise as well until his entry into flight training in July 1965. In July 1966 the intensive phase of his pilot's training ended and he moved into the astronauts' offices at MSC, where he acted as the interface between geologists on one side and the astronauts and engineers on the other. He worked with fifth-group astronaut Don Lind in developing the tools used on the Moon and helped streamline the design and deployment of the ALSEP, which originally had been a "monster" devised to give the astronauts something to do on the Moon.[1] He brought in Lee Silver, Dick Jahns, and other non-USGS or semi-USGS experts to help train the astronauts in ways more relevant to lunar fieldwork than some of the prior training had been. Schmitt was probably the main single reason the geologic fieldwork on the Moon attained the scope that it did.

So from the beginning Jack was a leading candidate to be the first professional geologist to set foot on the Moon. The Space Science Board in particular and the lunar geoscience community in general wanted it so, and the astronaut community felt the pressure. The prime crew for Apollo 17 had originally been the Apollo 14 backup crew of Gene Cernan, Joe Engle, and Ron Evans. Schmitt's position as Apollo 15 backup LMP put in him line for Apollo 18 along with Dick Gordon and Vance Brand until Apollo 18 was canceled in September 1970. In January 1971 Homer Newell got an earful from the scientist-astronauts in Houston and raised the issue of their flight assignments with NASA Administrator Fletcher, MSC Director Robert Gilruth, and OMSF chief Dale Myers (George Mueller's replacement). George Low supported Schmitt's Moon trip and scientists in space in general. Robert Gilruth, Chris Kraft, Rocco Petrone, and Deke Slayton also became convinced that Schmitt could and should do the job.[2] In March 1971 Myers informed the chairman of the Space Science Board, Charles Townes, that he and Gilruth had decided that if all continued to go well, a geologist should fly on Apollo, and Schmitt was their geologist.[3] Schmitt had worked well with the more extroverted Dick Gordon on the Apollo 15 backup crew and mentioned his preference for Gordon as the Apollo 17 commander.[4]

However, Deke Slayton stuck to the normal rotation except for Schmitt himself. On 12 August 1971, only five days after Apollo 15 splashed down, the final crew selection was announced. Eugene Andrew Cernan (b. 1934) would join the select group of three men (with Jim Lovell and John Young) who went twice to the Moon, having skimmed its mountains in the Apollo 10 LM in May 1969 with Tom Stafford. Ronald Ellwin Evans (1933–1990), a space rookie, would be CMP. The LMP would be Harrison Schmitt. X-15 pilot Engle would have to wait for the 1980s and the space shuttle to fly in space. A geologist was going to the Moon.

THE BEST REMAINING SITE

Schmitt's selection was only one aspect of the awareness that the Moon would not be visited again for a long time—how much longer we still do not know. Selection of the landing site was another aspect, and a very critical one. The Taurus-Littrow Valley was chosen only after many alternatives were weighed.[5] All the interested parties carefully considered how many of the goals originally set for lunar exploration had been satisfied (appendix 3).

Apollos 16 and 17 had been considered a pair during planning, and the Apollo 17 landing site was picked before Apollo 16 flew in April 1972. At this stage almost everybody still expected the Descartes Highlands to be volcanic. The maria and the Imbrium basin, formed in the middle of lunar geologic history, had been relatively well explored by the first four Apollo landings. The two biggest question marks bracketed the lunar time scale: the primitive terrae at one end and young volcanism at the other. Taurus-Littrow is an informal name that reflects this dual objective. Massifs of the Serenitatis basin rim, which are part of Montes Taurus in some interpretations of that vague selenographic feature, seemed likely to contain the ancient, pre-Imbrian rock. A 31-km crater and arcuate rille system named Littrow had lent their name to a supposedly young dark-mantled mare site 60 km farther west that had been intended as the Apollo 14 landing site before the Apollo 13 accident.

The effects of Apollos 12 and 13 were still being propagated in the selection process for Apollo 17. Apollo 12's possible dating of Copernicus had downplayed the importance of that otherwise scientifically desirable, though operationally difficult, target. If Apollo 12 had sampled a young mare at the Surveyor 1 landing site, the need to do so on Apollo 17 would not have been as compelling. If the Apollo 13 accident had not caused a postponement of Apollo 14, the dark material might have already been sampled at Littrow—and found to be old. Interest in dark coatings might also have been satisfied if the Apollo 15 drill core had not stuck and prevented Scott and Irwin from visiting North Complex.

The old and young priorities and the usual engineering and operational factors got several long-considered sites eliminated and some new ones introduced. Members of the same Ad Hoc Site Evaluation Committee chaired by Noel Hinners that had recommended Descartes for Apollo 16 now received sets of enlargements of the Apollo 15 orbital photographs and were chartered to look for sites, a charter they shared with their colleagues. In November 1971 Lee Silver and Bill Muehlberger convened the most vitally interested geologists for a critical skull session at the Caltech geology department to express the preference of the geology team.[6] The team was represented by its leader, Muehlberger, and by several team members or associates, including Eugene Boudette, Lincoln Page, Dallas Peck, George Ulrich, and Edward Wolfe. The geologic-mapping crowd sent Mike Carr, Keith Howard, Baerbel Lucchitta, Dan Milton, Spence Titley, and me. Hal Masursky was there as he was at all meetings, and Tim Mutch and Tom McGetchin also added their counsel.

Before telling what happened to the sites, perhaps I should tell what happened to some of the people at the meeting. Boudette left Houston during the Apollo 16 mission when its results did not match his predictions. Muehlberger gave nice-guy Ulrich the job of informing McGetchin, Page, and Titley that they were surplus to the needs of the geology team. Thomas Richard McGetchin (1936–1979), another Brown University student (master's degree), Caltecher (Ph.D., 1968), and student and protégé of Lee Silver and Gene Shoemaker, always seemed too occupied with other things to settle full time into lunar studies. After five years (1969–1974) at MIT, restless Tom moved to the bomb laboratory at Los Alamos in 1975 and founded its geosciences group, then became director of the Lunar Science Institute in 1977, whereupon he got it renamed the Lunar and Planetary Institute (LPI) in 1978. In the same year he and remote-sensing expert Carlé Pieters were married. Linc Page had been one of what Gene Shoemaker calls his "angels" because in 1955, as USGS–Atomic

Energy Commission liaison, he had got Shoemaker started on his cratering studies at the Nevada Test Site; but Page did not take lunar studies very seriously. Edward Winslow Wolfe (b. 1936; see chapters 15 and 16) would rise to prominence during Apollo 17. He had gone to Flagstaff to study the San Francisco volcanic field but got drafted somewhat unwillingly into SPE's astronaut-training turmoil. Despite his reluctance to take leave from his Earth career, Ed provided first-rate glue for the training, mission operations, and postmission reporting that were the core of SPE's geologic support.

To be sure nothing was overlooked we briefly granted another day in court to the main candidate sites from past site-selection rounds, but had to eliminate Copernicus, Davy, Marius Hills, and Tycho once and for all on either operational or scientific grounds.[7] Schmitt's desire for a landing on the far side had been brainstormed again and communication satellites had even been priced, but finally Chris Kraft had to tell him to stop mentioning the idea; there was no money, period.[8] So then there were three sites: Taurus-Littrow, Alphonsus, and Gassendi. Everybody knew by now that primitive rock would be hard to come by, but at least Apollo 17 could land as far as possible from the Imbrium basin's contaminating influence. This test finally sank the perennial contender Alphonsus, which had to be dragged out again because the ASSB had considered it the prime candidate for Apollo 17 when they settled instead on Descartes for Apollo 16 in June 1971. Anyway, we were all sick of Alphonsus and nobody voted for it.

Distance from Imbrium ushered to the fore the crater Gassendi, which straddles the border between Mare Humorum and its basin (18° S, 40° W). A landing site here would be near the base of the central peak. Hal Masursky in particular favored Gassendi because (1) it represented his old specialty, the floor-rebound craters; (2) it would lie along a favorable orbital track that would include the Orientale basin; (3) presumably it lay in a new geochemical province; (4) it seemed to possess a variety of volcanic materials; and (5) it could provide dates for the Humorum basin, for Gassendi itself, and possibly for the nearby young crater Gassendi A. Not a bad collection of objectives, except that the much-desired young volcanics were missing. The original Gassendi mapper, Spence Titley, volunteered to prepare one of the site maps "as soon as I get the latest guidelines from Menlo Park"—a pointed reference to past contretemps with his former coauthors and the mapping czar (me). The convened geologists liked Gassendi and ranked it only slightly behind the winner, Taurus-Littrow, and "would be pleased with either site for Apollo 17" as Bill Muehlberger put it in the memo he forwarded to Hinners.

Taurus-Littrow earlier had won a contest among six candidates on the highlands between Maria Serenitatis and Crisium. Every red-blooded geologist wants exploration sites whose geologic context is known, but few of these could be found in the generally nondescript highlands here—or, for that matter, anywhere on the lunar terrae. For the Apollo 15 preliminary science report, Mike Carr and Farouk El-Baz prepared sketch maps of one exception, Taurus-Littrow, and Baerbel Lucchitta and I did the same for another near the young crater Proclus.[9] MSC nixed Proclus because it was too far east for adequate tracking and communication with Earth during approach. A region southwest of Mare Crisium was rejected because it was in the zone accessible to the Soviet sample returners and thus might be sampled redundantly; and in fact Luna 20 did sample the Crisium basin rim in February 1972.

But the real reasons for the victory of Taurus-Littrow lay in what had happened on Apollo 15. Al Worden had seen dark-halo craters that looked like cones scattered all over the region's brighter surfaces. Shorty crater, of which we will hear more, was one of these. A lot of worthy people—including Farouk El-Baz, Jim Head, Tom McGetchin, and Worden himself—believed many of these were cinder cones.[10] The dark mantle also showed up clearly as streaks on the massifs, supporting its interpretation as a pyroclastic deposit that had been forcefully fountained from (unidentified) volcanic vents. The popular press picked up on the dark mantle as the product of the Moon's last "gasp" or "belch" before it had shut down, and downplayed the primitive massifs as a "bonus." The specially enlarged Apollo 15 panoramic photographs we used to evaluate the landing site showed a scene of considerable beauty that impressed us all and made a Taurus-Littrow advocate of Noel Hinners.

One count against Taurus-Littrow was its similarity in geologic setting along a basin-mare contact to Apennine-Hadley. Also, photograph-loving geologists, who always want to see new territory, were bothered because an orbital track tied to Taurus-Littrow or anywhere else in the Serenitatis-Crisium terra would largely duplicate the Apollo 15 track. The geochemists and geophysicists Hinners consulted were less worried about this because they would have different instruments on board.[11] One of the ragged aspects of the interaction between science and flight operations during the Apollo program was assignment of the orbital and ALSEP instruments to a specific mission *before* the landing site was selected. Apollo 17 would include no orbital gamma-ray, X-ray, or alpha-particle spectrometers, but did include a new radar sounder, which was advertised as a probe for subsurface ice, permafrost, or water, and which actually did detect subsurface mare layering and basin structures.[12] Apollo 17 would also carry an infrared radiometer to detect hot spots close-up and during the 14-Earth-day lunar night as Saari and Shorthill had done at the telescope during an eclipse. There might even be advantages in examining in these new ways the tracks already examined by the chemical sensors. Anyway, neither Gassendi nor Alphonsus was perfect either.

On 11 February 1972 the ASSB eliminated Gassendi for NASA-type reasons. MSC thought the rilles and ring trough in the crater floor were hazardous and would bar the astronauts from their main objective, the central peak. Gassendi's value for orbital science was of no help; Masursky remembers Rocco Petrone saying to Jim McDivitt, his manager at MSC, something like, "Orbital science never influenced site selection before, so let's not start now." Alphonsus was slightly better operationally than Taurus-Littrow. The ASSB accepted the scientists' preference for Taurus-Littrow, though, and approved it unanimously for Apollo 17 at this, its last meeting.

For the last time in the lunar program the USGS turned to the job of producing the premission geologic maps. As usual, this meant rounding up mappers who were not swamped by other assignments. One was the quick-working, relatively newly arrived geologist Dave Scott, who was paired with equally quick-working old Serenitatis hand Mike Carr on the 1:250,000-scale map and slower-working Howard Pohn on Howie's long-delayed 1:1,000,000-scale Macrobius quadrangle map, which included the landing site.[13] The detailed 1:50,000-scale map went, at her request, to another newcomer, Baerbel Koesters Lucchitta (b. 1938), a woman of classic slim beauty. In 1971 she had attended a meeting before the final choice of the landing site at which she perceived that Jack Schmitt favored Taurus-Littrow among the candidate sites, so she asked to be switched to that map assignment from another. Baerbel (or Barbara, or Barbarella) had joined Astrogeology in Flagstaff in 1967 as a physical science technician and became a part-time geologist in 1968, not graduating to full time until after Apollo 17 because of her alien status. The first Americans she ever saw were riding a tank painted with a white star near her home in the country near Münster, Germany; now she was in the midst of an American mission to the Moon. Baerbel was among the geologists who held after-dinner briefings for the crew in their quarters at the Cape (Ed Wolfe and Val Freeman did it almost every week). At her first briefing, Ron Evans walked in late, looked around, saw only Baerbel and a lot of ugly men he already knew, and asked, "Where's this Dr. Lucchitta who is supposed to brief us?" There is indeed a male Dr. Lucchitta, Baerbel's husband, Ivo, but he dropped out early from participation in Apollo. Although Baerbel was Americanized by this time, the German tabloid media made much of her participation with such phrases as "This woman has the Moon men dancing to her tune."

Mike Carr's telescopic work (described in chapter 4) had developed the idea that the dark mantling materials were pyroclastic and young, but he had claimed neither attribute for the dark materials at Littrow.[14] For these he favored an origin as flows and an age of Eratosthenian—young, but not youngest. The origin was escalated to pyroclastic and the age to Copernican on the 1:250,000-

scale premission map; but Mike entered in the map text an explicit caution against assuming a young age. The absence of craters on the dark mantle suggested extreme youth. Checking in from Ames, Ron Greeley and Don Gault counted the craters and published predictions for the young age of the dark mantle in a paper with the unfortunate publication date of 1973.[15] Geologist George McGill of the University of Massachusetts was visiting Menlo Park in late 1971 and early 1972, studying stereoscopic Apollo 15 photographs of the Taurus-Littrow area as part of a structural study. George came to me one day and asked, "What's all this about the dark mantle being young?" He had seen that it is truncated by the lighter mare surfaces of central Mare Serenitatis. This perceptive observation was never published, and I had to remind George about it recently.

But sampling young material remained a goal, and the dark mantle of the Taurus-Littrow site would have to be it. The geology team devised an exploration plan worthy of a J mission that could reach several terra units and the dark mantling material. Looming 2,000 and 1,500 m above the valley are the steep South and North massifs, on which ejecta of Serenitatis and possibly older basins should be exposed. A light-colored landslide derived from South Massif promised to bring massif material within collecting range. The geologic mappers thought that a hummocky or knobby terrain called Sculptured Hills (or "corn on the cob") that forms darker upland surfaces than the massifs was probably additional ejecta of Serenitatis or of the nearby Crisium basin, for it resembles knobby ejecta that they knew from the Orientale and Imbrium basins (Montes Rook and Alpes formations, respectively). Some hope lingered that terra volcanics would be found in the massifs or Sculptured Hills "domes."

The planar floor of the valley on which the LM would land was an additional objective. Geologists were gun-shy about volcanic interpretations after their record of successful premission interpretations ebbed with Apollo 16, and interpreted the floor material as either a new unit of mare basalt or a terra plains unit of fluidized breccia covered by the dark mantle. On a detailed 1:25,000-scale map prepared for mission planning by Ed Wolfe and Val Freeman, the name of the plains unit was watered down further to subfloor material, that is, whatever might be below the valley floor. Finally, the astronauts could visit the Lee-Lincoln scarp, which resembles the enigmatic mare ridges and cuts both the valley floor and the massifs.

Bellcomm—its job done—dissolved after Apollo 16 flew in April 1972.[16] NASA's personnel cutback was already well advanced.[17] The only survivors of AAP would be the nonlunar Skylab and Apollo-Soyuz, which was taking shape during 1972.[18] The future of American manned spaceflight resided in the space shuttle, foreshadowed in the Space Task Group's report in September 1969,[19] designed in 1971, promoted by Administrator James Fletcher and temporarily by most of NASA's other senior managers, approved and announced by President Nixon in January 1972, and promptly cheapened by such compromises as tacked-on external solid-rocket boosters.[20] The unmanned planetary program was coming on strong and would stay healthy for another few years; many astrogeologists, including me, had already shifted our attention to the Mariner 9 Mars mission.[21] The Moon was dead in more ways than one. Taurus-Littrow had better be good.

TRAINING AT THE ANALOGUES

The geologic preparation for the mission was running smoothly, if not effortlessly, by the time of Apollo 17. Because the Apollo 17 crew was designated eight months before Apollo 16 flew, training for the two missions overlapped, as had been true for pairs or trios of missions ever since the Apollo 15 crew began to train in May 1970. Given the hoopla attending the presence of a real geologist on the crew, Cernan was inclined to defer to Schmitt in scientific matters. However, Cernan was another of the exceptionally able observers with which the J missions were blessed, so Muehlberger and Silver made sure he got equal time and treatment in the training and briefings. He is one of the more articulate astronauts, and he possesses an exceptional ability to describe what he is observing. The mission scientist and EVA capcom was Robert Allan Ridley Parker (b. 1936), who received a Ph.D. in astronomy from Caltech at the age of 25.

When the training began, the backup crew had been the Apollo 15 crew of Scott, Irwin, and Worden. In the spring of 1972, however, NASA found out that some stamped envelopes (covers) Scott and Irwin had canceled on the plain at Hadley and all three had signed on their postsplashdown flight from Hawaii were being sold in Europe, partly for their own benefit. A furious Deke Slayton, who had expressly forbidden such goings-on, had Scott transferred out of the astronaut corps to the Apollo Spacecraft Program Office at MSC, from which he moved to Edwards Air Force Base and eventually command of its NASA center (Dryden Flight Research Center). Effective 1 August 1972, Irwin resigned from NASA and the air force to become a religious evangelist. Worden transferred to the NASA Ames Research Center in September 1972. The new Apollo 17 backup crew became John Young, Charlie Duke, and Stu Roosa.

The field training areas for Apollo 17 were drawn mainly from the familiar list, led off in October 1971 by a warm-up in the Big Bend of Texas in which Cernan, Schmitt, and Parker got out and described the geologic scene with little prompting, followed by visits to the Coso Hills and Kilbourne Hole in November and December 1971, respectively. In January 1972 an exercise in the McCullough Mountains southwest of Boulder City and a less formal trip to

Cleopatra Wash north of Lake Mead were accompanied at his request by President Nixon's supportive science adviser Edward David and his wife, Ann, both amateur rockhounds. The one-per-month trips for the next four months were devoted to the Chocolate Mountains in the Mohave Desert of California, Sierra Madera, the San Gabriel Mountains, and Sudbury. The next trip, to Hawaii in June 1972, began the series of exercises specifically tailored to Apollo 17's mission at Taurus-Littrow.

New field areas were added with Taurus-Littrow in mind. The hoped-for primitive rock led the crew and their instructors not only back to the same anorthosite and anorthositic gabbro complexes that the Apollo 15 and 16 crews had seen, but also, in July 1972, to the Stillwater layered intrusion in Montana. The Stillwater and similar complexes were formed by a combination of igneous processes, which controlled their mineralogy, and sedimentary processes, which segregated and settled the minerals into layers under the influence of gravity. The trip was led by Dale Jackson, a specialist in mafic and ultramafic rocks in general and Stillwater in particular. Dale, Gene Shoemaker, and Howard Wilshire had fingered Stillwater back in the Surveyor days as the likely analogue of lunar terra rock.[22] Other layered complexes (lopoliths) had been considered analogues to the lunar maria. Although that idea went out of fashion after Apollos 11 and 12, the Stillwater complex was and is a likely analogue for the raw material of the Apollo 17 (and Apollo 14) terra rocks.

In August 1972 the crew went to the old standby, the Nevada Test Site, and in September 1972 to the seemingly well-named Lunar Crater, in Nevada's Pancake Range, where geologist Dave Scott had earned his Ph.D.[23] Lunar Crater was added both as an analogue of the expected cinder cones and as an intensive general exercise with Grover. In October a great crowd of geologists and hangers-on assembled at the Blackhawk landslide in the desert north of the San Bernardino Mountains of southern California to get a foretaste of the landslide from South Massif. The Blackhawk trip included the whole schmeer: full EVA exercises with vehicles and simulations of the geophysical science experiments to be conducted during the traverses on the Moon. In November the final—emphasis on "final"—major field exercise, tied to Houston by radio, returned to arid Flagstaff's moonlike artificial crater fields and volcanic terrains. The thousand-year-old Sunset Crater National Monument included a young ash fall believed similar to the dark mantle at Taurus-Littrow.

Detailed planning for the geologic aspects of the mission was largely in the hands of geology team leader Bill Muehlberger, Jack Schmitt, Ed Wolfe, Val Freeman, and Jim Head. Petrologist Don Morrison filled the position as Paul Gast's mission science trainer that Gary Lofgren and Fred Hörz had filled on Apollos 15 and 16. As for all missions, the trainers worked closely with the mission scientist, Bob Parker, and through a NASA-MSC body called the Science Working Panel, established in early 1970, which made decisions about which experiments to fly and how to use them. The panel consisted of the principal investigators of all the geological and geophysical science experiments, a number of sample investigators from Paul Gast's group, and NASA personnel.[24] A Traverse Planning Subcommittee chaired by Jack Sevier of MSC's Apollo Spacecraft Program Office met in Houston every month for more than four years to grind out the details of the Apollo EVAS. As he had done in the days of Lunar Orbiter and Apollos 8 and 10, Sevier continued diplomatically and skillfully in the era of landings to keep track of and balance the often conflicting wishes of each type of science and of spaceflight operations. It was Sevier who had final control over the time line; that is, what could be done where, when, and for how long. Here was one more major consumer of the geology team's time, energy, and travel budget that I have not mentioned. Throughout the Apollo era the geology team leader and one or more other members of the team dutifully flew off to Houston each month to attend the subcommittee's meetings to be sure that their wishes were considered and that they did not miss anything. Muehlberger has estimated that in just one year he logged 250,000 airline miles just in the United States and just on commercial flights. The subcommittee's conclusions for Apollo 17 were spelled out in detail in thick books that went through three editions between 19 June and 1 November 1972. Nothing was done arbitrarily in Apollo.

IN THE BEAUTIFUL VALLEY

And so it was off to Taurus-Littrow. All previous Apollos had been launched in daylight and injected to the Moon over the Pacific to simplify ground support operations. For a winter mission to Taurus-Littrow, however, a night launch and Atlantic injection could save fuel and still land Apollo 17 at the desired Sun illumination.[25] And so a half hour after Florida midnight on 7 December 1972 (0533 GMT), after a two-hour, 40-minute hold, the Saturn 5 bearing Cernan, Schmitt, and Evans roared off in a glorious display of sight and sound that was witnessed by a huge crowd including me. We knew we would not see its like again.

The new trajectory gave the three last lunar astronauts a good look at the approaching Moon, something denied the eight crews that had preceded them. Cernan had given their lunar module the name of a famous nineteenth-century scientific exploration ship, and his first words after landing, echoing Armstrong's 3 1/2 years earlier, would seem chillingly ironic 13 years later: "Okay, Houston. The *Challenger* has landed!"[26]

After half a minute during which both astronauts exchanged technical data with capcom Gordon Fullerton — Schmitt performed as a pilot just as Cernan performed as a geologist — Cernan observed, "Jack, are we going to have some nice boulders in this area," and, "oh man, look at that rock out there." Jack's reply did not advance either geological science or the astronautic vocabulary but did convey his state of mind: "Absolutely incredible. Absolutely incredible." Then: "Hey, you can see the boulder tracks." "There are boulders all over the massifs." The tracks and some of the boulders had been visible on high-resolution photographs, but the number of boulders had been uncertain and worrisome in view of the rarity of these vital aids to sampling on Hadley Delta and Stone Mountain. A few minutes later Cernan agreed, "The boulder tracks — they're beautiful." He and Schmitt would be able to take samples conveniently at the base of a mountain and identify the ledges they had fallen from by tracing the tracks back up the hillsides.

Eschewing the long rest taken by Apollos 15 and 16 between landing and emerging, they began the first EVA almost at the stroke of Greenwich midnight of 11 December, only four hours after touchdown. Even if the commercial television networks had deigned to show the event, viewers on Earth could not have watched them descend the ladder because the necessary TV connections and tripod had been sacrificed in favor of fuel for an extra second of LM hover time (not needed in the event). John Young had collected no contingency sample, and neither would Cernan. On looking around he commented that the Sculptured Hills looked "like the wrinkled skin of an "old, old, 100-year-old man," not like the smoother massifs. When Schmitt climbed down he expressed surprise at the roughness of the landing area and pointed out, as had other LMPs, "You landed in a crater!" He soon experienced trouble picking up rocks, "a very embarrassing thing for a geologist." Cernan exclaimed, "God, it's beautiful out here!" and later in the EVA recommended a nonscientific diversion of a type the astronauts did not normally admit to appreciating, "You owe yourself 30 seconds to look up over the South Massif and look at the Earth." Schmitt, obviously delighted to be where he was, affected the offhand answer, "You've seen one earth, you've seen them all."

As usual, a major chore of the first EVA was deploying the ALSEP, and also as usual, this and the deep drilling took more time than allotted. Cernan drilled two 2.5-m holes 11 m apart for the heat-flow probe and a 2.8-m hole from which he extracted a core sample and into which he inserted a probe for measuring the rate at which cosmic rays produce neutrons at various depths in the regolith. After more than an hour of labor he echoed Scott's comment at Hadley with, "I hope this core is appreciated." So do I; the drilling ended up consuming about 8% of Cernan's total EVA time. To mention only the geoscience experiments, the ALSEP included a heat-flow probe, unfortunately set up near a mare-mountain contact just as the other surviving probe was, and a new instrument from the Goddard Space Flight Center called the *lunar ejecta and meteorites experiment* (LEAM), which harked back to the 1963 Gault-Shoemaker-Moore calculation of how many secondary-ejecta particles might be flying around on the surface.[27] There was also a new *lunar surface gravimeter* (LSG), which was paired with one on Earth to detect Einsteinian gravitational waves propagating through space and, more practically, to detect moonquakes and deformation by Earth tides. I do not think that either the LEAM or the LSG experimenters definitively extracted the gems they were seeking from the signals their instruments sent them.

To make up some time the geology team devised a way of shortening the traverse planned for the rest of the EVA without sacrificing good data. The original plan had been to travel 2.5 km to the rim flank of Emory crater, named by Schmitt after a nineteenth-century Western geologist-explorer in recognition of the parallel with lunar exploration. However, the traverse was truncated by a kilometer at Steno crater, which Jack named for the seventeenth-century Danish physician whom geologists credit with first stating the basic laws that underlie the science of stratigraphy.[28] The 600-m Emory and Steno belong to a "Central Cluster" of craters in their approximate size range accompanied by a swarm of smaller craters. On the USGS premission geologic maps the cluster was dated as Copernican and identified by its high crater density and north-northeast–south-southwest orientation as secondary to a crater somewhere to the south-southwest. Mappers Scott, Carr, and Lucchitta daringly suggested that the source was the Copernican-age crater Tycho, lying a distant 2,250 km away but in the right direction and along a ray connecting it with Taurus-Littrow. The Central Cluster craters have dark rims, and so seemed to be covered by the dark mantling material, adding weight to the estimate of Copernican age for the blanket.

During the short trip south the astronauts stopped briefly about 150 m from the LM (and, purposefully, even farther from the ALSEP) to unload the transmitter for a *surface electrical properties* experiment (SEP). A large experimenter team led by Gene Simmons of MIT and MSC had designed the SEP to measure the dielectric properties of the subsurface, which are strongly affected by water or ice, and so to work in conjunction with the orbiting radar sounder and other radar experiments. Signals from the transmitter that passed both above and below the surface were picked up by a receiver mounted on the rover, which also carried a tape recorder to record the data for return to Earth.

The astronauts began their geophysical and geologic duties in earnest at Steno, which became Station 1. They planted the first charge for a seismic experiment much like those used in petroleum exploration. An array of four geophones near the ALSEP would pick up reflections of the sound waves sent into the subsurface by eight explosive charges placed around the valley and set off after the astronauts had lifted off safely from the Moon. The experimenters—Stanford geophysicists Bob Kovach and Pradeep Talwani and former USGS Flagstaff resident Joel Watkins, since moved to Gary Latham's department at the University of Texas at Galveston—hoped to determine the local subsurface structure with new precision. Cernan and Schmitt went about collecting vesicular rocks and other samples that Schmitt kept calling gabbro or intermediate gabbro in reference to their basaltlike mineralogy but seemingly coarser-than-basaltic crystalline texture. Apparently this gabbro was the subfloor material. Procedures of establishing scale and orientation with the gnomon, documenting sample collection points with several before-and-after photographs, describing rock and soil properties, and bagging the haul were all running smoothly, except that Schmitt commented several times during the EVAs that he had forgotten part of the documentation photography, a classic case of "do as I say, not as I do." Also, the location problem did not go away even during this last, skillfully executed Apollo. At one point Schmitt informed capcom Parker, "We're not where you think we are. We're not sure where we are."

In this case it would not matter. The back rooms were functioning smoothly, too, and were able to reconstruct positions and relation to samples without any major problems. For the first time there was a direct line between the capcom and the geology EVA team, although it was still only one-way and did not go to Bill Muehlberger: Parker could call Dale Jackson but Dale could not call him. As Tim Hait had done before, Ed Wolfe followed the progress of each EVA and made notes and sketches projected on the wall of the back room interpreting what the astronauts were saying. Bob Sutton kept track of the samples as usual. As he had for Apollo 16 and Gerry Schaber had earlier, George Ulrich marked each event on a map the capcom could see on closed-circuit TV. Ray Batson and his crew kept track of photographic matters in a room on the second floor of the Mission Control building, mosaicking photo prints of the TV scenes and taking them upstairs to the EVA, planning, and tiger teams. Court reporters made real-time transcripts on IBM Selectrics, also for transmittal upstairs via closed-circuit TV. To further grease the effort, their colleague Schmitt summarized the geology of each station. The geology team and the astronauts had simulated this mission so many times that they had trouble realizing this one was real. Morale was high, and there was much laughter, a heightened feeling of camaraderie, and a certainty that the team was doing something important.

While returning from Steno, Cernan spotted a landmark (Trident crater) that reassured him he was not lost and that he had landed in the right place. They made some critical observations of the relation between the dark mantling material and the Central Cluster craters. Cernan noted a dark coating on most of the craters and rocks. Schmitt added that there were enough well-formed craters to show that the blanket was not very extensive, and, "matter of fact, for example, hasn't filled the bottom of the craters." Thus arose the first doubt about the youth of the mantling material. They made a brief stop to deploy the SEP and arrived back at the LM after an EVA of seven hours and 12 minutes.

During a debriefing in the LM, Parker read them a well-founded question from the back room, "We're still puzzled as to whether there is a dark mantle. . . . There's a lot of discussion, today, about whether or not it could have been a regolith derived from the intermediate gabbro which you were sampling as boulders." Schmitt did not think so because the boulders were too light in color, but he did acknowledge that the dark regolith "could be derived from some other material that has blanketed the area." He summed up the status of their knowledge by saying, "All it means is that we don't yet know the origin of the dark mantle." He hazarded the guess "that the mantling we're seeing here, is just dark fine glass — darker than usual, because of the iron and the titanium in the rock itself. . . . We haven't seen any clear mantling relationships between the dark mantle or the surface materials here."

The capcom read a long and professionally detailed summary of the day's geology up to Ron Evans in the command module *America*, including the tentative but correct conclusion that the dark mantling material is thin and could be part of the regolith. He also told Evans the status of the ALSEP and passed on instructions from the orbital science back room run by Farouk El-Baz. Gene Shoemaker's vision of a sophisticated mission dedicated to science and staffed by geologically trained people on both ends of the Earth-Moon radio link was being fulfilled.

THE BRIGHT MANTLE AND SHORTY

Beginning with Cernan's descent from the LM bedroom at 2328 GMT on 12 December, the second EVA began with preparation near the LM and a few minutes of sampling near the SEP station. Schmitt commented, "I had to relearn how to document samples, Bob. I just have. The first part of my roll will have a lot of random exposures and focuses" (it does). During the drive back from Steno on the first EVA Cernan had knocked a fender off the rover, and the astronauts got sprayed with a plume of the dark soil. John Young had stirred up a lot of lunar dust himself, and now down in Houston he worked out a new and important use of Cernan's and Schmitt's geologic maps as a makeshift fender. The fix worked, and the rover could strike out westward. Other than this small problem the rover performed magnificently and was praised by all three J-mission crews.

On the way to Station 2 Schmitt remarked that he had looked at the gabbro with his hand lens in the LM and found it to be "standard," not unusually light in color as he had thought during the EVA. The small meteorite zap pits that had been well known since Apollo 11 were doing the brightening. While passing Camelot crater, a member of the Central Cluster that Republican Schmitt had named for the Kennedy Camelot to commemorate how he got where he was, he commented on its dark gray mantling material and very sparse craters. Since the crater is evidently young, faith was restored in the youth of the superposed mantle as well. The 650-m Camelot is very blocky, but the smaller craters away from it are not because they had not penetrated to bedrock. Cernan and Schmitt made three quick "LRV stops" not in the time line that supplemented the heavier work at the main stations. Schmitt chose the stopping points and Cernan took over all the mechanical tasks at the rover so Schmitt could look around. Earlier crews had also made such stops, but now they were formally named after the fact (LRV-1, LRV-2, etc.). A handy new scoop enabled Schmitt to collect samples without getting off the rover. As the mission progressed, the geology team wrote down the tasks that he performed, and the tasks also became official after the fact.

The main goal of the second EVA was officially called bright, light, or white mantling material for objectivity but was likely to be an avalanche or landslide from South Massif. Craters in line with the Central Cluster lie atop South Massif, and the geologic mappers had dared extend their interpretation of a Tycho connection to the mantle. They thought it might be ejecta of the Tycho secondaries or perhaps had been set off by the impact of the Tycho projectiles. The connection with Tycho fulfilled the wildest dreams of the geologists and geochronologists. Measurements of the length of time the rocks of this mantle and the Central Cluster ejecta have been exposed to cosmic rays ("exposure ages") all point to around 109 million years, with a formal error of only 4 million.[29] The synchronous formation of such different features as craters and the bright mantle, already thought to be related to each other and to Tycho, left little doubt that Tycho had been dated. So a crater lying 2,250 km away from the valley was added to the list of absolutely dated lunar features. Tycho's rays splashed out across of the face of the Moon about 44 million years before another great impact (probably) ended the reign of the dinosaurs on Earth.[30]

An hour and a quarter after leaving the LM on the second EVA, Cernan and Schmitt arrived for an hour-plus stay at Station 2, Nansen crater, named for the Norwegian polar explorer (as is a much larger crater near the Moon's north pole).

The objective was not Nansen itself but the bright mantle that covers its near-massif half completely and its northeast half partly. Hundreds of blocks larger than meter size were part of the deluge, and three major boulders were sampled. The more they looked, the more variety of color and clast size they found: white, blue gray, pinkish tan, pastel green, small, large, dark-in-light, light-in-dark. There were solid rocks and clods of regolith that looked like rocks until they were handled. They collected soil also, once at Parker's request, to which Schmitt complied, accompanied by, "One-scoop-Schmitt, they call me."

After a short traverse they stopped the rover for 11 or 12 minutes of collecting and photography at Station 2A, or LVR-4, farther north on the rim of Nansen. To Muehlberger's annoyance, the experimenters of the traverse gravimeter wanted and got the stop added to establish a gravity station, a procedure that required a bare minimum of 3 minutes once the astronaut aligned the axis of the instrument to within 15° of vertical and pushed the right button. The gravimeter was supposed to measure the local gravity at every rover stop so that the valley's subsurface could be characterized in detail—an optimistic objective considering how difficult this job is on Earth.

As they left Station 2A and drove north to Station 3 across the Lee-Lincoln scarp, Schmitt remarked that it looks more like a series of lobes than a scarp, and Cernan noticed that it seems to flow onto North Massif. Mare ridges, or wrinkle ridges, had been high on the list of mysterious special features ever since the early telescopic days. Their exploration had been one of Harold Urey's suggestions for manned exploration and was one goal both at the original Littrow site and at Taurus-Littrow. Were they volcanic flows, swellings over subsurface intrusions, purely tectonic faults or folds, or none of the above? No astronauts would ever get closer to a ridge, but the problem was not amenable to on-site inspection or sampling. After the mission many geologists, including Keith Howard and Bill Muehlberger, retackled the ridge problem with the good topographic and photographic data on Lee-Lincoln. One or the other of them revived and supported all the old hypotheses. I think, though cannot prove, that all the volcanic notions have been discredited. Most ridges, including Lee-Lincoln, result from shortening of the mare surface area caused by subsidence of mascon maria—as Ralph Baldwin had proposed in 1968. Heavy Mare Serenitatis sank within its basin, and the basalts near its surface were compressed and pushed into Taurus-Littrow Valley and onto South and North massifs.[31]

Station 3 was on the northeast rim-flank of the 500-m crater Lara, which is deformed by the Lee-Lincoln scarp and covered by the light mantling material. The mantle was the main objective, and it yielded up 5.4 kg of mostly light-colored rock and soil during a 45-minute assault. Schmitt named the craters at

Taurus-Littrow from his recent reading and is surprised today at how much he was able to do. Lara was named for Dr. Zhivago's lover, and *Dr. Zhivago* is a long book.

Lara was at a dogleg in the traverse on the bright mantle, and the rover rolled northeast after leaving it. Figuring out details of the deposition process from ground level—whether it slid smoothly or tumbled—was proving just as difficult for the mantle as for the Lee-Lincoln scarp; such things are best left to study back on Earth. Rocks were the order of the day. Cernan and Schmitt made a brief unplanned stop at LRV-5 to sample and photograph a crater that caught their eye, then stopped again, at LRV-6. A voice from Houston interrupted the proceedings:

Capcom:	And, 17, the word from the back room is—with that last Rover sample you got, we'd like to go straight to Station 4—and we won't get the one here . . .
Schmitt:	I thought the purpose was to sample the light mantle?
Capcom:	I—we talked to them about that, but they—
Schmitt:	We didn't sample the light mantle at that last one.
Capcom:	—I agree. I talked to them about that. But they are so anxious to get to Station 4, I guess they don't want to do it.
Schmitt:	Well, how about it, Gene? A little real-time—
Cernan:	I think we got to, right here. . . .
Schmitt:	We'll get the sample—anyway.

In other words, to hell with the back room, we are here and they are there. A professional geologist was on the Moon, and his companion and commander was no geologic slouch either. Hindsight attests to the correctness of their judgment in most cases.

Not all the geologizing was immaculate, however. The yearned-for Station 4 demonstrated that. Approaching the famous Shorty crater, named for a legless San Francisco wino from a book by hippie-era author Richard Brautigan,[32] Cernan and Schmitt could see that it was indeed as dark as the photographs had foretold. In fragment population, however, it did not seem different from other craters of its size (110 m across). When the astronauts looked inside they saw a hummocky inner wall and floor and a blocky and jagged central mound. Then, excited voices from the Moon exclaimed:

Schmitt:	Oh, hey! Wait a minute . . .
Cernan:	What?

Schmitt:	There is orange soil!
Cernan:	Well, don't move it until I see it!
Schmitt:	It's all over! Orange! . . . I stirred it up with my feet.
Cernan:	Hey, it is! I can see it from here!
Schmitt:	It's orange!
Cernan:	Wait a minute, let me put my visor up. It's still orange!
Schmitt:	Sure it is! Crazy! Orange! I've got to dig a trench, Houston.
Cernan:	Hey, he's not—he's not going out of his wits. It really is. . . . How can there be orange soil on the Moon? Jack, that is really orange. It's been oxidized.
Schmitt:	It looks just like—an oxidized desert soil, that's exactly right. . . . if there ever was something that looked like a fumarole alteration, this is it.

After a few minutes of furious sampling and photographing by the two astronauts, Cernan exclaimed, "Even the core tube is red! The bottom one's black—black and orange, and the top one's gray and orange!" Schmitt added that the bottom of the core was blacker than anything else they had seen and ventured that it "might be magnetite. . . . God, it's black isn't it?" He repeated his idea that "if I ever saw a classic alteration halo around a volcanic crater, this is it." The folks in the back rooms in Houston could not restrain their excitement either. The news media recounted Gerry Wasserburg staring at the TV monitor as if he were "looking at God."[33] Not only did there seem to be crater volcanism on the Moon but, since the colors had not been blended into standard lunar tan gray, young volcanism. The Wasserburg quote contains a hint of skepticism, however, and Gene Shoemaker did not buy the volcanic story at all.

A duller truth began to occur to Schmitt during the drive to the next station: "I didn't have time to really think at that station but—if I hadn't seen that alteration, and all I'd seen [was] the fractured block on the rim— which looked like the stuff in the bottom—I might have said it was just another impact. But having all the color changes and everything, I think we might have to consider that it could be a volcanic vent." But his thought that Shorty's blockiness means that it formed by an impact is correct. The orange and black glass at Shorty is billions of years old, and Shorty is only millions. An impact happened to expose an ancient volcanic glassy deposit. The same titanium-rich droplets are orange if still glassy, and black if devitrified (crystallized).[34] It had been known ever since Orbiter 5 photographed Copernicus H in 1967 that impacts quarrying dark material from beneath lighter material can create dark crater halos. Impact appears as the first choice for the dark craters on Baerbel Lucchitta's premission map and as an alternative to volcanism on Scott and Carr's map.[35] Almost surely, Al Worden was seeing soft, dark mantling material excavated by impacts. Volcanic materials were sampled on the Moon, but no volcanic craters.

Cernan and Schmitt stopped at LRV-7, saw more orange, and heard capcom Parker opine, "That's what you guys were sampling at Station 4, I bet." They agreed. Orange and black glass are not restricted to Shorty. The team curtsied at LRV-8 and arrived at Station 5 half an hour after leaving Shorty. Station 5 was near their outbound tracks at Camelot, and in 15 minutes it yielded soil and more of the crystalline lava rock that Schmitt was calling gabbro. Camelot was the largest crater visited during the mission, so these samples should have been from the greatest depth. They drove back to the ALSEP and the LM, and closed the hatch after an EVA of seven hours and 37 minutes and a traverse of 19.5 km, the longest of any Apollo mission.

THE LAST EVA

As on Apollo 16, the first EVA of Apollo 17 had been a short stab from the LM and ALSEP, the second had gone far afield to the south, and the third was planned to go north. North of Apollo 17's landing point lay North Massif and the Sculptured Hills, mountain country of great beauty. It presented not only Schmitt and Cernan but lunar science and humanity with the last chance until the twenty-first century to explore the Moon's rocks in person.

Shortly after the third EVA began, at 2226 GMT on 13 December, capcom Parker informed Schmitt, "They're expecting a little solar storm, and before the rain gets on the cosmic ray experiment, they'd like to retrieve it." This nonchalant language did not refer to a sweet-smelling sprinkle like one that might refresh green Earth but to a long-known hazard of space travel. Solar storms in August 1972 had probably been intense enough to kill anyone outside Earth's atmosphere. This was one more bullet the Apollo program dodged, and it lends some support to early termination of lunar missions. A real Apollo 18 might have suffered the fate of James Michener's 1982 fictional one.

As they drove off due north, past more coarse pyroxene gabbro, Schmitt looked ahead at North Massif and observed that the boulders on its flanks "seem to start, more or less, from [lines] of large boulders . . . roughly horizontal across the face that we're looking at." The tracks that mark the downhill paths of many boulders are curved in places and have little clusters of craters where the boulders bounced. The Sculptured Hills have boulders too, though fewer and smaller than those on North Massif—another reassurance to the geologists who had mapped them as photogeologically different units. They made quick stops at rover stations LRV-9 and LRV-10 and arrived at Station 6 an hour and 20 minutes after beginning the EVA.

They had driven the rover up an 11° slope without fully realizing how steep it was and had to block the wheels and make sure they had set the brake. Their Station 6 was at exactly the position planned for Station 6, something not always achieved during Apollo. Schmitt described the object of their attention as "a beautiful east-west split rock" 18 m long, 10 m wide, and 6 m high. Its downhill roll from a point about one-third the way up the massif left a nice track that looks like a chain of craters and is what Henry Moore used to refer to by the technical term "a real donicker" when he was carefully studying boulder tracks as a means of estimating the lunar soil's engineering properties.

After about 25 minutes at Station 6, capcom Parker said, "And so its sort of your option as to how much time you spend here." They ended up spending 75 minutes and collecting 17 kg of rock, rake, core, and soil samples — including almost 5 kg from four of the five pieces of the boulder — and taking 207 pictures. Schmitt remarked, "The more I look at this — the south half of this boulder, the more heterogeneous in texture it looks." He was summarizing the main characteristic of lunar bedrock breccias, their complexity. He compared the relations to an anorthositic magma catching up a lot of inclusions. Later he more correctly described a "fragment of breccia that got caught up in this thing." Cernan responded, "Yes, well, the whole thing is obviously a breccia. I'd sure like to get that . . . ," at which point Schmitt backslid to, "I'm not sure . . . I think it may be an igneous rock with breccia inclusions." Capcom Parker said Charlie Duke was sitting there "mumbling something about it looking just like House Rock," to which Schmitt replied, "It's very crystalline. I'll tell you, it's not a breccia — not like House Rock [which is fragmental and less cohesive]. Not to take anything away from House Rock though." The matrix looked igneous to Schmitt for the same reason sample 14310 looked igneous even in the laboratory: it *is* igneous in the sense of having crystallized from a melt, but the melt was created by the shock of a great impact, not by heat that built up from radioactivity or other sources in the Moon's interior.

At Station 7, half a kilometer east of Station 6, they collected a boulder only 3 m across that seems roughly similar to the Station 6 boulder but features veinlets or dikelets (as Cernan called them at the time). Such relations are common in endogenic igneous rocks but are also well within the range of what can happen in an impact-melt sheet. Station 7 was allotted 22 minutes, a victim of the extended time at Station 6.

After a short stop at LRV-11 came the turn of the Sculptured Hills at Station 8, 2 km east of Station 7. The astronauts confirmed the paucity of boulders they had noticed from a distance, though they saw some out of reach up the slope. The lack of obvious geologic features and shortage of time led to the advice from Houston to hurry through the station activities and to hang their hopes for sampling the Sculptured Hills on a rake sample. Cernan and Schmitt partly complied by avoiding pieces of subfloor gabbro they were completely sure did not come from the Sculptured Hills, but turned their attention to one terra-type boulder they had spotted sitting on the surface uphill from the rover. When they cracked open pieces of it Cernan exclaimed, "Boy, is that pretty inside. Whoo! We haven't seen anything like this. I haven't. Unless you've been holding out on me." Schmitt denied holding out and agreed that it was a nice crystalline rock, then accurately described its mineralogy as probably plagioclase (white) and orthopyroxene (yellow). So they had found a real plutonic rock of the lunar crust. Jack was worried that it might not have come from the Sculptured Hills because he saw no boulder track and because of its impact glass coating, a sign of ejection from a crater, which could be located far away.

The relation to the Sculptured Hills of the 400 g of rock samples from the boulder is still uncertain, but at least they are from the terra hills bordering the Taurus-Littrow Valley. Like a satisfyingly large number of breccia clasts from earlier stations, this Station 8 boulder had survived the violent shock, dislocation, mixing, and redeposition inflicted by great impacts; it was shocked at least once but is close to pristine. Its plagioclase and orthopyroxene define it as a *norite.*[36] The Station 8 norite may have originally crystallized 4.34 aeons ago, and a troctolite (plagioclase and olivine) raked up at Station 6 may be as old as 4.51 aeons — almost as old as the Moon itself.[37] All the pristine samples are, of course, older than the Serenitatis basin. They may have reposed in mafic layered plutons like the Stillwater Complex for hundreds of millions of years before suddenly finding themselves perched high on a mountain next to a crowd of rocky, crystalline, and glassy strangers unknown in their ancestral depths. Anorthosites and anorthositic particles from Tranquillity Base, Hadley Delta, the Crisium rim, and the Descartes Highlands had nourished the concept that the terra crust is anorthositic scum that rose in massive amounts from a magma ocean of melted primordial material several hundred kilometers deep. The concept remains very much alive; petrologist Jeff Taylor has told me that 80% of petrologists believe the crust is 80% plagioclase and that this much plagioclase would require a magma ocean. Complicating the oceanic model are "magma ponds" created by impacts and magnesium-rich intrusions into a more nearly anorthositic upper crust as indicated by the norites, troctolites, and related rocks collected in particularly large amounts by Apollo 17.[38]

After extending capcom Parker's desired 30 minutes to 40, Cernan and Schmitt rolled south. At Station 8 they had reached the easternmost point of the mission — and therefore of any Apollo. By occupying it they completed the exploration of an entire lunar valley. On the way to Station 9 Cernan reiterated that the valley of Taurus-Littrow is not planar, and Schmitt said, "I'm glad we changed it to subfloor instead of a plains unit." Later Schmitt's "gabbro," a term usually applied to intrusive rocks, was replaced by "basalt," more appropriate for the extrusive flows that fill the valley. Like Apollo 15, Apollo 17 ended up returning more mare basalt than terra material, although at least Apollo 17 got plenty of terra samples too.

An objective at Station 9 was to get a radial sample of the 90-m Van Serg crater (the science fiction pen name of economic geologist Hugh McKinstry) in order to probe the dark mantling material and subfloor basalt according to the overturned-flap model. Van Serg turned out to be very blocky and young (less than 4 million years) and to be made of rock the astronauts had trouble identifying beneath a dust cover. After a while the back room aborted the radial sample and Schmitt agreed, saying, "I think that's a smart move. I don't think the radial sample's going to tell you much here." Meteor Crater on Earth may have ejected an overturned flap of target rock, but the lunar Van Serg seemed more chaotic. Parker hurried the work along and then added, "We've had a change of heart here again, as usual. And we're going to drop Station 10 now that we've hurried you so much, and we're going to get a double core here." Schmitt objected, "You don't want a double core here. I don't think we can do it, Bob. It's too rocky." Cernan wanted to give it a try, though, and succeeded in getting the first section of the core easily and the second with some difficulty. After a long 54 minutes they headed back to the SEP station. Schmitt was amazed that "there's no subfloor [basalt] around here." The 10.26 kg of rock and soil from Station 9 turned out to be regolith breccias from an indurated old regolith about 11 m thick excavated in Van Serg and containing fragments of terra rock, subfloor basalt, and dark mantling material. This idea did not occur to Schmitt until a sleepless "night" during the coast back to Earth, but then he got it right even before the samples were examined.

During the drive Schmitt commented that he was "more and more convinced that there's a [dark] mantle." He repeated his surmise that it is hard to see because it is so fine. After the mission the geologists finally solved the mystery of the missing mantling material. The part mapped photogeologically as mantle on the valley floor is not a discrete mantling deposit but a regolith containing black and orange glass droplets or beads. The geology team concluded that these were probably quarried by impacts from a droplet deposit about 1.5 m thick that lies on the subfloor basalt. Similar droplet-rich regoliths or droplet deposits still reside on the mountains, forming the dark streaks that show up so well on the high-Sun photographs. The droplets seem to have been fountained by a still unidentified gas — a rare manifestation of the elusive lunar volatiles.

Finally, back at the LM and ALSEP, came the time to tidy up film magazines and sample bags, pull the neutron probe out of its deep hole, adjust the gravimeter again, set more charges, and look around the moonscape one last time. Schmitt and Cernan had driven a total of 35 km and were bringing back 110 kg of rock and 2,218 pictures. They said words appropriate to the glad-sad occasion and held up a breccia "composed of many fragments, of many sizes, and many shapes, probably from all parts of the Moon, perhaps billions of years old" whose cohesiveness symbolized the harmony among Earth's people for which they and the Apollo program hoped. Cernan unveiled a plaque reading, "Here man completed his first exploration of the Moon, December 1972 A.D. May the spirit of peace in which we came be reflected in the lives of all mankind." They climbed back in *Challenger* for the last time, threw out equipment and trash, repressurized the cabin, rested or slept a while, and repeated the trash disposal and pressurization.

Sent off at 2255 GMT on 14 December with Cernan's "Okay, now let's get off" (official version) or "Okay, let's get this mother out of here" (actual phrasing), and Schmitt's "3, 2, 1, *ignition*,"[39] the ascent stage of *Challenger* shot up from the launching pad provided by the descent stage as Captain Video moved the camera up to watch it disappear into the blackness. After rendezvous and docking two hours and 15 minutes later, they sent *Challenger* to its final crash on South Massif to become the ninth and last artificial impact recorded by the passive seismometers left by the earlier missions, and also by the four geophones of this one. The geophysicists started methodically firing off the eight explosive charges Cernan and Schmitt had left behind, which together with the LM impact and data from the traverse gravimeter revealed a singularly solid subsurface interpreted as a slab of subfloor basalt as thick as 1,400 m—almost a mile.[40] The geology team calculated that about 130 m of this was quarried in the Central Cluster and was spread as a basalt-rich upper layer of the regolith.

The crew of three orbited the Moon in the command module for almost two days to extend the orbital photography into new territory not covered by Apollo 15 and to follow up their surface findings with visual observations. The Sculptured Hills still looked like a distinct unit to them. Schmitt was still entertaining the idea that it consists of igneous intrusions. Farouk El-Baz in the orbital science back room circled some dark craters near the landing site for them to examine, but craters near Mike Carr's original dark mantling material discovery near Sulpicius Gallus, already spotted by Ron Evans a few days earlier, out-Shorty-ed Shorty in orangeness. Then came Greenwich midnight of 16 December and TEI. The next day the Moon yielded gravitational control over Apollo 17 to Earth, and, in three trips totaling 47 minutes, Evans retrieved the film and orbital data from the SIM bay in view of Earth television and handed them to Jack Schmitt.

On 21 December 1968 Frank Borman, Jim Lovell, and Bill Anders had been the first humans to set off for the Moon. Only four years later, on 19 December 1972, Gene Cernan, Jack Schmitt, and the late Ron Evans were the last in our century to complete the return trip.

THE LAST SAMPLE BAG

The geology team blended their now-polished note taking with the real-time reporting from Schmitt on the Moon into a splashdown report that was as good as earlier 90-day reports. The sample bags were opened in an order suggested largely by the splashdown report, and the last one was logged into the processing cabinets at the LRL on 30 January 1973.[41] Working and essentially living in cramped and leaky trailers where people constantly dropped by to chat, the geology team, as before, spent the three months after the mission laboring on green horrors, including their 90-day report, while the sample analysts were performing parallel labors of their own.

The Lunar Science Conferences were moved from January to March beginning with the fourth one (5–8 March 1973), and some preliminary Apollo 17 results were ready for reporting. The usual journal articles and preliminary science report (actually quite complete) followed apace, the latter derived in geology's case from an edited version of the 90-day green horror.[42] Ed Wolfe took on the larger and longer-lasting job of preparing the USGS professional paper that summarized and detailed the geology of Taurus-Littrow,[43] and did it in a way entirely different from George Ulrich's for Apollo 16. George had divided the Descartes Highlands into study areas and topics and assigned each to one or more members of the field team. Ed worked through the mission chronologically and wrote almost the whole thing himself, except for petrologic matters supplied by Howard Wilshire, who looked at every sample and generated enough notes to fill a large box.

Most of the terra samples are complex, severely deformed, and extensively melted multicomponent breccias of types that by now were expected from terra deposits but had never been collected before in such variety. Their intricate makeup patently called not for the exhaustive scrutiny by specialists of each tiny fragment that was characteristic of the early missions but for major assaults on the samples as integral assemblages. Therefore consortia of investigators from assorted institutions were formed for each boulder: Consortium Indomitable led by John Wood for boulder 1 at Station 2, a Caltech consortium for boulders 2 and 3 at Station 2, a mixed-nationality consortium led by USGS petrologist Odette James for two Station 3 rocks, a Johnson Space Center consortium led by Charles Simonds for the huge Station 6 boulder, and the International Consortium led by Ed Chao for the Station 7 boulder. The geochemistry-petrology crowd got their bonanza of pristine rocks that had more or less survived the trauma of great cosmic collisions, and geologists and geologically disposed petrologists got plenty of textural complexities to contemplate in their effort to determine how basins form. Basin impacts are not like the pipsqueaks that created Meteor Crater or even the much larger (25 km) Ries. They create vast volumes of melt-rich deposits that are enormously complex in fine-scale lithology, chemistry, and stratigraphy. Each basin-scale impact severely shocked and melted the Moon's crust, and mixed, sheared, and threw huge masses of its rock out of the basin cavity.[44] During flow and flight the ejected mass was mixed again in ways the human brain can begin to envision but not to model numerically. After coming to rest, the partly hot, partly cold mass crystallized and metamorphosed in other intricate ways. Multiple breccia-in-breccia relations do not necessarily mean origin in multiple impacts. Part of the end product looks igneous, as does much of the Apollo 17 collection and a few samples from Apollo 15, and part is insubstantial junk, as much of the Apollo 16 material is. The highly melted rock comes from a zone close to the impacting projectile, and the less highly shocked rock comes from closer to the cavity's edge.

Because Imbrium basin materials dominate earlier sample collections, it would be nice if this rich collection proved to be part of the Serenitatis basin. Most analysts, I believe, think that it is. However, some nagging questions remain. We still do not know for sure how basin massifs form or what they are made of. Surely they must form partly by some kind of deformation of the prebasin rock during basin formation, but how much basin ejecta covers them? This was not established at Hadley Delta, and it was not established at South and North massifs despite the tracing of some samples to lines of near-outcrops on the massif flanks. Are those lines uplifted prebasin rock, Serenitatis ejecta, or superposed Imbrium ejecta?

Nor do the absolute ages of the Apollo 17 samples definitively solve the problem of their origin. Their dating included a complex and subtle process in which laser beams drive off minute amounts of gas from grains less than a tenth of a millimeter apart. Not only do ages for the collection as a whole range from 4.51 aeons (for pristine grains of the Station 6 troctolite) to 3.86 aeons (for some groundmass material from the Station 3 bright-mantle rocks), but the geochronologists have found age ranges of hundreds of millions of years for pieces of the *same* breccia sample. Average age thus has no meaning for geologic events. The youngest reliably measured age, 3.86 or 3.87 aeons, may date the Serenitatis basin. However, this is barely distinguishable from the 3.83–3.85 aeons found for the Imbrium basin because of the inevitable imprecision of even the best laboratory dating. *Are* these Imbrium dates? Or did Serenitatis form shortly before Imbrium? With its low, degraded ring massifs and numerous superposed craters, Serenitatis *looks* older than the absolute age of the samples indicates; but looks can deceive.

A more popular means of reconciling the young absolute age and old-appearing relative age of Serenitatis is the famous (or infamous) "terminal cataclysm" whereby a barrage of huge impacts formed most ringed basins within a very short time between episodes of relative quiescence. In this theory, spawned in the Lunatic Asylum of Caltech,[45] the cataclysmic barrage is responsible for a concentration of lunar terra ages in the interval between 3.85 and 3.95 aeons. The idea appears in almost every professional article written about the Moon, and the expression "late heavy bombardment" escapes the pens or lips even of those who do not believe in the cataclysm. Ralph Baldwin, Bill Hartmann, Gene Shoemaker, Ross Taylor, and world-class geochronologist and Solar System dynamicist George Wetherill are among those who do not believe that the cataclysm happened as originally stated. However, petrologist Graham Ryder, who probably spends more time examining the Apollo samples these days than anyone else, points out that no impact melts have been dated as older than 3.95 aeons.[46] Impacts capable of creating basins always generate great quantities of melt. To learn how many basins formed before the time of the alleged cataclysm, we need to collect and date impact melts from relatively dated old basins like Nectaris and the very old South Pole–Aitken basin on the far side.

Though very much younger in relative terms, the young end of the age bracket of mission objectives turned out to be much closer to the old end in absolute ages than had been expected and hoped. The dark mantling deposit is pyroclastic alright, but recent laboratory analyses have placed its age at 3.64 aeons.[47] This is getting young by lunar standards but falls more than 2 billion years short of the Copernican age that had been predicted. The low crater densities and dark crater rims that make the deposit seem young have come about because it is weak; craters formed in the thick, glass-rich regolith and the original pyroclastic layer had softer initial shapes and then softened more quickly than they would have in hard rock. A better story is told by the overlaps of mare units on the dark mantling material that George McGill saw and are there for everyone to see if they only look.

Finally, overlaps viewed on stereoscopic photographs taken under favorable illuminations put to rest another annoying old lunar problem. They showed that the brighter central units of Mare Serenitatis abut, and therefore postdate, the darker marginal unit, including both the subfloor basalt and the dark mantle.[48] We had been misled because large subdued craters of the Serenitatis border were less easily visible on telescopic photos than the bright specks made by the craters in the center. So, once and for all, dark mare units are not always young and light mare units are not always old. Colors and albedos are related in a complex way; but to cut a long story short, the darkest maria are also generally the richest in titanium and iron.[49] The subfloor basalt is 3.72 aeons old and chemically and mineralogically similar to the titanium-rich suite collected at the Apollo 11 site. However, the entire 130 m in the Taurus-Littrow Valley may have poured out in a geologically brief time, nothing like the 170 million years that the measly 30 m at Tranquillity Base required.

By the time of Apollo 17 a magnificent and sophisticated network of rocketry, flight operations, geologic and geophysical support, and geologic and laboratory analysis was functioning with smooth precision. Now it was time to shut it all down and turn out the lights. Let each of us reflect once again on the marvel of it. It could not be done today. But at least scientists now have access to a rich trove of data on craters, basins, maria, the ancient crust, and geologic history that has been assembled from the once-mysterious Moon.