



Mysterious Descartes

1972

THE HIGHLAND SITE

Geologists had a record of four straight successes in predicting what would be found at the landing sites. Apollo 16 would break the string. Those who wish always to be right were chagrined or downright embarrassed. But those who wish to learn were immensely pleased, for the mission to the Descartes Highlands illustrated once again that science advances most when its predictions prove wrong.¹ Apollo 16 gave lunar geoscience its greatest boost in knowledge since Apollo 11.

Astrogeologists had been interested in the Descartes region west of Mare Nectaris ever since Dick Eggleton noticed a 60-by-100-km patch of hummocks that looked like others ejected from the Imbrium basin but seemed to be isolated from them.² The patch also seemed unusually bright. Dan Milton examined the patch closely and suggested that a form of a viscous volcanic rock superposed on the local Imbrium ejecta made the hills.³ Newell Trask and I attributed pits in and near the patch to secondary impacts of Imbrium ejecta.⁴ In 1967 Lunar Orbiter site selectors considered including the tract among the targets of Lunar Orbiter 5, but I got it rejected because I thought Lunar Orbiter 4 had already shown all the detail likely to be visible.

After the Orbiter flights ended we continued to ponder the tract on the Orbiter 4 photographs because it looked so different from anything else on the Moon. Almost everybody who looked at it agreed that it resembled terrestrial volcanic landforms created by eruptions of silicic lavas or cinders. We treated the patch as a geologic unit and named it Material of the Descartes Mountains, or the Descartes Formation.⁵ Its status as a true, three-dimensional geologic formation was enhanced by its appearance of partly burying the 48-km-diameter crater Descartes. While "compiling" our 1971 near-side map, Jack McCauley and I

highlighted this and seemingly similar patches elsewhere (altogether 4 or 5% of the near side) and gave them the red color that is traditional on geologic maps for volcanic units. Following Milton's earlier suggestion and the prevalent assumption that bright = young in the terrae, we distinguished an especially bright patch as younger than the rest. A landing at Descartes would show whether or how magmas in the lunar terra differed from those of the basaltic maria. The young patch would show how magmas evolved with time.

The Descartes Formation was only one attraction at the site. Filling depressions was a second putative volcanic unit, a patch of light-colored, rolling terra plains typical of the dispersed geologic unit I had named the Cayley Formation in 1965. The Descartes Formation was (and is) hard to date, but the Cayley's crater densities put it between the Imbrium basin and the maria in age. Plains like the Cayley Formation cover about 5 or 6% of the near side. Shoemaker and Eggleton originally thought the largest patches were part of the Imbrium ejecta blanket because they are peripheral to the typical hummocks of the Fra Mauro Formation. Then the new group of us hired in the early 1960s reinterpreted them as volcanic because, except in albedo, they look more like small maria than hummocky basin ejecta.⁶ Volcanic and impact basin origins were (and are) equally consistent with the plains' morphology and concentration in depressions near basins, but a basin origin seemed excluded by the many plains patches on the rims of young craters, on the floors of such craters as Clavius (almost 3,000 km from the center of the Imbrium basin), and, in fact, almost everywhere on the Moon.⁷ The hot-Moon bandwagon was definitely rolling in the late 1960s.

Descartes was put on the list of candidate Apollo landing sites in early 1969, was targeted for Apollo 18 or 19 in June, and was the front-runner for Apollo 16 by November. Like Apennine-Hadley, Descartes had been foreseen for a late mission but quickly rose to contention for an early J mission when MSC found it was relatively undemanding operationally and partly relaxed the photographic requirements. It was even considered for a walking mission at one time. Hal Masursky and I, and our intellectual recruits like Farouk El-Baz and Jim Head of Bellcomm, presented the volcanic story more than once to GLEP and other influential forums.

The terrae are five times more extensive than the maria, yet because of the Apollo 13 accident they had not been visited by the time the ASSB approved Apennine-Hadley for Apollo 15 in September 1970; and the Apollo 15 landing point was actually on a mare surface. Moreover, many planners mistakenly referred to the Fra Mauro site that Apollo 14 would visit in February 1971 as a mare site, even though it is entirely terra in the geologic sense.⁸ Scientists therefore agreed that Apollo should concentrate on the terrae after Apollo 15. Alphonsus, Copernicus, and a new site on the Kant Plateau east of the Descartes

Highlands contended with Descartes for the honor of being the terra landing site. The Marius Hills also temporarily stayed in the running for Apollo 16 but succumbed to the drive to the terrae in April and May 1971, when the Apollo 16 and Apollo 17 missions were being planned. Site selection was now in the hands of the Ad Hoc Apollo Site Evaluation Committee convened and chaired by Noel Hinners of Bellcomm and rounded out by Paul Gast, Hal Masursky, Lee Silver, geophysicist David Strangway of MSC and the University of Toronto, geologist Robert Phinney of Princeton University, and petrologist John Wood.

Alphonsus is pre-Imbrian and therefore potentially valuable as a terra-sampling site, but the committee took the advice of the photogeologists and declared it probably "contaminated" by the already sampled Imbrium ejecta or mixed debris. It could be held in reserve for Apollo 17 if earlier missions failed to get pre-Imbrian rock or the other specialty of Alphonsus, the coveted xenoliths from the lunar mantle supposedly erupted out of its dark-halo craters. Also held in reserve for both purposes was Davy, which had lost out for Apollo 15 but was not dead yet. Gast even favored the dubious Davy over Alphonsus as a source of xenoliths.⁹

Before the number of landings was cut in January and September 1970, the search for deep samples and the desire for a highland mission had briefly converged on the long, linear Abulfeda crater chain south of Descartes. Stu Roosa had seen the chain from a distance during his Apollo 14 orbits and said it looked even less distinctive than Davy. Hal Masursky promoted Abulfeda as vigorously as he had Davy because the chain's linearity suggested a string of diatremes that might sample deep-seated material. However, the rest of us rejected Abulfeda as too simple and too uncertain for a J mission, especially one so near the end of the Apollo program.

By 1970 the origin of central peaks by violent rebound of the target rock had been widely accepted. Deep-seated terra material therefore probably could be sampled at the Copernicus peak, and other terra material could be obtained from the crater's walls. Copernicus, like Tycho at the Surveyor 7 landing site, has smooth-surface "pools" and various flow features superposed on its rim and walls that were believed by almost everybody except Gene Shoemaker to be volcanic. In May 1971 Copernicus was still being considered as a backup site to Descartes, but Noel Hinners led an anti-Copernicus movement because he believed that it had been dated by analysis of the Apollo 12 samples and because it was too near the Apollo 12, 14, and 15 sites to provide new kinds of terra material or a good geophysical station. Anyway, its origin was no longer in doubt except by those like Jack Green, who was still saying that the facts were in and they supported him and Spurr.¹⁰ One more count against Copernicus was the belief that impact-triggered volcanism as represented by the pools and flows was

so well understood that the subject need not be pursued further. Chapter 18 shows the irony in this premature supposition.

In all scientists' minds, Tycho was still in the running for Apollo 17, if not 16. It had drilled into a thick section of the all-important southern highlands in a place seemingly out of Imbrium's reach. Samples brought back from its ejecta could show how well the Surveyor 7 alpha-scatterer had worked. It was a geophysical station far removed from the others and a datable young stratigraphic marker. NASA was leery of Tycho, however, because it looks rough and lies beyond the envelope considered accessible to Apollo landings, though they admitted it was marginally accessible in some months. I remember Jim McDivitt, the former Apollo 9 commander who had become manager of the Apollo Spacecraft Program Office at MSC in late 1969 when George Low moved back to NASA Headquarters, telling a GLEP meeting in early 1970, "no way, over my dead body." The dead body was Tycho. Critics of the manned program as an effective exploration tool pointed at Surveyor 7 sitting unscathed on the forbidden rocky field and felt vindicated.

The Kant Plateau, which is part of the mountainous rim of the pre-Imbrian Nectaris basin, put up a good fight for the Apollo 16 slot. The Apollo 14 high-resolution Hycon camera had failed over Descartes but had successfully photographed Kant. Kant appealed to geochemists and petrologists like John Wood, who were more interested in the primitive Moon than in speculative volcanism. It looks like a block of the lunar crust without any features suggestive of volcanism. Most geologists, however, thought that any primitive material in the Kant Plateau was probably covered by impact debris of uncertain origin — an ironic reason for its rejection in view of the difficulties the Descartes samples have presented. Hinners, Masursky, Silver, and most of us who advised the committee favored Descartes because it seemed to offer the clearer geologic context and the all-important young terra volcanics from two distinctive volcanic units. Even if the interpretations of the Descartes and Cayley formations were wrong, sampling them was desirable because together they represent some 10 or 12% of the terrae. At this time the other 88 or 90% of the terrae was considered too undistinctive to be placed in a geologic context. Essentially, they would provide random grab samples.

The plains proffered a landing field, and the astronauts could proceed in the rover or on foot to sample bedrock conveniently excavated by two "drill holes": the young, fresh, 1,000-m North Ray crater, and the younger, very fresh, 680-m South Ray crater. Another advantage of Descartes (and Kant) was its location in the southeastern near side, far from all other active ALSEPs and therefore favorable for geophysical and geochemical purposes. Rocco Petrone, who always looked carefully at the evidence himself, never doubted our volcanic interpreta-

tions of the Descartes site.¹¹ The way to Descartes was cleared when the quick-thinking Apollo 14 CMP Stu Roosa shot the necessary high-resolution photographs with his Hasselblad and chalked up a mark for Man in Space. The ASSB settled on Descartes as the Apollo 16 site on 3 June 1971, two months before Apollo 15 explored the Apennine Mountains and Hadley Rille.

PREPARING THE CREWS

John Watts Young is another actor in our story who presents a deceptive exterior. He usually talks only when he has something to say — for example, on the Moon. Though born in San Francisco in 1930, that banner year for astronauts and geologists, he has lived mostly in the South. Young has flown six times in space, more than any other astronaut (Gemini 3 and 10, Apollos 10 and 16, two shuttles). Geologists also learned very early about his competence, and I believe that all who worked with him ranked him near the top of their list of lunar explorers. He is one of the few astronauts who still keep up with what is going on in lunar science, and he comes around to every Lunar and Planetary Science Conference. As we shall see, he knew about the scientific controversies over his landing site but did not choose sides, an objective trait that Lee Silver noticed during the premission training. Lively commentary from the Moon also attests to the diligence, knowledge, and enthusiasm of LMP Charles Moss Duke, Jr. (b. 1935), the capcom during the *Eagle's* landing. CMP Thomas Kenneth Mattingly II (b. 1936) was going to make up for testing nonimmune to rubella at the time of Apollo 13. The original backup crew was Fred Haise, William Pogue, and Gerald Carr, but Pogue and Carr were replaced by Ed Mitchell and Stu Roosa on 3 March 1971, a month after their Apollo 14 mission and more than five months before Apollo 15. Tony England was the mission scientist.

Apollo 16 was the middle mission of the J series and got the full blast of geologic preparation. All the astronauts had been on earlier field exercises, and beginning in September 1970 (when Apollo 15 was announced as a J mission), they spent an average of two days each month in the field. Their instructors spent much more. Bill Muehlberger was now the leader of the geology team, despite furious opposition from Paul Gast (Tony Calio had eased off his pressure after Apollo 15). Bill worked with the prime crew during the field training while Gordon Swann switched to the backup crew. Bill and Gordon would also switch positions during the EVAs, as Gordon took over the planning team in the back, back room, which had been Bill's position for Apollo 15. Although Young and Duke apparently had caught the geology bug from Silver in the Orocopia Mountains in September 1969 while they were members of the Apollo 13 backup crew, Silver was still working intensively with Apollo 15 when the Apollo

16 training began, and was furthermore embroiled in his Caltech duties and some personal worries. He could not repeat his Apollo 15 leadership role, but he helped guide many Apollo 16 trips and was in the back room during the mission.

The one-per-month field exercises raged on between September 1970 and February 1972. Days in the field were about evenly split among show-and-tell exercises, walking-traverse simulations, and rover-traverse simulations.¹² That is, two-thirds of the time the astronauts were acting as if they were on the Moon. They had cameras hung on their suits and practiced documenting samples and firing off the cameras like western movie gunfighters. The sample bags hung on rings under the cameras as they would on the Moon. The geology team first interpreted and mapped each area from aerial photographs whose resolution was degraded to match that of the site photos, and then planned the EVAS. In May 1971, at volcanic terrain in the Capulin Mountain area of northeastern New Mexico, Young and Duke did the photogeology themselves, then went on the ground to check their interpretations. These men were learning real geology, no compromises.

During EVA simulations Dale Jackson often walked along with the crew and the local expert on the region, listening in on the two-way radio by which the crew communicated with the astronaut serving as mission scientist and capcom. The team of geologists acting as the back-room staff also listened and had the opportunity to pass on suggestions through the capcom. After each EVA, Dale would walk through the area again with the astronaut crew and back roomers, criticizing both: "Crew, you should have seen this and this." "Back room, if you had said so-and-so, they would have got such-and-such."

In December 1970 Paul Gast chose Ries specialist Friedrich (Fred) Hörz as his mission science trainer for Apollo 16. Hörz, who had already been on field trips, spent much time on the photography and sample documentation during the field exercises. Gast, Hörz, and others in their group, coordinating their efforts with Tony England, also organized three one- to four-hour lectures per week for the astronauts, delivering them themselves or calling in outside specialists. They discussed science topics, reviewed past field trips, and taught the art of rock description in the presence of laboratory specimens or actual Moon rocks in the LRL. The USGS had little to do with this indoor instruction except as "outside" speakers.

Some field exercises were conducted at the same volcanic terrains, natural and artificial craters, and anorthosites that other crews had visited. However, the Apollo 16 crew got plenty of unique opportunities to prepare themselves specifically for what the geologists expected to find at the Descartes Highlands. In June 1971 they examined the silicic domes and ashflow tuffs around the Mono craters in eastern California. Minds were not set on volcanism, however,

and Muehlberger also wanted Young and Duke to see breccias. Though rare, impact breccias do exist on Earth. The Apollo 14 astronauts had visited those at the 25-km, 14-million-year-old Ries crater in August 1970, but certain incidents on the trip caused Deke Slayton to forbid future European excursions. Closer to home was Sudbury, Ontario, whose nickel ores occupy a basin measuring 27 by 59 km, now believed by most geologists to have originated as an impact crater about 1.7 billion years ago.¹³ Sudbury's surroundings offer good exposures of impact breccias and other features. So it was that in July 1971 the crew and their instructors got a preview of the Descartes Highlands.

Farouk El-Baz orchestrated the crew's training in observing from orbit. CMP Ken Mattingly was especially eager to learn all he could. (I have an American flag on my wall that was taken into lunar orbit by Apollo 16 and bears a comment by Mattingly thanking me for helping him to learn how to observe — at least I think that is what it says; the words have faded along with the Apollo program.)

I should mention negative aspects of the training I have been describing so glowingly. Whereas most geologists who participated were dedicated and proud to be a part of it, the experience was not appreciated 100%. A few abandoned it because of the havoc it wreaked on their family lives. Others were unwilling recruits because they were not interested in the Moon or even scorned it as an object unworthy of study. Another view was expressed by the Space Science Board of the National Academy of Sciences, who cautioned from the very beginning against scientists becoming astronauts or otherwise participating in the Moon program at the expense of their own careers. To me, the antimoon attitude was incomprehensible and the academy's attitude excessively precious, for what could be more important than sharing in the grand adventure of Apollo? However, experience bore out the academy's fears in some cases. A scientist-astronaut could spend many years in the astronaut office without getting a flight assignment or enhancing his scientific standing. Some SPE geologists who threw themselves wholeheartedly into the training later noticed great holes in their bibliographies (some cared, some didn't). There was much nonscientific grunt work on the training trips, which one member of the geology team characterized as "making sandwiches for astronauts."

Dan Milton and Carroll Ann Hodges took on the job of mapping the Descartes site at large scales. Dan had been one of the originators of the volcanic model for the Descartes and Cayley formations with his 1:1,000,000-scale map of the Theophilus quadrangle, and he now graduated to the 1:250,000-scale site map. Carroll Ann was a newcomer to the Branch of Astrogeology (1970) and was given the allegedly less desirable and less prestigious job of preparing the 1:50,000-scale map that nested within Dan's regional map, a position on the pecking order she duly noted. She knew that regional lunar mapping usually

yields the most geologic plums because the regolith obscures detail at large scales. In fact, indications of the origins of the Descartes and Cayley at both mapping scales are ambiguous.

Still closer looks at still larger scales found the well-defined features and hardened the volcanic interpretations. Don Elston, a longtime astrogeology enthusiast, and Eugene Boudette, one of the balky recruits to SPE, took on the job of constructing high-resolution (1:12,500) photomaps of the site on analytical stereo plotters. They examined second-generation film positives of the 500-mm Hasselblad pictures taken by Roosa and mapped every narrow line and tiny spot. I have described instances where looking too closely is as bad as looking carelessly. So it was with these photomaps, and for the Descartes region as a whole. To Boudette and Elston every line unfortunately was a dike or fault, every hill a cinder cone or fault block, every noncircular pit a maar. They thought they detected flow units in the Descartes and Cayley formations and suggested that both units, especially the Descartes, might be younger than the maria because the surface appears undersaturated with craters. On the positive side, they also mapped every block and boulder larger than about 5 m across and found few enough to suggest that landing and traversing would not be excessively hazardous. They realized that much of the Cayley was not planar and that other distinctions between the Cayley and the Descartes were blurred. However, they were volcanic-origin fanatics. Bill Muehlberger and the rest of the geology team were more tentative in their support of the volcanic interpretation, having seen all volcanic interpretations at the Apollo 14 Fra Mauro site disappear after the sampling.

Some non-USGS geologists also bought the volcanic line. Jim Head and Alex Goetz at Bellcomm performed a quantitatively impeccable analysis of the remote-sensing data that supported the notion that the bright spot of the Descartes Formation was young and granitic.¹⁴ Here we had the all-important Copernican lunar volcanism. Farouk El-Baz, and therefore his orbiting student, Stu Roosa, also rode the volcanic bandwagon.¹⁵ So almost everybody was more or less convinced that the Descartes Formation consists of volcanic rock, probably of a viscous type. They believed that the Cayley consists of a more fluid lava or pyroclastic debris or both.¹⁶

In November 1971 Newell Trask and Jack McCauley submitted a paper supporting the volcanic origin of the Cayley and Descartes formations and outlining a scheme of lunar thermal history to explain the post-Imbrium, premare age of these nonmare basaltic rocks. The paper contains the following lines:

Photogeologic interpretation alone cannot rule out the possibility that all the hilly and gently rolling terrain belongs to one or more of the hum-

mocky ejecta blankets surrounding the large circular basins. Surface textures, particularly of the furrowed linear hills, resemble those seen in the "deceleration dunes" of the Orientale blanket [reference to a 1968 paper by McCauley]; furthermore, the two largest areas of hilly and furrowed material . . . are approximately equidistant from the center of the Imbrium basin.¹⁷

These lines contain the only published reference I know of to doubts that had been surfacing about the volcanic hypothesis. I remember Maurice Grolier, Henry Moore, and myself all drawing the comparison between those deceleration dunes at Orientale and Descartes. In the Menlo Park office we had mosaics of all the Orbiter 4 frames mounted on six large, two-sided sliding panels to show the regional relations so critical in understanding lunar geology; there were the Orientale deceleration dunes adjacent to Cayley-like Orientale ejecta plains, all clearly derived from Orientale. McCauley has told me that he discussed the dunes at length with the astronauts during premission briefings.¹⁸ Why did this discovery not stick? One reason was that Jack was trying to get away from Shoemaker's emphasis on impact, even though Jack himself had discovered the dunes. Newell and Jack were worried enough to insert those lines in the paper. My own worries caused me to withdraw as the third author. Nevertheless, our doubts were overcome by the inertia of the volcanic idea, in which we had all invested much time and effort.

LUNAS 18, 19, AND 20
(SEPTEMBER 1971 - FEBRUARY 1972)

Before we watch Apollo 16 blast off for the Descartes Highlands, let us briefly examine what the Soviets had been doing since Apollo 15 put their robot program in the shade. They too were heading for the lunar highlands, though not necessarily by design.

In September 1971 the USSR launched Luna 18, an "opportunity to improve space vehicles" that was probably supposed to return samples, considering that it crashed near the edge of Mare Fecunditatis, at 3.6° N, 56.5° E, in the landing zone of the Luna 16, 20, and 24 sample returners. Launched in the same month was Luna 19, which carried a Lunokhod without wheels and transmitted television images. From heights above the surface on the order of 127-140 km it acquired pictures in the area between 30° and 60° S and 20° and 30° E, and also obtained data on radiation, micrometeoroids, and lunar topography (by tracking). These sound suspiciously like the goals of a mission preparing the

way for people, but no such plans were announced. By this time four U.S. manned landings had already taken place.

Of more concrete interest to our story is Luna 20, a sample returner that contributed substantially to the unfolding picture of the Moon's crust. On 18 February 1972 Luna 20 landed near the site of Luna 16, but this time on the flank of the Crisium basin (3.5° N, 56.5° E). It returned to Earth a core consisting mostly of regolith fragments of ANT composition like those scooped up by Luna 16.¹⁹ The Genesis rock had whetted the analysts' appetite for anorthositic terra samples, and here were 30 g of terra soil that seemed to fill the bill. However, severely abused regolith fragments are far from being pristine rocks of the original lunar crust.

The geologists did not think such rocks would be found at Descartes, and the geochemists and petrologists had preferred the nearby Kant Plateau as more likely to yield them. But you never know. It was time to go and see.

THE PLAINS AT DESCARTES

Three explorers with heads crammed full of geology lifted off in their monstrous seven-piece machine on schedule from the Cape just before Sunday noon, 16 April 1972 (1754 GMT). Three days later the LM and CSM were inserted into lunar orbit at 2022 GMT, and at 2102 the S4-B that got them there hit the Moon a couple hundred kilometers off target but with the expected and inevitable effect on the Apollo 12, 14, and 15 seismometers.

During the thirteenth revolution, after separation of the LM from the CSM and self-correction of one problem, another problem occurred that affected the rest of the mission.²⁰ The backup to the system that aligned the SPS engine for steering the CSM was malfunctioning. Rooms full of experts at MSC and contractor plants around the country went into action as they had for Apollo 13. The problem was not life-threatening this time, but it did threaten the landing. That geologic disaster was avoided, but the landing was delayed almost six hours. The LM *Orion* finally landed at 0224 GMT on 21 April 1972 at 8.99° S, 15.51° E, between North and South Ray craters and only about 250 m from the preplanned point.

When Young and Duke looked out the LM windows they quickly commented that they would not have to go far to find rocks. Nor was the topography of the Cayley "plains" nice and smooth. Only ten minutes after landing came the first use, by Young, of the *B* word: "I see one white [rock] with some black . . . it could be a white breccia." Well, you would expect even some volcanic rocks to be brecciated by impacts on the scar-faced Moon. Over the next three hours a highly professional dialogue sparked back and forth between the explorers look-

ing out the LM windows and capcom and mission scientist Tony England at his console in Mission Control. There was the usual effort at locating *Orion's* position, about which Young remarked, "this is the first place I was ever at on a geology trip that I thought I knew where I was when I started." They tried to find a spot smooth enough for the ALSEP (hard to do) and to estimate the trafficability for their rover traverses (probably alright). Young could see South Ray crater and commented that it was "a doggone interesting crater. I wish we could get to it." South Ray seemed to Duke to be within range of a well-thrown rock, though he knew it was not. He was also aware of another typical lunar deception: they could see the same false lineations looking like fractures that Scott and Irwin had seen at the Apennine Front. Less illusory were the many black-and-white rocks they could see. That was where the rock descriptions had to rest for the time being. The delay in landing required Young and Duke to go to "bed" instead of beginning their outdoor activities as had been planned.

At 1656 GMT, about 14 hours after landing, Young finally emerged, with the clairvoyant comment, "There you are, our mysterious and unknown Descartes Highland plains, Apollo 16 is gonna change your image." Young's egress (the official term) was not seen on Earth because of an antenna problem, but the American public probably would not have watched one more moonwalk on a Friday morning anyway. Young and Duke noticed that one of *Orion's* footpads had just barely missed a half-meter rock, breaking the two-mission string of leaning LMS (we should remember that all the lunar landings benefited from a certain amount of luck). A half hour after Young's descent and after deployment of the rover and miscellaneous equipment, Duke exclaimed, "Man, look at that breccia, John! Right there." "This big rock is a two-rock breccia." They set up the rover, installed the TV camera on it, and deployed the ALSEP, which shuffled the experiments on the Apollo 12, 14, and 15 ALSEPS into a new combination. To mention only the geoscience experiments, it had a stationary magnetometer, as did 12 and 15 but not 14; an active seismometer, as did 14 but not 12 or 15; a heat-flow experiment, as did 15 (and the aborted 13) but not 12 or 14; and a passive seismometer, as did all the earlier ALSEPS (appendix 2).

Next came time to see if Duke could avoid Scott's problem by using a redesigned deep drill for the heat-flow probe and cores. Buried rocks temporarily stalled the drilling, but it went well and Duke inserted the probes with the words, "And, Tony, Mark has his first one all the way in to the red mark on the Cayley plain" ("Mark" meaning the principal investigator, Marcus Langseth of the Lamont-Doherty Geological Observatory). England responded, "Outstanding. The first one in the highlands." Heat flow had the highest priority among the ALSEP experiments. But then came ominous words from Young, who had been busying himself with other ALSEP instruments: "Charlie. Something happened

here. . . . Here's a line that pulled loose." Duke did not reassure Houston or Langseth as he replied, "Oh-oh. . . . That's the heat flow. You pulled it off." All hope that it might be repaired was lost when Young, one of the astronauts most interested in the scientific aspects of lunar exploration, said, "God almighty. Well, I'm wasting my time. God damn. I'm sorry. I didn't even know—I didn't even know it." Geologist Don Beattie, the manager of the surface experiments program at NASA Headquarters, admitted to the press that it was "a major blow."

Young and Duke explored, sampled, and photographed around the ALSEP, then headed 1.4 km west in the rover to Station 1. On the way capcom England asked, "Those rocks that you collected; were they all breccias, or could you tell?" Getting the answer from Duke, "I'm not sure, Tony," England pressed the point by asking, "And have you seen any rocks that you're certain aren't breccias?" Duke: "Negative. I haven't seen any that I'm convinced is not a breccia." They were not spared the locational difficulties that had plagued earlier missions. Those who had worried throughout the 1960s that locations would be a time-consuming problem were being proved right. But Young and Duke soon established Station 1 on the rim of Plum crater, a small fresh crater on the rim of the 290-m Flag crater. The idea was that Flag was big enough to penetrate the regolith to the Cayley Formation, and Plum would sample Flag—hence Cayley. Young and Duke swung into the photography, sampling, and describing that was becoming standard for lunar explorers. Watching through their television monitors, Bill Muehlberger and his back-room geologists saw a big rock that seemed to have large crystals of plagioclase and passed a request for a sample through the chain to the capcom. By means of an Earth-Moon videoconference, England and the crew collaborated in collecting the rock: "This one right here?" "That's it. You got it, right there." "Are you sure you want a rock that big, Houston?" "Yeah, let's go ahead and get it." "If I fall into Plum Crater getting this rock, Muehlberger has had it." And so the 11.7-kg gray-matrix, white-clast breccia named Big Muley was destined for a trip to Earth.²¹

Young and Duke retraced their route and resumed their geologizing at Station 2, the small fresh Buster crater superposed on the larger old Spook crater, only a kilometer from Flag and therefore suitable for exploring fine-scale differences in the Cayley's stratigraphy. At 370 m, Spook was exactly the size of Apollo 14's much younger Cone crater. Though much older and more degraded than Cone, Flag and Spook could serve almost as well as gopher-hole excavations to sample the underlying bedrock. Meteor Crater, the Nevada Test Site craters, and chemical and laboratory craters were bequeathing the means to squeeze the most possible information out of the time limitations imposed by space suits and the requirement that the astronauts had to be able to walk back from any point if the rover failed. No more than 21 hours could be spent outside the LM, 7 hours per EVA.

The main event back at the LM at the end of the EVA was the Grand Prix. Young drove the rover through every conceivable maneuver, bouncing high off the ground and throwing rooster tails of dark lunar dust, while Duke filmed the event and commented excitedly in his sonorous Carolina voice. Here was one of the few exceptions to the solemnity that dampened the Apollo program. Although they spent literally years going through all the films and videotapes that have survived the dumpster, filmmaker Al Reinert and his team of editors found few movie films from the lunar surface worthy of inclusion in his splendid full-screen film *For All Mankind*, released in 1989. Most of the activity is preserved only on grainy second-generation videotapes, the first-generation versions (none too good themselves) having been lost or thrown out. The rover traverses and some of the action on foot were recorded by a 16-mm movie camera called, tellingly, the *data acquisition camera* (DAC), but only at slow framing rates unsuitable for realistic re-creation. The scientists, only a few of whom were actually stuffy, must share the blame for this failure to share the adventure of Apollo with the American and world public of 1972 and posterity.

Once inside their "humble abode," the LM, Young and Duke discussed their observations with capcom England and expressed their enthusiasm for the mission and their appreciation of the enormous effort that went into their training. In addition they evaluated the way Apollo 15's problem with potassium loss was handled on Apollo 16. The following classic passage is remembered by everyone who heard it, though not all of it is recorded in quite the same terms in the official voice transcript.

Capcom: Great. Oh, I'm looking forward to tomorrow. I—I—The day went so fast today. The first thing I knew, I didn't have a chance to eat or get a cup of coffee or anything. It was really really hot along here. Doggone exciting. . . .

Duke: . . . Let's say that — that all our geology training, I think, has really paid off. Our sampling is really — at least procedurally — has been real teamwork, and we appreciate everybody's hard work on our exemplary training.

Capcom: Okay, and I sure think it's paying off. You guys do an outstanding job. . . .

Young: I got the farts again. I got 'em again, Charlie. I don't know what the hell gives them to me. Certainly not — I think it's acid in the stomach. I really do.

Duke: It probably is.

Young: I mean, I haven't eaten this much citrus fruit in 20 years. And I'll tell you one thing, in another 12 fucking days, I ain't never eating

any more. And if they offer to serve me potassium with my breakfast, I'm going to throw up. I like an occasional orange, I really do. But I'll be damned if I'm going to be buried in oranges. . . .

Capcom: *Orion*, Houston.

Young: Yes, sir.

Capcom: OK, John. You're where you have a hot mike.

Young: How long—how long have we had that?

This exchange was immediately followed on commercial television by an advertisement for Tang, an orange-drink mix used by NASA for its potassium and vitamins. Tang's manufacturers (General Mills) played an important role in informing the public about the details of the Apollo missions. I remember Dan Milton once commenting that if the Russians wanted to know what was happening, "we should tell them to write Tang, and see if they can figure *that* out."

Near the end of the EVA, when CMP Mattingly asked the capcom, "Did they have any surprises in the things they saw or that they didn't expect?" he received the answer, "I guess the big thing, Ken, was they found all breccia. They found only one rock that possibly might be igneous." Mattingly's reply has become famous in the halls of lunar geology: "Well, it's back to the drawing boards or wherever geologists go."

RICHES OF THE SOUTH

The second EVA had been planned to take a very large bite out of the premission objectives. The astronauts were supposed to sample thoroughly both geologic formations—the Descartes and the Cayley—as exposed by half of the region's obvious landmarks, Stone Mountain and South Ray crater. Stone Mountain, named for the big granite mound incised by a Confederate memorial that protrudes above the plain in Georgia, is characterized by the transverse furrows that were the main attraction of the Apollo 16 landing site. The geology team assigned Stations 4, 5, and 6 (from high to low in elevation) to the prime task of sampling the Stone Mountain Descartes. South Ray crater had always been considered a promising sampler of the Cayley, just as Cone crater was a sampler of the Fra Mauro Formation. Its rim lies less than 6 km south of the landing point and thus could easily have been reached by the rover. Radar had suggested that small blocks would bar the way to South Ray, though, so the geology team settled for sampling the crater from blocks along its rays. Passing overhead, Ken Mattingly had noticed benches on Stone Mountain and layers in South Ray, making both landmarks more promising than ever; but the blocks would have to serve as an indirect sampler of the different layers in South Ray and of the Cayley Formation.

Young and Duke climbed out of *Orion* on 22 April almost 16 hours after they had climbed in, collected samples and took photographs near the LM for 45 minutes, and began their drive south. The white rim of South Ray stood out like a sore thumb in the distance, and its diffuse but blocky rays hindered progress, reminding Young of a crater at the Nevada Test Site. The topography of the lower slope of Stone Mountain seemed like swales to Carolinian Duke and mountains to (transplanted) Floridian Young. There was no sharp contact with the Cayley plains. South Ray blocks peppered the slope as they had the plains. About 35 minutes after setting out, Young and Duke picked out a blocky crater to become Station 4; it was about 150 m above the plains, the highest vantage point any Apollo astronaut ever reached.

Neither the crew nor the geology team initially knew exactly where Station 4 was; later, it appeared to be near the 65-m-wide *Cinco a*. The bedevilment by the South Ray blocks was not yet over. The crew was aware of the problem and tried valiantly to sample blocks excavated from the Descartes by the *Cinco a* impact and not from the Cayley by South Ray, but commented, "You know, John, with all these rocks here, I'm not sure we're getting Descartes." And, "That's right. I'm not either." Very unfortunately, neither are the sample analysts sure to this day. Young and Duke commented on South Ray's prominence and beauty and took telephoto pictures of it. They described the scenery from the mountaintop as "just dazzling." They took many rake, trench, and core samples, and capcom England commented hopefully, "Maybe we're getting down to Descartes there" when driving in the tubes got difficult at one point. After almost an hour at Station 4 the crew headed back downhill.

Frustrated by the ambiguity of the blocks at Station 4, they thought of resorting to sampling a nonblocky crater that could not be contaminated by that annoying South Ray: "Suppose we give you a primary impact with no blocks?" But orthodoxy ruled, and capcom England insisted, "We don't want one without blocks. It'll almost have to be blocky." So Station 5 was set up at a 20-m crater that at least had rounded blocks likely to be older than the angular ones from South Ray crater. Their hopes also turned on a rake sample of friable soil and another rake sample from a slope they thought should be shielded from South Ray: "Then we ought to be looking at real Descartes" (Duke). Today the Station 5 rocks remain a reasonable bet to be Descartes, though I doubt anyone would put much money on it. After 50 minutes at Station 5 the crew spent 23 minutes at Station 6, near the base of Stone Mountain, where a firmer regolith suggested a different bedrock, the Cayley Formation.

Nobody has anything against the Cayley, but Apollo 16 landed on it and derived most of its sample collection from it, and the Descartes was, and is, the

more puzzling unit. Nevertheless, the plan called for proceeding to Station 8 (Station 7 had been deleted to save time) and getting more Cayley. There were boulders galore of it, an embarrassment of riches that was the reverse of the problem on the Descartes. After more than an hour of raking, coring, and picking up, Young and Duke had collected a variety of rocks, notably some "black-and-white" breccias consisting of two main rock types. They also got four pieces from two 1.5-m and one 0.5-m boulders. The larger boulders yielded mostly dark breccias, but the smaller is a nearly homogeneous, light-colored, plagioclase-rich, sugary-textured crystalline boulder whose samples (68415 and 68416, totaling 550 g) were going to raise a fuss.

Sampling and photography at the interray Station 9 took a little more than half an hour, after which they returned to the ALSEP to try (unsuccessfully) to repair the heat-flow cable and to explore Station 10. The extra time gained by trimming time from other stations made so much time available for sampling near the LM that its vicinity is the most intensively sampled area on the Moon.

In talking with me and in a section titled "Hindsight" in the USGS professional paper about Apollo 16, Bill Muehlberger has lamented the excessive influence the ground-based radar data on blockiness had on planning the mission. The low-tech photographic counts by Boudette and Elston had proved more accurate in predicting the block density at South Ray than did the high-tech remote sensing. If the geology team had believed the photographic evidence instead, they might have designed the second EVA to reach South Ray and also the neighboring Baby Ray. Along with the ALSEP deployment, the first EVA might have been devoted to Stone Mountain instead of Flag and Spook on the Cayley plains. These alternatives had in fact been entertained, and I am among those who wish they had been adopted. The Descartes Formation would have been better explored on Stone Mountain because Young and Duke would have had time to find a fresh crater uncontaminated by South Ray blocks, much as Scott and Irwin did on their second EVA to Hadley Delta. The Cayley Formation would have been better sampled at the two rayed craters than in the less clear geologic context at Flag, Spook, and the LM. A seven-hour EVA devoted both to a charge up Stone Mountain and to the boulder field of South Ray could do justice to neither.

A little radar knowledge is a dangerous thing. According to Muehlberger, the radar had seen subsurface blocks because the region is iron-poor, unlike the maria where the radar signals had been calibrated with block frequencies.²² No one I have talked to remembers who made the critical interpretations. I would guess that the communication between the radar astronomers and the geologists was incomplete. In the face of today's enormous body of scientific knowledge

and pressure of time, individual scientists tend to accept the conclusions from other fields less critically than they would those from their own, where they know all the ins and outs of how the conclusions were reached.

THE DASH NORTH

NASA, eager to stick to its schedule, figured that if you lost six hours at the beginning of a mission, you should chop six hours off the end. That meant canceling the last EVA altogether. The geology team blanched and called in its third subdivision, the tiger team, which shared the back, back room with the planning team. A report prepared under the leadership of Dallas Peck helped convince NASA that the third EVA was absolutely necessary to achieve the goals of this mission, and they agreed to cut the EVA by only two hours. The geology team deleted some of the planned photographic tasks and Stations 12 and 14-17 to make time for sampling. Only two stations, 11 and 13, remained for the examination of North Ray crater and Smoky Mountain. (Whether it hurt the science, the reduction of the original 17 Apollo 16 stations to 10 at least benefited a new sample-numbering system devised by Bill Muehlberger, because each of the remaining 10 stations could be designated by a single digit.)²³

And so on 22 April Young and Duke rode off 4 km northward to North Ray crater with the send-off from capcom England, "Out again on that sunny Descartes plains," to which Young replied, "Ain't any plains around here, Tony. I told you that yesterday." The 1-km North Ray is similar in diameter to Meteor Crater (1.22 km), where so much that was being done here began, and penetrates Smoky Mountain.

Boulders loomed ever larger as the LRV sped toward North Ray. Young commented about some 3- or 4-m boulders that "if you didn't know better you'd say that they were bedrock outcrops, but they are just laid in there I'm sure from North Ray." Finally, two lunar explorers got a chance to look down into a relatively large fresh crater. Half the interior of North Ray is covered by boulders. Young and Duke saw many boulders oriented horizontally, but no actual bedding. They could not see the bottom and to do so would have had to "walk another 100 yards down a 25 to 30 degrees slope and I don't think I'd better" (Young). Sampling the rocks on the rim that came from the greatest depths was the main point, and this Young and Duke did for an hour and 20 minutes at the North Ray rim (Station 11), frequently commenting on the friable, probably shocked nature of the rocks and the difficulty of examining their surfaces because of dust. While looking for really big boulders they found one 25 m wide by 12 m high about which Duke commented, "Well, Tony, that's your House rock right there." As is true for massive boulders or outcrops on both Earth and Moon,

House rock presented too formidable a face to sample, so they sampled instead a similar-appearing 3-m piece right next to House that some wit called Out-house rock.

Next they retraced their tracks and made the eight-minute drive to Station 13, one crater diameter from the rim and right on the previously mapped contact between the Descartes Formation of Smoky Mountain and the Cayley Formation of the "plains." As in the South Ray block field, the idea was to re-create a vertical sample of the stratigraphy beneath North Ray by means of a radial sample of its ejecta. They spent half an hour here, collecting, among other things, a much-sought soil sample from a place beneath a large rock that they believed had never been reached by sunlight. Then they headed back along their tracks to *Orion*, setting a never-surpassed LRV speed record of 22 km per hour, photographing, getting a (high) reading with the portable magnetometer, but not being allowed the time to sample. Near the ALSEP and LM they set up Station 10', reoccupied Station 10, and added some rake, core, and soil samples to their already large haul from this central area. Some samples with the hopeful appearance of vesicular basalts turned out to be glass-coated breccias when the astronauts cracked them open with hammers.

Finally it was time to leave the mysterious Descartes Highlands to future visitors and to the remote scrutiny from back home. The astronauts weighed the samples, reported the weights to Houston, and after some worry were relieved to find they could bring them all back (they total 96 kg). At 0126 GMT on 24 April *Orion's* ascent stage popped into orbit to rendezvous with Ken Mattingly in the command module. The plan had been to stay two days in orbit and change orbital planes to cover more of the Moon with the SIM bay instruments and cameras. But worry about the SPS engine scrubbed the plane change and the second day in orbit. Orbital scientists — including photogeologists — thought the worry excessive, but NASA engineers had the last word. The narrow ground track of Apollo 16 and the premature crash of the subsatellite after only 35 days in orbit (because the SPS was not allowed to fire to optimize the orbit) are there to remind us.²⁴ But the ground track differs from the largely redundant ones covered by Apollos 15 and 17, and the pan and metric cameras obtained excellent photographs of geologic features, the landing site, and the small craters made by various crashed spacecraft.²⁵ For the first time, the pan camera joined the metric camera in photographing the east limb and far side west of about 140° east longitude after TEI, making up for the poor Lunar Orbiter coverage of the region.

During the transearth coast, Young, Duke, Mattingly, capcom England, and the geologists in the back rooms had time to reflect on the transformations that had come over the scientific picture of the Moon during the previous three days.

- Capcom: . . . I think the fact that you recovered from the picture we had given you before you went and went ahead and found out what was there and sampled it so well — I think that's a good indication that the training was good and you guys are really on the ball.
- Young: Well, we tried hard, Tony; and I think we got — a piece of every rock that was up there. I really do. . . . you guys tried to beat [the training] into us long enough, I'll tell you that. . . .
- Capcom: [I'll] describe a theory that's coming up as a result of the rocks that you saw there. A possibility is that an older theory . . . may be the right one, that the Cayley is an outer fluidized ejecta from Imbrium. Fra Mauro would be an inner ring, and then Imbrium sculpture would be outside that of that, and then the Cayley would be sort of slosh that filled up all the valleys farther out.

This quote shows that geologists had begun to revise their thinking while Apollo 16 was still in space. But John Young had been there, and he responded to England's comment with: "I'd say it's premature to be making those kind of statements, Tony," and repeated his concern several times when told that the press was eager, as usual, for some simplistic one-liners.

Young: In other words, it ain't good science.

Capcom: Yeah, John. I think you're right on, and I hope they heard you in the back room, because — I think I said the same thing this morning.

A team of astronauts equipped by their training and their own mental resilience had described the Descartes Highlands as they are, not as they were supposed to be. Although the volcanic hypothesis had dominated the selection of the landing site and their training, they had also seen breccias at Sudbury and elsewhere and knew very well one rock from another. Their descriptions on the Moon were excellent; they were scientists.

John Young spoke the last geologic word at this interplanetary press conference: "Mr. Descartes . . . said 'There's nothing so far removed from us as to be beyond our reach, or so hidden that we cannot discover it.' . . . My personal assessment of where we are right now, as soon as we get the rocks back in the LRL, we'll be making headway toward proving him right."

THE DRAWING BOARDS

The laboratory quickly showed that Young and Duke were right when they reported finding only impact breccia and not volcanic rock.²⁶ The skeptics, including some bitter critics of the whole idea of doing geology from photographs,

felt vindicated when the volcanic notion went down the drain. But geology *can* be done from photographs—up to a point. We have worked out the overall scheme and many of the details of lunar history and surface-shaping processes from photographs. Like all sciences, however, lunar and planetary geology advances in steps. Photogeology sets up hypotheses which are then tested by the process called a field check. Old-time geologists who looked down their noses at astrogeology would sniff, “Needs field checking,” by which they meant that if you can’t walk on it and rub your hands in it, it ain’t geology. The dark dust that dirtied Young and Duke left no doubt that they were field checking the photogeology of the Cayley and Descartes formations. There was nothing basically wrong with the science itself.

But there was something wrong with the way we used it in the case of the Descartes Highlands. No question raised by lunar exploration is more vexing to anyone involved than, why did the photogeologic predictions go wrong? The following is my attempt to answer it dispassionately.

Basically, we goofed; we violated a cardinal rule of science by abandoning multiple working hypotheses in favor of one. But in our partial defense let me recall the era in which we were working. We succumbed to three pervasive notions this book has been describing. Hot-Moonism was rampant, and most USGS astrogeologists actually resisted it fairly well. Second, geologists were too captivated by terrestrial analogues. Third, looking closely took precedence over standing back and viewing the big picture. The field check showed that Dick Eggleton’s original general photogeologic interpretations of the hummocks and plains as impact units, made on the basis of overall geologic setting and regional relations, were more nearly correct in principle than the later interpretations based on detailed studies of morphology, terrestrial analogues, and local setting.

One premission observation that should have rung more warning bells than it did is that the short furrows radial to the Imbrium basin which characterize the Smoky Mountain (northern) Descartes extend well beyond its mapped boundaries. Characteristics used to delineate geologic units are supposed to form when the units did and are not supposed to be superposed on more than one unit. Strict adherence to the rules of unit mapping would have kept us from calling at least the Smoky Mountain Descartes a discrete formational deposit. We knew that photogeologic mapping alone can seldom define the origins of lunar units, and usually we kept alternative ideas alive by stating them in the maps’ verbal explanations. But our eyes were always drawn to the similar, though transverse, Stone Mountain furrows that are brightened, purely incidentally, by the rays of the craters Descartes C and Dollond E.

Let us give the final word about those furrows to the third member of this expert crew, CMP Ken Mattingly.²⁷ Ken had simulated his lunar observations by

doing his own photogeology on areal photographs of Earth, then flying over the same areas to learn what he could add visually. He carried, for the first time, a pair of 10X binoculars with which he thinks he saw speckles of light from the landed LM and the rover. He spent five days in orbit and became thoroughly familiar with the Moon. In trying to pin down why the near and far sides looked so different to all the Apollo astronauts, he settled not only on the obvious difference of the proportion of maria but also on the Imbrium sculpture of the near-side terra. And he pointed out that the Descartes Highlands looked like only one part of a much more extensive terrain.

Which raises the central point about the visual observations. Would we have believed an astronaut if one had reported this nondistinctive character of the Descartes region before the mission? Without a photographic record, impressions, interpretations, and even factual observations are of little value except to the observer. But they do have a role to play, as Mattingly said very well in a memorandum for the record dated 6 September 1972 and titled "Confessions of an Amateur Geologist": "It seems to me that the proper role for these undocumented observations is to serve as a provocative note to the theorists and as a guide to the types of observations and observational equipment we should plan in the future. Within this concept the accuracy of my interpretations seems less important than the fact that something was observed." In the same memo Mattingly recorded another interpretation that also accords better with the mission results than with the mission predictions: "The Cayley represents a pool of unconsolidated material which has been 'shaken' until the surface is relatively flat." If someone had said these things before the flight, and if the geologists had had the sense to listen, the mission might have been conducted differently.

But such hindsight asks too much of any science. No geologist, physicist, or any other scientist gets everything right at first try. Scientists, like everybody else, usually arrive at their destinations by a process Arthur Koestler aptly called sleepwalking.²⁸ Quantitative-minded scientists commonly regard geologic thinking as fuzzy because they do not understand the complexity of Nature.²⁹ But some of them do have the decency to admit it: "Physicists have paid little attention to rock, mainly because we are discouraged by its apparent complexity. We are well trained in working with idealized models, but when faced with a piece of rock, not only do we not know where to begin, but we also may question whether it is even possible to find interesting physics in such a 'dirty' and uncontrolled system."³⁰ So if geologists muffed it at Descartes, physicists would not even have known where to start. Theory can come along after observations and summarize them with numbers, but it has a poor record of predicting what will be found on planets, or even of limiting the possibilities.

I do not want to leave the impression that geophysicists and geologists never see eye to eye. For example, in the years since Apollo 16 splashed down, experiments by Verne Oberbeck and Bob Morrison at the NASA Ames Research Center have contributed significantly toward devising impact models for terra plains and crater chains and clusters previously thought to have been created volcanically. Independent post-Apollo work by Dick Eggleton and myself on the numerous and large secondary craters of basins agrees with theirs.³¹ Moving these plains and craters to the impact camp left almost nothing in the hot-Moon one.

This is partly to say that necessity is the mother of invention. But it is also more than that; necessity is the basic motivator of scientific progress. Volcanism was an easy way to explain the Descartes Highlands because, in the absence of tests, volcanism can explain everything. Impact models required more thought, but in their modern form fit the morphology and distribution of most terra landforms better, I believe, than do the endogenic mechanisms. If Apollo 16 had not landed where it did, we would not have learned this, for volcanism would still have been an "out."

But we still do not know everything about Mr. Descartes's highlands. Those blasted transverse Stone Mountain furrows that caused all the trouble in the first place are still not understood. Carroll Ann Hodges, Bill Muehlberger, and Henry Moore have drawn the obvious lesson from their similarity to the Orientale deceleration dunes and proposed that they are the Imbrium equivalent, which gained access to the Descartes region down a trough that extends back toward Imbrium.³² This mass of Imbrium rock rests on Nectaris basin deposits. These interpretations fit observations very well, but few other people are willing to believe that ejecta flowed along the surface more than a thousand kilometers from the rim of the Imbrium basin. The same Ames and Brown scientists who favored secondary-impact origin for the Fra Mauro³³ more plausibly suggest that secondary impact of a mass of Imbrium ejecta somewhere closer to the basin started a flow which then slid along the surface the rest of the way, dislodging and depositing the Cayley and piling up the Descartes Formation as deceleration dunes. Or possibly the transverse furrows are secondary craters of Imbrium, as the radial furrows almost certainly are. At least we know now that they are not volcanic vents.

Since the Cayley Formation consists of impact breccia, and since its crater densities are Imbrian, most investigators have assumed it is Imbrium ejecta ever since the demise of the volcanic hypothesis. But the crystalline samples 68415 and 68416 collected at Station 8 on Cayley are too young (3.76 aeons) to be from Imbrium. Their age and composition suggest Orientale origin—that is, from 3,300 km away. Ed Chao adopted this model and enlisted Hodges, Larry

Soderblom, Joe Boyce, and myself in his cause. After expending quite a bit of work on this idea I got cold feet and dropped out, as I had from the premission paper with Trask and McCauley. Chao was peeved at me, but being burned once by the Cayley was enough.

Bill Muehlberger turned over the job of pulling the Apollo 16 professional paper together to someone he knew could do it, the conscientious and competent George Ulrich. In addition to his other qualities, George is a nice guy. He modestly considered himself merely the chief editor of the report and assigned authorship of individual sections to members of the field team, making sure that they all got full credit for their contributions — or, I would add though he would not, more credit than was deserved in a few cases. The result was predictable by anyone who has tried to manage a major multiauthored work: long delay in receiving some of the contributions and careless preparation of others. The Technical Reports Unit (TRU) of the USGS then added more delay of a type familiar to anyone who has dealt with the USGS publication mill. The resulting paper is not an integrated whole, but it is an absolutely indispensable compilation of information that could never be reconstructed by anyone who had not been in those back rooms during the mission. This is especially true of the 294 pages dealing with sample documentation by the late Bob Sutton, to whom let us once again tip our collective hats with admiration and appreciation.

Originally the sample analysts discerned little difference in general composition or style among the breccias from all the stations. As outlined by Ulrich in one of his personal contributions to the professional paper, however, the Cayley breccias seem to be richer in impact-melt rock than the more friable and lighter-colored samples from Smoky and Stone mountains. These differences could be reconciled if the Cayley Formation, which furnished most of the samples, is Imbrium ejecta, and the Descartes is basically Nectaris basin ejecta. A productive and enjoyable workshop held at the Lunar and Planetary Institute at the late date of November 1979 favored this conclusion.³⁴ Perhaps the conferees were a little too eager to grasp some unifying notion that would make sense out of the samples. As one who helped start this dual-origin bandwagon rolling, I am a little embarrassed by its wide acceptance. I think it is fair to say that beyond the conclusions that the Cayley and Descartes formations are impact breccias and acquired their surficial morphology in the Imbrian Period, little has been decided about the details of their history.

At least one idea for the origin of the material has been definitively discarded. Jim Head is a friend of mine and has contributed greatly to the advancement of planetary science. But he came up with a real lulu in trying to explain the two units by *local* origins. He detected a chronologic succession of rock types in the samples and traced the sources of two types to two craters he called “unnamed

A" and "unnamed B."³⁵ The problem is that, if the craters exist at all, they are too old to have been the sources of said samples. Jim simply got his stratigraphy wrong. I would not mention this bump on the rocky road to knowledge if it had not been so influential. For some reason, probably because it seemed to explain compositional differences among the impact melts,³⁶ the Apollo 16 "community" rode Jim's bandwagon for half a decade until it was traded in for the 1979 model.

Let us hope that some Nectaris basin material got into the samples, for we desperately need to date the Nectaris basin. Odette James and Paul Spudis have concluded independently that the age of 3.92 aeons determined for some samples does indeed date Nectaris.³⁷ Confirmation of this age is one of the most important tasks confronting lunar geology. The Nectaris basin is a key stratigraphic horizon of the lunar stratigraphic column because its *relative* age is well known: it clearly divides terra units older than the Imbrium basin into major groups, which Desirée Stuart-Alexander and I named the Pre-Nectarian and Nectarian systems based on her discovery of the Nectaris ejecta blanket and secondary-crater field.³⁸ Know the age of Nectaris and you know when giant objects were raining down on the Moon and the Earth from the early Solar System.

In contrast, North Ray crater and South Ray crater were confidently dated absolutely but poorly dated relatively. They are 50 million and 2 million years old, respectively.³⁹ Because they are so small, however, they are hard to use as accurate standards for dating other craters and determining the recent impact rate.

As always, the geochemists and igneous petrologists were looking for what had happened *before* the early impact bombardment, back when, they hoped, the Moon contained nice, simple, pristine bodies of igneous rock. *Pristine* was, in fact, the term they settled on to describe lunar igneous rocks solidified from endogenic magmas.⁴⁰ The pristine rocks of the terrae are never found where they originally solidified because they are removed by several generations of impacts from whatever flows or plutonic bodies they once formed. The petrologists and chemists have to pick pieces of them out of the messy breccias of deposits like the Fra Mauro, Cayley, and Descartes formations. The Apollo 16 sample suite includes the largest lunar collection of anorthositic materials, which had been shaping up as the typical terra material. Here it was in the heart of the highlands. The Apollo 15 and 16 orbital geochemical sensors apparently detected more of it in the cratered highlands of the far side. Calling the lunar terra crust anorthositic seemed more justified than ever, and the magma-ocean model for its origin seemed supported.

While the photogeologists adjusted to the reality of impact breccias where they had predicted volcanics, some geochemists identified volcanics where the astronauts had found breccias. Paul Gast (I believe) called one compositional

class of material at Apollo 16 *very high alumina basalt* (VHA), and he and his colleagues meant basalt in the volcanic sense.⁴¹ They were still looking for highland basalt. But the only volcanic basalt brought home by Young and Duke was small fragments of mare basalt recovered from the regolith samples and probably thrown to the site in Theophilus ejecta, just as Theophilus probably threw anorthositic fragments to the Apollo 11 mare landing site.

Geophysicists also got a good return from Apollo 16. On 23 May they set off three mortar charges, and on 17 July, only three weeks after Young and Duke set up the Apollo 16 seismometer, Nature set off the best seismic experiment before or since when the largest impact ever recorded hit the far side.⁴² The local crust is about 75 km thick, probably closer to the global average (74 ± 12 km)⁴³ than the 60 or 65 km in the Apollo 12–14 region. The ALSEPS continued to send back data for seven years, waiting for but not getting another large impact. The loss of the heat-flow experiment is unfortunate because this would have been the only heat-flow data from the heart of the uplands, and no one feels worse about this than John Young. The geophysicists will just have to speculate with one less data point, something that should not cramp their style very much (joke).

So, Apollo 16 went to an interesting and important site for the wrong reasons. Intense preparation by the geology field teams and expert execution of the fieldwork by the astronauts set lunar geology on the path it is still following. Internal origin of special features would finally be put to rest after a few more years of meditation by geologists and impact physicists back at those drawing boards. Now we know that almost all lunar craters were created by impacts and that impact basins dominate the Moon's crust, having disbursed their sundry effects into its farthest realms.⁴⁴ The lunar terrae contain a lot of plagioclase, which seems indeed to have floated to the upper crust early in the history of the rocky Moon. The samples also contain the best hope for determining the age of the stratigraphically important Nectaris basin until the next round of exploration begins.