9

The View from Lunar Orbiter
1966–1967

PRELUDE (1960 – 1965)

Almost everyone who wanted to explore the Moon knew that the overall views that orbiting spacecraft could provide would complement the "ground truth" obtained by soft landers. This coupling had been recognized in JPL's original plans for the Surveyor program in May 1960. Five Surveyor orbiters were to attain resolutions on the order of meters on the central near side to support the Surveyor landers and on the order of a kilometer on the entire far side and limbs to provide the kind of general reconnaissance that geologists knew was needed.

In June 1962, two days before the Iowa City summer study, OMSF specified to Homer Newell's OSS the orbital data then thought necessary. It wanted better resolution than the Surveyor orbiter was thought capable of delivering and far more coverage than the drop in the bucket Ranger could squeeze out. In September 1962 Oran Nicks, director of lunar and planetary programs in OSS, requested a study of a whole new kind of lightweight orbiter to be launched with an Atlas-Agena combination that was less powerful than the Atlas-Centaur planned for Surveyor.[1] Nicks asked U.S. Navy Captain Lee Richard Scherer, Jr. (b. 1919), an honors graduate of the Naval Academy then on temporary assignment to NASA, to direct the study.

The program that evolved from this beginning suffered fewer problems and returned more data per dollar than any other unmanned program. Its five photographic missions covered almost all of the Moon. It was also my favorite program and the one which involved me most closely, yet the one the public knew least about. So let us revive its story.

In January 1963 Oran Nicks found an institution to manage the new project that was both less cantankerous and less overcommitted than JPL and the rival Goddard Space Flight Center. This was the venerable (1917) Langley Research

Center, called Langley Memorial Aeronautical Laboratory when it was NACA's headquarters.[2] Nicks then began to harvest information from the report prepared by Scherer and the busy Eugene Shoemaker, then working at NASA Headquarters. Bellcomm submitted another report. Langley prepared its own study and concurred with the others that an Agena-class lunar orbiter could spot a landed Surveyor and otherwise fulfill Apollo's requirements. Some of the money and technical support for the Agena-class orbiter could be freed by dropping Ranger block 5.[3] At the end of August 1963 NASA approved the project and Langley sent out the request for proposals to private industry.

Lee Scherer became the program manager at NASA Headquarters, and electrical engineer Clifford Herman Nelson (b. 1914) the project manager at Langley. The two were similar in important ways. Both knew how to keep the project firmly in hand by applying just the right touch at just the right time without making waves. Largely because of these two competent and amiable men, cooperation between the program office at NASA Headquarters and the Lunar Orbiter Project Office (LOPO) at Langley started smoothly and remained better than for Surveyor or any other lunar spaceflight project. The assistant project manager (before his reassignment to the Viking Mars project in 1967) was another competent hand, James S. Martin. My own observations verified the quality and round-the-clock dedication to the project of the people lower on the LOPO totem pole. One detriment to public awareness of the project was its bland name. Oran Nicks knew that calling it Lunar Orbiter was like calling your favorite pet "Pet," but Newell's deputy, Edgar Cortright, overrode his objections and stuck with the working name Langley used.[4]

Determining the Moon's figure and gravitational field was an objective secondary to photography. Physicist-astronomer Gordon MacDonald of UCLA, a pioneer in lunar studies who was serving on the Planetology Subcommittee of the OSS Space Science Steering Committee in 1963, suggested that tracking orbiters at low altitudes would reveal details about the Moon's gravity field not accessible to astronomical techniques, and his suggestion was accepted.[5]

I agree with those who believe that another happy element in the history of Lunar Orbiter was the company whose proposal was accepted, The Boeing Company of Seattle.[6] Boeing had no experience in space but had built Bomarc missiles, had geared up to create the conceptual forerunner of the space shuttle called Dyna-Soar, and had acquired experience in writing NASA proposals while proposing to build the lunar module (which went to Grumman). The company had a productive research organization, the Boeing Scientific Research Laboratories, which included a Geo-Astrophysics Laboratory that hosted the infrared work of Saari and Shorthill and hired old pros Ralph Baldwin and Zdeněk Kopal as consultants at one time or another. In December 1963 the Department of Defense canceled Dyna-Soar and NASA announced Boeing as the Lunar Orbiter prime contractor, despite a relatively high cost estimate. A Boeing team of 1,700–1,800 people built around veterans of Bomarc and Dyna-Soar and efficiently concentrated in one building worked on Lunar Orbiter at its peak. LOPO personnel give maximum credit to Boeing's project manager, Bomarc veteran Robert J. Helberg, an outstanding manager who meshed perfectly with Cliff Nelson.[7] Other LOPO and Boeing counterpart personnel also worked far more smoothly together than did, say, JPL and Hughes personnel in the early years of Surveyor.[8] Profit was not Boeing's motive — Tom Young used to say they "rounded off" what they made on Lunar Orbiter — they wanted to prove themselves worthy of space work. They did.

Eastman Kodak would be the subcontractor for the two-lens photosystem (80-mm and 610-mm), a predecessor of which had already been used for military surveillance on Earth-orbiting Agenas. These lenses would obtain detailed, high-resolution photos of small areas (*H frames*) nested within eight-times-less-detailed medium- or moderate-resolution photos of larger areas (*M frames*). The H frames could reveal details at the scale of a landed lunar module while the M frames would show the regional setting of the H frames. Each mission could shoot 211 frames of each type, though more were coaxed from some missions.[9]

Lunar Orbiter was the first lunar "new start" since the decision to land men on the Moon and was taken very seriously by NASA, Boeing, and geologists, if not by the public. Creative ways were found to reduce costs and accelerate testing and technical-fix schedules without compromising success. The 386-kg spacecraft was in its final configuration by April 1965. NASA's previous and subsequent obsession with subsystem redundancy was largely set aside; after all, the mission as conceived before 1966 required only two or three successful flights to find and "certify" smooth landing sites for Apollo. Some problems showed up early: in the shutter of the 610-mm lens, in a sensor that measured the ratio of velocity to height (altitude) in order to eliminate image smearing (*V/H sensor*), and in a thermal door designed to keep the cold of space from causing internal condensation that would fog the lenses. The photosystem was the pacing item both in cost and scheduling and remained so until the last minute.

EARLY ORBITERS FOR EARLY APOLLOS (1965)

If Ranger and Surveyor had evolved from scientific programs to Apollo support, the purpose of Lunar Orbiter was never in doubt: pathfinding for the first one or two manned landings. What happened after that goal was achieved held no interest for a large fraction of the "manned" people in NASA Headquarters and the Apollo field centers (MSC, Kennedy, and Marshall). Orbiter was also to support

Surveyor in the way the original Surveyor orbiter and lander had been planned to work together; but this was Apollo support, too, for Surveyor had also been pressed into serving Apollo. As it happened, the first Surveyor landing took place on 2 June 1966, in the midst of the final preparations for the first Lunar Orbiter launch. Surveyor had to land "blind" and did so successfully. No one was willing to take a similar chance with Apollo.

Although geologists think of photography as a scientific tool, engineers thought of it as a tool for learning the critical engineering properties of the lunar surface. The pictures would show crater density, slope distribution, other roughness elements, and such clues to bearing strength as boulders resting on the surface. Photographs could reveal elevations east of each site that might give spurious signals to the radar of an approaching Apollo lunar module, or hills west of a site that might block the LM's departure. The tentative latitude and longitude of potential landing sites were also fixed by the requirements of Apollo. Scientists preferred near-polar orbits so that most of the Moon's surface could be photographed, but Lunar Orbiter's orbits would have to be near equatorial to remain a maximum time over the equatorial Apollo zone.

The unmanned and manned factions debated how to distribute targets within this 300-by-2,700-km strip. Coverage in one block, plan A-1, was originally specified as Lunar Orbiter's design requirement. The Surveyor program wanted the Orbiters to photograph large blocks of contiguous coverage because Surveyor's landing accuracy was uncertain. Each Orbiter could shoot three or four such blocks. The Apollo managers, however, wanted smaller target blocks distributed throughout the Apollo zone to provide backup sites in the event of launch delays, a mission design plan that LOPO and Boeing called A-4.

The outcome might be predictable from Apollo's clout. Plan A-4 met resistance, however, when Boeing pointed out that plan A-1 was specified in their contract and that Lunar Orbiter was designed to achieve it. LOPO mission design manager Norman Leroy Crabill (b. 1926) had hired a former Wallops Island sounding-rocket engineer from the Eastern Shore of Virginia with a peculiar accent and the seldom-revealed full name of Almer Thomas Young (b. 1938).[10] As an introduction to the new job, Norm had given Tom an immense stack of reading material and thought, "Well, I'll see this kid again in six months." Tom returned three days later, having fully committed the stack to his photographic memory, and asked for the next assignment. Norm sent him to Boeing, where two weeks sufficed for Tom to show that plan A-4 would be 57% reliable versus 59% for A-1. The upshot was that the first three Lunar Orbiters photographed 9–13 rectangular blocks spaced regularly along the Apollo zone.

As was true for Surveyor, the search for specific sites was the job of the USGS. Shoemaker did not follow up his early interest in Lunar Orbiter because he was fully occupied with Ranger and Surveyor. He therefore asked Jack McCauley to ease out of the Surveyor rover study and head the USGS Orbiter project. This suited Jack's interest in regional geology just fine. The terrain study project led by Jack had already located the potential Surveyor landing sites and was the natural home for the Orbiter effort. Its Apollo support role meant that Lunar Orbiter would have no formal experiment teams or principal investigator as was the practice for Ranger, Surveyor, Apollo, and all subsequent planetary missions (thereby alleviating the sometimes disruptive factor of ego). Among the new geologists Jack hired when the terrain project received an infusion of money in 1964 was Larry Rowan, whose Virginia origins qualified him in McCauley's view to play a key role in a project that would deal with Langley and the many Virginians and other southerners who staffed LOPO.

In May 1965, concurrent with the search for Surveyor sites, Larry's group began to identify potential Lunar Orbiter sites on the basis of geologic interpretations and terrain studies. The site-selection effort continued during the Falmouth conference, and in August 1965 the planners presented a list of 10 sites for the first Lunar Orbiter mission, still called mission A.[11] The job of the scientists and terrain analysts was to pinpoint favorable landing spots within the Apollo constraints. Each mission A site was assigned to an astrogeologist and described in a form of Astrogeology "gray" literature more precisely referred to as "green horrors" because of the color of their covers and the need to churn out one after the other against deadlines.[12] Chapters 4 and 8 show how telescopic observations and geologic interpretations led to the prediction that the smoothest spots in the maria are the darkest. Just in case this was wrong, the terrae and a few other terrain types were included in the mission A sites; some "science" could also be worked in this way.[13]

Rowan formally presented the mission A plan to the SOUC on 29 September 1965, five weeks after the overlapping Surveyor list was presented to the committee. Nine prime (P) Apollo sites were to be shot, including three and a half not in the smooth maria. Although there was nothing they could do about it, the Planetology Subcommittee was disturbed that "no scientific missions were planned."[14]

Let us focus for a moment on the third site from the eastern end of the Apollo zone and introduce a hardworking, gentlemanly newcomer hired in October 1965 by Jack McCauley for the photoclinometry-terrain project, geomorphologist Maurice Jean Grolier (b. 1918). Maurice (who yields to the many Americans who pronounce his name Morris) had emigrated from France in 1936, returned home at the outbreak of the Second World War to take some shots at the Boches, survived wartime captures and escapes, and returned to the United States after the war. By the luck of the draw, A-3 was assigned for analysis to the careful, scholarly Grolier, who thoroughly and objectively analyzed and described it in his green horror.[15] Although Maurice refrained from praising its virtues, large tracts of A-3 passed the tests of freedom from rays and visible obstacles. It would become famous under a different name on 20 July 1969.

THREE OUT OF THREE (AUGUST 1966 – FEBRUARY 1967)

Less than a year after the mission A sites were chosen, at 1926 GMT (1526 EDT) on 10 August 1966, after a one-month delay caused by the Surveyor 1 launch and the late delivery of the photosystem, mission A became Lunar Orbiter 1 as its Atlas-Agena lifted off from Cape Kennedy. Some of the many brilliant flight-operations maneuvers that would greatly benefit the program got the spacecraft out of trouble en route. On 14 August, at 1523 GMT (morning at JPL), the Deep Space Net began to transmit commands for insertion into lunar orbit. This was an era of ghetto riots in Los Angeles and other American cities, and somebody in the bullpen support room in JPL's Space Flight Operations Facility yelled "Burn, baby, burn." When lunar orbit was confirmed, the previously impassive Lee Scherer finally broke into a grin.

An overheating problem showed up but was overcome. New and worse trouble, however, showed up when the first photos were read out on 18 August. Two prelaunch problems reappeared when the H frames were hopelessly smeared because the V/H sensor and the shutter of the 610-mm lens were out of synch. The original mission plan called for the spacecraft to descend from its initial orbit with a 189-km perilune to one with a 58-km perilune to photograph fine-scale hazards at the Apollo sites. This plan was obviously futile now. That being the case, any reasonable scientist would recommend keeping the spacecraft in its high orbit and photographing large swatches of the Moon at 20- or 30-m resolution. USGS mission advisers Jack McCauley and Larry Rowan so suggested. They showed that this first Lunar Orbiter could achieve the entire task of eliminating unfavorable terrain in the Apollo zone if it stayed where it was. Douglas Lloyd and the other Bellcomm mission advisers who were present agreed and performed the necessary supporting calculations. In the early evening of 20 August, McCauley, Rowan, and Bellcomm presented the plan to the Langley project people, who also saw its wisdom, and Lee Scherer shook hands on the deal. At about 9:00 or 9:30 P.M. Jack and Larry went out to eat and otherwise celebrate what they considered a major contribution to spaceflight sanity. They returned to SFOF about 10:30 or 11:00 the next morning, expecting to have little to do because the high-altitude mission would require little intervention from the ground. They found the spacecraft in the orbit with a 58-km perilune. Only 38 frames had been exposed in the higher orbit. Cliff Nelson had vetoed the change with the concurrence of Helberg and other Boeing managers. They hoped that the higher velocities of scenes passing under the V/H sensor at the lower altitudes would jar it into activity so that Lunar Orbiter 1 could fulfill its original mission plan. The ploy did not work, however, and all but about a dozen of the 205 H frames were useless. A few high-altitude near-side frames show what could have been: a Lunar Orbiter 4–type mission along the equator. Jack never again showed much interest in spaceflight mission support until he switched planets and became geology team leader for the Mariner 9 Mars orbiter in 1971.

The mission was not a complete loss; in fact, LOPO, Boeing, and Lee Scherer considered it a success. The early M frames and even some of the later ones of the near side proved useful.[16] More important, several excellent M frames of the east limb and far side, some with nested H frames, were welcomed by the geologists and still provide the only coverage of these areas. Despite Boeing's worries about an added-on procedure,[17] Lunar Orbiter 1 also acquired the first images of the whole Earth, with novel and ghostly oblique views of the Moon in the foreground.

Complete readout of all frames began on 30 August, and a so-called extended mission to check orbital behavior, micrometeoroid flux, and systems conditions began on 16 September. On 29 October, after 577 revolutions, the spacecraft was crashed, on the far side, because its attitude-control gas and battery were depleted and it had to be cleared out of the way of the next mission.

The news media showed some interest, quoting Larry Rowan liberally and reporting that "30 analysts from half a dozen federal agencies were examining 200 miles of film" (maybe they meant meters) and finding some rocks.[18] They were referring to the massive screening effort that was under way between 25 August and 4 November 1966 at Langley. Geologists, terrain analysts, and technicians from MSC (the largest staff), the USGS, LOPO, and the two military cartographic agencies (ACIC and AMS) were confronting the wholly new type of data.[19] Representatives from Bellcomm and the Surveyor project made sure the interests of OMSF and Surveyor were considered. The analysts were drawing ellipses in smooth-looking places for more detailed study back home and found 23 of them. The USGS drew terrain maps resembling those that they had drawn from telescopic data in Flagstaff, and the other agencies outlined terrain units according to their concepts. MSC evaluated the ellipses according to an *N number.* An ellipse earned low (bad) N numbers if it had too many fields of large blocks, sharp-appearing craters, or slopes greater than 7°. The N numbers got better with increasing Sun elevation, so Hal Masursky facetiously suggested that Apollo land at full moon.

Because of the fast-paced flight schedule in this generally fast-paced year of 1966, planning for the second Lunar Orbiter had begun before the first was launched. The "mission B" set of sites therefore had to be based on telescopic and Ranger data, as were those for mission A. Thirteen prime Apollo sites, some overlapping with the Orbiter 1 sites and some new, would be strung 9°–13° apart along the northern strip of the Apollo zone.

A respectable total of 17 "supplementary" or "secondary" sites (*S sites,* that is, nonprime) having "only" scientific or pictorial interest were incorporated into the mission plan, including some with multiple exposures. The Apollo people could not complain about these S sites because Orbiter's film had to be moved along every eight hours to avoid being deformed by one of the bends in the winding mechanism or sticking to the Polaroid-like Bimat strip by which the film was developed in the spacecraft.[20] Hence many of these film-set S frames had to be shot where Apollo had not called for them, including on the far side. Some even came out of Apollo's prime frame budget. Not that all this happened unaided. The two-birds-with-one-stone concept of the film sets was another outstanding achievement by Tom Young and Ellis Levin of Boeing. Boeing originally maintained that the film-set moves had to be made with the thermal door shut. A large proportion of scientific and engineering ideas originates in restaurants and bars rather than in the office or laboratory. Young and Levin came up with this one in a Chinese restaurant called the Golden Door, and LOPO knows the film-set photography as the Golden Door solution. It saved about 230 photographic M or H frames from the first three Lunar Orbiters for science, and starting with the second Orbiter became an important part of the plan.

Lunar Orbiter 2 was launched on 6 November 1966. When photography began on 18 November, telemetry showed that the V/H sensor and everything else were working. Two days later the Ranger 8 impact point was shot, and on the next orbital pass so was an extension of the adjacent site A-3. This and another Orbiter 2 smooth site farther east in Mare Tranquillitatis, near the crater Maskelyne DA, remained in the forefront as possible Apollo landing sites. The rest of the sites revealed more craters, and a site in the light-colored Cayley terra plains and one with crossed bright rays of Copernicus and Kepler were loaded with them; the bias toward dark spots in the maria was looking pretty wise. A film-set exposure was required in an orbital pass at about 20° west longitude. Doug Lloyd of Bellcomm got the idea of taking a north-looking oblique shot of Copernicus. The result was the famous "Picture of the Century" that appeared on front pages around the world and excited even the general public. The photographic mission ended 26 November, and the readout concluded on 6 December. Problems developed in the readout on that day, but less than 3% of the frames were lost. Data from a secondary experiment of the Lunar Orbiter program were also obtained in the form of three meteoroid hits, probably from the Leonid shower that the Earth, Moon, and spacecraft were passing through. (The five Lunar Orbiters suffered 11 micrometeoroid penetrations, an incidence that seemed too low to bother the Apollo astronauts.)

The site screeners descended on Langley again. With 26 participants, the USGS contingent, led by Larry Rowan, now outnumbered those from MSC. The 26 included me, making my first appearance at a screening effort. In the 1960s few people involved in the lunar program gave much thought to such things as holidays or overtime, and we worked pretty much straight through the period between 5 December 1966 and 3 February 1967, although I managed a couple of nights in beautiful, serene Christmastime Williamsburg. This time we had far better photos on which to draw terrain maps. Geologic maps could also be drawn now, although none were completed for the obviously very rough Cayley and crossed-ray sites.[21] I performed my usual duty of setting up a scheme of map units and mapping conventions for the geologic work. Dick Eggleton devised a method of estimating the thickness of a regolith above the bedrock layer on the basis of crater profiles,[22] based on observations by Henry Moore and Jack McCauley of missile craters at White Sands and from experiments by Don Gault, Bill Quaide, and Verne Oberbeck with Gault's crater-making gas gun. Quaide and Oberbeck followed through on this idea, and the method is now associated with them.[23] The communal Brain of science was at work again. Sometimes the brains of individual scientists work less felicitously. A USGS astrogeologist who should have known better (and who is not named anywhere in this book) interpreted the long shadows cast by boulders under low Sun illumination as shadows of spires, and this blunder was picked up by the sensationalist press and various nuts as evidence of missiles emplaced on the Moon.[24] A UCLA astronomy student pestered me for an entire year afterward in an effort to get me to admit that we were covering up a military secret.

Apollo was almost satisfied by Lunar Orbiter 2's haul of 184 frames of the 13 prime sites, and the third Orbiter could concentrate on confirming the properties of promising sites rather than search for new ones. The mission was more sophisticated than its two predecessors despite the identical hardware and similar orbits. Apollo had requested targets on both sides of the equator because at the western end of the Apollo zone, Apollo summer launches were more favorable to northern sites, and winter launches to southern. The Orbiter 1 prime sites were on or south of the equator, and those of Orbiter 2 were on or north of it. Lunar Orbiter 3 would clean up sites on both sides by an orbit inclined 21° rather than the earlier 12°.[25] Orbiter 2 had successfully tested the possibility of stereoscopic coverage, so Orbiter 3 would do much more of it. The Surveyor 1 site, for example, was to be saturated with 32 exposures (64 frames) in three overlapping blocks taken on successive orbits.[26]

Speaking of saturation, consider Sinus Medii. The ever-pessimistic Apollo operations engineers at MSC loved Sinus Medii because it could back up sites farther east in case a launch had to be postponed. So Lunar Orbiter 1 fired 16 exposures, Orbiter 2 fired 41 exposures (including a 24-frame barrage in three overlapping strips), Orbiter 3 made 17 more, and 8 more were later wrung by the unsatisfied Apollo program from the "science" mission flown by Orbiter 5. Multiplied by 2 (H frames + M frames), that is a grand total of 164 frames out of the total Lunar Orbiter potential of 2,110—almost 8%. Surveyor 6 landed within this coverage, but no Apollo ever went near it.

Because the Picture of the Century was so spectacular and because there were glimmers of a future life after the early Apollos, science was coming on more strongly in the planning. Lunar Orbiter's options for sequencing photographic frames were going to be varied more extensively. Orbiter was designed to take 1, 4, 8, or 16 exposures in a string. These could be fired either rapidly, so that the H frames overlapped slightly and the M frames overlapped substantially, or with longer delays between exposures, giving wide separations between the H frames but preserving some overlap of the M frames. The *fast rate* concentrated overlapping H frames on spots of interest and was routine for the Apollo prime sites. The *slow rate* was better for areal coverage and M-frame stereoscopy and so was thought better for geoscience. A site's suitability for landing might depend on which mode had been used. I, for one, became deeply involved in the business of justifying acquisition of S-site photos. The process was aided enormously by the competence and cooperation of Norm Crabill and Tom Young, chief and member, respectively, of a subdivision of LOPO called Mission Integration. This meant that they meshed the recommendations for sites with the capabilities of the spacecraft and the mission. Tom in particular could remember all the facts about everything and had them at the tip of his tongue. When Tom and Norm sat down with us scientists in the cramped trailers that were LOPO's offices, the information and ideas flowed freely and effortlessly in both directions.

All conceivable types of photographic "footprints," including obliques of the main Apollo P sites, became S sites. There were potential Surveyor sites, including some in the highlands like the broad floors of the craters Hipparchus and Flammarion (3° S, 4° W; 5° S, 5° E, respectively). Officially, other highland sites were photographed to calibrate their roughness relative to the maria, though actually we wanted to look at something more interesting than the maria. West-looking obliques previewed the views the astronauts would have while approaching their landing sites.[27] Side-looking obliques north and south of the orbital track provided scenic views for the astronaut, scientist, and popular news media (Theophilus, Hyginus Rille, and Kepler). We still wanted to view more craters, young and old, large and small, impact and volcanic. One oblique shot was devoted to figuring out (unsuccessfully) what geologic unit Luna 9 had landed on. Tom Young wrote up justifications for each S site with such phrases as "to shed light on" or "will provide data of scientific interest." Some S-site photographs were shot at a feature that happened to lie where a film-set exposure was required. Others were selected with a future use firmly in view. We phoned Dick Eggleton in December 1966 to get a target point within his favorite geologic unit. So it was that the crucial Apollo 14 landing on the Fra Mauro Formation was made possible not by one of MSC's beloved P sites or one of the scientists' beloved Orbiter 5 sites, but by an Orbiter 3 "supplementary" site. SOUC approved the mission plan on 5 January 1967.

Spacecraft 6 became Lunar Orbiter 3 at 0117 GMT on 5 February 1967.[28] The craft was injected into its initial orbit on 8 February, and four days later was lowered into its site-seeking photographic orbit of 40–54 by 1,850 km. Orbiter 2 was still transmitting its position and micrometeoroid data, and both spacecraft were tracked for a while. Orbiter 3's photographic mission began 15 February with the long burst of exposures that had to begin all Orbiter missions to unwind the leaders of the film and the Bimat from their spools, and the resulting 16 frames extended the coverage of the smooth-surfaced prime Apollo site in eastern Tranquillitatis. In the effort to reshoot fuzzily photographed Orbiter 1 sites, Orbiter 3 covered one we encountered in chapter 8 as the landing site of Surveyor 3 and will encounter again in chapter 12.[29] The rest of the photographic mission proceeded, but telemetry indicated some trouble in the readout mechanism. Thus the mission was cut off one site short and the final readout was begun earlier than planned — another intelligent move, for there was indeed trouble. The film-advance motor burned out on 4 March. But the shrewd handling of the readout resulted in 71% of the frames being recorded.

The screeners attacked again. Newell Trask replaced Larry Rowan as the overseer of the USGS part of the screening report and escalated the investigation he began with the Ranger data of the engineering properties of the regolith that can be inferred from crater sizes and morphologies.[30] A lower Sun angle than that used on the two preceding Lunar Orbiters added sharpness to the Orbiter 3 frames.

During the screening, on 15 March 1967, Bellcomm hired a geologist who made a major mark on all subsequent choices of Lunar Orbiter and Apollo photographic targets and Apollo landing sites. The supervisor of Bellcomm's Lunar Exploration Department, Welsh nuclear physicist Dennis James, told me that he had just hired an Egyptian but that "he probably won't work out." Farouk El-Baz (b. 1938) had left Egypt in 1960 to study ore deposits at the Missouri School of Mines and Metallurgy, with the view of establishing a mining and geology institute in Egypt. After a year at MIT, more time at Missouri (Ph.D. 1964, dissertation on the Missouri lead belt), and a stint at the University of Heidelberg, he tried to teach geology in Nasser's Egypt but was told to teach organic chemistry, a subject about which he knew little. On his 125th try for a job back in the United States, he responded to Bellcomm's ad in *Physics Today* and got into an instant argument with James (a schoolmate of Tommy Gold) about the Egypt-Israel conflict that was then coming to a head. Nevertheless, he was hired by James and Richard Nixon's geologist brother, Bellcomm personnel man Ed Nixon. Two weeks later Farouk was sitting with us at Langley and asked me if anyone had classified the features of the Moon. I smelled special featurism and brushed off the question. Farouk proceeded to go back to Bellcomm's offices in Washington, organize their chaotic Lunar Orbiter photo collection, and classify all the features that appeared in the photos.

The first three orbiters fulfilled the program's initial objectives. Thirty-two prime Apollo sites, clustered in 11 groups along the Apollo zone, were exhaustively photographed. These 11 groups together with 9 less intensively photographed equatorial spots constituted a "set A" of 20 sites that were to be considered for landings. With OMSF and MSC temporarily satiated, Lunar Orbiter could look farther afield.

A PRECIOUS BONUS (LUNAR ORBITER 4, MAY 1967)

The unexpected success of the first three Lunar Orbiter flights released the last two for different types of missions. To obtain the coveted global coverage, Lunar Orbiter 4's orbit was to be inclined 85° to the equator and to have perilunes 50 times higher than the previous three missions. The Falmouth conference, Ralph Baldwin, Don Wise, and Norm Crabill all proposed this mission plan, and the rest of us certainly were in favor of it. SOUC approved the plan on 3 May 1967. Eighty percent of the near side could be covered at 50–150 m resolution from near perilune, and as much of the far side as could be worked in would be shot at lower resolutions from near apolune.[31]

Our present understanding of the Moon's geology would have been impossible without Lunar Orbiter 4, whose global coverage has yet to be repeated or excelled. Geologists and chart makers would no longer need to peer through telescopic eyepieces hoping for the atmosphere to settle down or try to discern the reality concealed by fuzzy telescopic photos. The new era began with the launch on the evening of 4 May 1967, less than 24 hours after Surveyor 3 was shut down for what proved to be its final lunar night of wakefulness. I reckoned I could pack up a set of Orbiter 4 photos and conduct the rest of my career from a café in Paris. All went well with this plan at first. The initial south-to-north photographic pass, on 11 May, yielded good images of Maria Australe and Smythii on the east limb, territory that had been only glimpsed with the telescope at times of favorable libration. I was among the mission advisers in the SFOF when a voice from the flight controllers' room came loud and clear, "Thermal door closed." The door was supposed to be open during photography and closed between shots. I was watching G. Calvin Broome, chief of the photosubsystem section of the Langley LOPO, who was watching LOPO's telemetry teleprinter in our room. Cal exclaimed, "No!" and drew his finger across his throat. Prospects for the Parisian café and for lunar geology suddenly faded.

Needless to say, all the Boeing and LOPO engineers and USGS mission advisers followed the ensuing drama with considerable interest (I did so indirectly; I came down with the flu and was replaced in the SFOF by Mike Carr). Commands from the ground might close the thermal door, but could it be opened again? You didn't want to fly one of your two remaining Lunar Orbiters with the lens cap on. On the other hand, a door left open might allow the lens to fog or direct sunlight to leak in and degrade the film. Skillful maneuvering and partial closing and opening of the door stopped the light leakage, but the lenses were still fogging. There was a puzzle here; some frames were better than others. USGS mission adviser Howard Pohn came to the rescue with the answer.[32] Howie simultaneously watched the television monitors and the telemetry printouts and realized that the fogging appeared only when the temperature of the lenses fell below a certain level. The temperature depended on the orientation of the spacecraft. To visualize the orientation Boeing made a model of the spacecraft, complete with a movable thermal door, out of a plastic coffee cup and a couple of pencils (contrasting amusingly with the gleaming multi-thousand-dollar machined metal replica of Surveyor built by JPL for a similar purpose and set up in another room of the SFOF). The solution emerged: orient the spacecraft to warm the lens, then quickly reorient it to take each picture. This was done after orbit 14, and good images were obtained west of about 45° east longitude. Howie calculated that at about $100,000 per frame, he saved the taxpayers some $10 million. Cliff Nelson thanked him in writing, but Branch Chief Hal Masursky squelched his outstanding performance rating because (he said) Howie talked too much. The lunar scientific community owes LOPO, Boeing, and Howie Pohn a debt, although I had to give up Paris and settle for examining the pictures in my bullpen office at Menlo Park.

Fogging was not the only problem of this Perils of Pauline mission. On the thirty-fifth revolution, on 25 May, difficulties that had been noticed in the readout drive got worse. The Orbiter had got as far as 100° W, 10° onto the far side, and had recovered images as far as 75° W; 163 frames had been processed. The fogged area between 45° and 90° E had been successfully rephotographed, though one frame got lightstruck because of the maneuvering.[33] Nelson called a council of war and asked what should be done if the mission had to be cut short with the irrevocable command to cut the Bimat developer strip. Should certain areas of special interest be read out, or should the attempt be made to proceed as far as possible with the planned contiguous coverage? Most advisers were in favor of photographing their pet spots, but Nelson favored the contiguous coverage. There might be something interesting on the west limb. Something interesting! Only the Orientale basin, the sharply concentric-ringed basin that justifiably was Jack McCauley's favorite feature on the whole Moon. McCauley, contacted in Flagstaff by telephone in the middle of the night, agreed with Nelson and pleaded for continuation of the mission. LOPO and Boeing found ways to do it, and the most important harvest of information gathered by any Orbiter mission was the result; more about why later.

There was no screening report. As Tom Young put it, "The screening report will be the geologic study of the Moon."

THE "SCIENCE MISSION" (LUNAR ORBITER 5, AUGUST 1967)

Incredible; four out of four, if one counted Orbiter 1 a success. So the fifth spacecraft, which originally had been dedicated to certifying early Apollo sites, could be turned over to science. It would be used to find landing sites that were sufficiently safe and interesting to be visited by the manned missions that would follow the first cautious steps.

Here was food for scientists. Since August 1965, just after the Falmouth conference, these late missions had been called the Apollo Applications Program (AAP).[34] The later AAP landings would be released from the equatorial belt but were still confined to a zone that bulged north and south in the east. The edges of the zone were approachable in some months but not others. The corners of the near side were considered in some planning but were ultimately excluded. Far-side landings were impossible without a repeater satellite, which NASA never seriously considered. In the mid-1960s, however, there was a program variously called post-Apollo or post-AAP in which anything was possible.

Larry Rowan had ably led the earlier site-selection efforts but was wrung dry and pushed aside by the time of Orbiter 5. Masursky had replaced Larry with himself and me, probably the USGS astrogeologist most familiar with the Moon's geology at this point. Ewen Whitaker, who could instantly pull from his briefcase a beautifully illuminated telescopic photo of any part of the Moon, represented Kuiper's Lunar and Planetary Laboratory. Geologist Don Beattie represented OMSF at NASA Headquarters. Robert Bryson, the former USGS geologist who now monitored our contracts from NASA Headquarters and distributed our money, also contributed targeting suggestions. Geologist John Dietrich brought the word from MSC. Farouk El-Baz became the organizing force of the site work. By 1967 he had completely mastered the English language, including a better handwriting than most of us, so he was an ideal secretary for the site meetings, keeping track of what was said and contributing his own rapidly expanding lunar insights. Our knowledge of the whole Moon was called into action because of the need for film-set exposures. If interesting fresh features or Apollo sites did not lie directly under the spacecraft's path, it could roll to the right or the left and cover them with oblique views. We had learned, however, that distant obliques were not very valuable, and asked for only two of them (Altai Scarp and Alpine Valley) in addition to the forward (west-facing) obliques for previewing the appearance of the Moon for an astronaut coming in for a landing.

We asked for new pictures of the plains-covered floor of Hipparchus because of its potential as a landing site for both Surveyor and early Apollo, but otherwise wished to employ Orbiter 5's high resolution on objects with fine detail such as small rayed craters or sharp-edged blocks. Maybe I should say "I" instead of "we." I made the search for detail my special crusade, arguing against targets that Orbiter 4 showed were likely to possess only the smooth, rolling, bland topography that characterizes most of the Moon's surface. Since we were picking sites for AAP, there should be blocks or outcrops for an astronaut to sample.[35] Deep, fresh craters whose impact origins were already established served as "drill holes" that scattered samples from the depths onto the surface (Petavius B, Stevinus, Censorinus, Dawes, Tycho, Copernicus, and Aristarchus). Photos of such craters might also "shed light on" impact and hybridizing processes. Deep samples might also be obtained from blocky crater central peaks (the larger, the deeper), certain volcanic craters, or bright, fresh-appearing scarps of any origin. The search for sharply defined objects meant a concentration on some kinds of special features; maybe they would reveal some fine-scale detail that would prove their origin. So it happened, for example, that the last 36 shots of the mission (72 frames in all) were devoted to the nest of special features in northwestern Oceanus Procellarum. After an isolated 4-frame sequence covered two "Gruithuisen domes" thought to be composed of terra-type silicic volcanic rocks, came a blanket of 24 overlapping frames that showed (1) the Harbinger Mountains with their dark mantling deposits and large sinuous rilles called Rimae Prinz; (2) the crater Aristarchus, an impact crater but of interest because of its "transient phenomena"; (3) Schröter's Valley and the Cobra Head; and (4) the Aristarchus Plateau (25° N, 45° E). The mission ended with 8 frames targeted at the Marius Hills, though only 6 1/2 could be squeezed out of the film.

Many sites were along mare-terra contacts. Dennis James asked us why, since we had always objected to Apollo's love for mare sites, did we now include so many in "our" mission? One reason was that we sought smooth landing surfaces for AAP next to interesting, topographically sharp features. Also, we wanted each mission to include more than one objective, and the terrae offered few clear distinctions between adjacent features. If you've seen one part of the ancient lunar terrae at high resolution, you've seen them all. This search for distinctness was, of course, also the reason so many special features were included in all lists of photographic targets and landing sites.

The Lunar Orbiter 5 mission was almost flawless. The success was generally ascribed to Lee Scherer's garish plaid sport jacket, which he had worn to every Lunar Orbiter mission since the launch of Orbiter 1 and was not about to abandon now. After a launch on 1 August 1967, Orbiter 5 was inserted into an orbit inclined at 85° like that of Orbiter 4 but lower, about 200 by 6,050 km at first. The spacecraft's perilune was then lowered to 100 km and it shot oblique views of the western part of the Orientale basin on the far side. Finally, apolune was lowered to 1,500 km and the rest of the photographic mission proceeded from this 100-by-1,500-km orbit, twice as high at perilune as Orbiters 1–3 in order to increase the areal coverage of each site. Science was not quite ready to take over the entire mission. Early Apollo still required 20% of the exposures to supplement the Orbiter 1–3 coverage, including eight more of Sinus Medii and eight near-vertical and two oblique shots of Maurice Grolier's site A-3. But "we" got the other 80%. In addition to 31 potential AAP sites scattered across the near side, gaps in the far-side coverage obtained by the first four Orbiters could be filled, unfortunately mostly by oblique views.

An active year in space concluded when the last Orbiter 5 frame was read out on 16 August 1967 and the spacecraft, like its predecessors, was deliberately crashed on 31 January 1968 to clear the deep-space airways for future flights. At a party at Pasadena's classic Huntington Hotel, Scherer's jacket was torn into shreds that were distributed to project members.[36] The screening effort was dominated by science in general and USGS Astrogeology in particular, and it incorporated up-to-date interpretations of all the lunar features thought important at the time; too bad it was buried in the gray literature.[37] The rest of this book has much to say about the use to which the Orbiter 5 sites were put: lots of science, two landings (Apollos 15 and 17), and a dozen serious contenders for late Apollo or AAP missions.

Orbiter 4 had brought home the meat and potatoes, and Orbiter 5 added the sauce and spice. The background views from Orbiter 4 and the zoom frames of Orbiter 5 were the tie between telescopic and astronautic study of the Moon.

CHECKING THE DARK SPOTS

Orbiter photographs were quickly put to use in mission planning. The intense screening efforts after Orbiters 1, 2, and 3 identified targets for Apollo, Surveyor, and the next Lunar Orbiter mission. As always, the regional views — the M frames — were examined first to identify terrain units or geologic units. The units were then characterized from representative spots on the corresponding H frames in terms of crater densities, slope-frequency distributions, blockiness, and so forth. Morphologic features were compared with those at the landing site of Surveyor 1, whose success two months before the Orbiter 1 mission had allayed fears about unsuitable surface properties.

Eight or nine near-equatorial mare areas that looked good enough for further consideration by geologists and NASA had emerged by March 1967 from the postmission screening of the Orbiter photos as prime candidates for early Apollo landings. Two sites of this "set B" were in Mare Tranquillitatis, one was in Sinus Medii, and the other five were in Oceanus Procellarum. The ninth site, in Mare Fecunditatis, was also granted membership in set B in March 1967 but hung on tenuously after that. Parts of all these sites had satisfactory N numbers. Point landings were still thought impossible, so each nominal landing point was surrounded by three concentric ellipses indicating three degrees of landing probability; the largest (most certain) ellipse measured 5.3 by 7.9 km. The USGS and outside collaborators prepared nested geologic maps at scales of 1:25,000 and 1:100,000 for each of the eight.[38] Large, shallow craters were not a problem. In fact, the eastern sites had high densities of such craters. Sites that were flatter, but rougher in detail, lay in the west. Here we have the distinction between so-called eastern and western maria that later played an important role in site selection.

So the Apollo project got its dark spots and "we" got two Lunar Orbiters for science. Then, as was increasingly the case, NASA got cautious. A sixth spacecraft existed that could have been flown for a measly $13 million.[39] Lunar Orbiter 6 could have obtained, for example, complete coverage of the far side at least as good as Orbiter 4's of the near side. Naturally, all geoscientists would like to have this coverage; we still do not have it. However, Lee Scherer in particular and NASA Headquarters in general felt that Orbiter had more than achieved its purpose, and anyway, their "plates were too full."[40] An assured record of five out of five was better than a possible five out of six.

THE BIG PICTURE

All scientists who dealt with NASA during the lunar exploration era were torn between criticism of the space agency's shortsightedness and praise of its successes (the criticism far outweighs the praise today). The sixth Orbiter that was not flown and many later examples showed what could have been. But much more was achieved than might have been.

Some 1,650 of a maximum 2,110 frames were useful, a good 78%. Lunar Orbiter acquired the only global coverage of the Moon obtained by any nation, covering most of the near side with resolutions better than 150 m and providing almost the only coverage of the far side useful for mapping except for some narrow strips from Apollo and Zond. It missed only a shadowed spot near the south pole and a few small gores elsewhere. In 1972 Czech artist Antonín Rükl published a novel series of views of the Moon drawn from six directions in space. ACIC was able to produce the first small-scale maps (1:5,000,000) of the whole Moon. AMS and ACIC mapped belts 50° and 80° wide centered on the equator at scales of 1:2,500,000 and 1:2,750,000, respectively. Although the LAC series was almost complete, ACIC also added details from Orbiter 4 to some of the last sheets. Both mapping agencies also quickly turned out large-scale photomosaics and airbrush charts for the most likely AAP sites. However, measurements of the third dimension for the production of topographic maps could not be improved much because the stripelike framelets that comprise all Orbiter frames give the appearance of steplike topography when viewed stereoscopically.[41] Typically, engineer-dominated NASA cared less about the Lunar Orbiter photographic atlases than about gathering the data in the first place.[42] The best collections of Orbiter photographs appear in books devoted to their scientific interpretation.[43]

Orbiter quickly cleared up a number of nagging interpretive questions, three of which concerned craters. Chapter 5 refers to the argument about whether Sabine-Ritter-type craters with high floors and smooth rims are calderas or impact craters whose floors rose like elevators. One such crater, Vitello, at the southern edge of Mare Humorum, is a Saari-Shorthill infrared "hot spot," is fractured, and is blanketed and surrounded by a dark deposit. If there is a caldera on the Moon, this ought to be it. The Orbiter 5 frame devoted to it shows that the cracks contain blocks. So many other block fields seen by Lunar Orbiters coincide with the telescopic hot spots that no doubt remained that blocks are the source of the "heat" — that is, they radiate solar heat relatively quickly. Volcanic heat evidently is not escaping from Vitello, so if it is a caldera, its activity expired long ago.

Circular dark-halo craters were a second type that most observers thought were volcanic, although Mike Carr had suggested the possibility that they were impact craters.[44] An Orbiter 5 frame devoted to the typical dark-halo crater Copernicus H settled the issue to most people's satisfaction: it showed the same ejected blocks and secondary craters typical of all impact craters of its size. Such craters are dark because they excavate dark mare basalts from beneath rays and other bright materials. The only craters still accepted as internal are those relatively rare irregular dark craters that have smooth ejecta, are aligned along rilles (like those in Alphonsus, also rephotographed by Orbiter 5), are centered at the tops of true domes, or are surrounded by evidently related dark blankets. This is not far different from the list of internally generated craters that had been in the minds of such stalwart proponents of impact as Gilbert, Kuiper, and Shoemaker.

The third and most significant revision of crater interpretations resulting from Orbiter photographs concerns chains of craters that are satellitic to primary-impact craters but not radial to them. Such a chain, mentioned in earlier chapters, is Rima Stadius 1. Even cold-mooners like Shaler, Spurr, and Alter had realized that bright raylets radiate from satellitic craters; but the overall ray pattern of Rima Stadius 1 parallels the chain and does not radiate from Copernicus. Off-center rays and secondaries provided major solace to the cold-mooners. Gilbert cited Stadius as a likely example of a chain of maar craters that accompanied the larger population of impact craters. So did Barrell. So did Dietz. So did Baldwin. So did Kuiper. And so did Shoemaker, even though Rima Stadius 1 sits there in the midst of the field of Copernicus secondary craters he did so much to unravel.[45] The maar interpretation was maintained as late as 1966 when Jack Schmitt and Newell Trask completed the geologic map of the Copernicus quadrangle that Shoemaker had begun in 1959.

But Rima Stadius's location so near to Copernicus worried many observers. In his impact phase, Gilbert Fielder interpreted it as a secondary-impact chain of Copernicus.[46] Orbiter targeters hoped that the increased resolution provided by an Orbiter 5 four-frame (slow mode) barrage would settle the issue. It did—and it showed that even the giants of lunar geology are human. The V-shaped patterns of ejecta from each crater in the chain point straight back at Copernicus. Herringbone or bird's-foot patterns of ejecta continue outward as radial raylets. Elegant experiments by Verne Oberbeck and Bob Morrison with the gas gun at Ames later showed that the impact of ejecta of artificial craters interfering at certain spacings and timings reproduces exactly the range of V forms seen on the Moon.[47] Here was learned one of the most significant diagnostic features of impact craters. Not only Rima Stadius but myriad other chains and clusters on the entire Moon, large and small, near and far from their sources, were created by the secondary impact of ejecta from larger craters and basins.

The hot-mooners won some battles outright. The lava flow lobes in Mare Imbrium that had been seen telescopically were beautifully photographed by Lunar Orbiter 5 — not that any sensible person doubted their volcanic origin at this point. The 36-frame barrage in the northwest also came through beautifully and confirmed or added some true volcanic special features. The sinuous rilles officially called Vallis Schröteri, Rimae Prinz, and Rimae Aristarchus are amazing when seen in detail. The pyroclastic dark blankets are there. And no one could doubt any longer that the Marius Hills are what Jack McCauley had said: a hotbed of volcanic activity by lunar standards and one set of special features that really is special.[48] But many other small "cones" and "domes" in the region show no trace of volcanic origin in the detailed pictures and are probably just parts of basin rings. The jury has still not decided whether the cold-mooners or the hot-mooners win the case of the Gruithuisen domes.

Strangely, the improved resolution was not always a blessing. After the final two Lunar Orbiter missions, lunar geologists were busily examining the Moon in great detail. They also assembled rosters of terrestrial analogues of lunar features. As this history has shown for the telescopic era, when detailed examination of the Moon is combined with detailed examination of the Earth, the result is endogenic hypotheses for lunar features. So it was that many "hilly and pitted," "hilly and furrowed," and just plain hilly tracts in the terrae were identified as volcanic. The moral of the story of Apollo 16 (to be told later) is that investigators should have stood back and viewed the big picture — the regional setting of individual features.

I refer to basins, which dominate the Moon's geology. We have traced the history of the discovery that Copernicus-type craters and all basins were created by impacts; that was well known by 1967. What was not known was the dominant role of basins in creating features in the terrae at what Dan Milton called the "middle scale," a few kilometers to tens of kilometers,[49] that is the realm of the crater clusters and chains, light-colored terra plains, undistinctive terra surfaces, and all the special features I have been belittling. The key to the middle scale was Orientale. We all stared with amazement at the scenes coming from the real-time monitor and being built up framelet by framelet on a light table as the first negatives were mosaicked. There were radial ridges, grooves, transverse dunelike forms, plains, and clustered craters in unequaled abundance and variety. I think most of us had temporary notions of volcanic or tectonic origin. But as time wore on, a consistent picture emerged: Masses of material were ejected laterally from the 930-km basin and flowed along the surface, creating streamlines or piling up against obstacles and forming the dunes.[50] Lesser though still considerable masses were thrown through the "air" and created secondary craters when they reimpacted over a vast area. Comparisons with Orientale have revealed similar features around other basins less completely exposed to view.

There is another lesson here about the relationship between the scale of data and their interpretation. The USGS mapped one-third of the Moon — the 44 LAC quadrangles of the near side — at the scale of 1:1,000,000. Because so many diverse landforms are related to basins, however, the detail that happens to be most significant to the lunar big picture is better shown at regional scales of 1:2,500,000 or 1:5,000,000. The lesson was learned, and the whole Moon has been mapped at a scale of 1:5,000,000.[51]

Orbiter data also fueled the debate about lunar compositions. Moldinglike accumulations of material line the bottoms of steep lunar slopes, such as those of the Flamsteed ring surrounding the Surveyor 1 site. John O'Keefe, still looking for silicic material as a source for tektites, compared the ring with ring dikes and saw the moldings as evidence for viscous, silicic volcanic flows that spread out on the mare basalts.[52] However, Max Crittenden, one of the experienced non-Astrogeology geologists rounded up by Masursky in Menlo Park, pointed out excellent terrestrial analogues that formed by down-slope movement of rock without any assistance from volcanism.[53] Spence Titley and Dan Milton showed that the moldings probably consist of debris shaken from the slopes of impact craters by the seismic energy released from nearby impacts.[54] Therefore, nothing exotic is required to explain the apparent paradox of a premare feature (the large circular crater) yielding a postmare deposit (the basal debris).

A key finding came from a nonphotographic experiment. The spacecraft did not follow the perfect orbits they would have followed around a homogeneous Moon. Astronomers knew that either the Moon's shape or its distribution of density or both are irregular. The Orbiters did not settle the question of figure, though their data suggested that the near side was not bulged but a little flattened relative to the Moon's center of mass. Of more immediate interest were the many irregular distributions of density disclosed by the tracking data. The ways the orbits were tugged suggested that concentrations of mass with greater gravitational attraction than the average Moon lie beneath many circular maria. That is, the maria are out of isostatic equilibrium. Paul Muller and Bill Sjogren of JPL discovered these mass concentrations and gave them a name that is firmly established in lunar science: *mascons*.[55] They had to be understood before the trajectories soon to be followed by Apollo spacecraft could be predicted accurately.

The old guard and some upstarts sprang to the interpretive battlefield.[56] Urey had found his raisins in the lunar pudding: he thought the mascons were the iron meteorites that had formed the maria and were prevented from subsiding to isostatic equilibrium because the Moon was cold and stiff. John O'Keefe, discoverer of the pear shape of Earth and fully conversant with the interpretation of gravity, knew that one of Urey's meteorites would sink even if the Moon were cold, and correctly guessed from the mascons that the mare material originated hundreds of kilometers inside the Moon. Admirably, O'Keefe did not try to force the mascons to fit his silicic Moon hypothesis. Six months later, in a paper published one day before Apollo 11 landed, John Gilvarry juggled the numbers to support his notion that the maria consist of water-laid sediments.[57] I would be kinder to Gilvarry if he had not employed such phrases as "From the present treatment, it can be noted again that the argument for the presence of water on the Moon is quantitative [citing four papers by himself], in contrast to the essentially qualitative considerations of the lava hypothesis."

Let Ralph Baldwin have the last word on mascons for the moment. In 1968[58] he put forth a model for their origin, based on observations beginning in the 1940s, close to the one accepted today: Mare Imbrium (i.e., the Imbrium basin) was formed by a giant impact, remained "dry" for a while, began to adjust isostatically, and before it could flatten out completely was filled in its low spots by the mare basalt. The basalts did not flood in all at once but in many flows over a long period of time. Being denser than the rest of the Moon, the mare rocks sank a little, cracking their peripheries (forming arcuate rilles) and compressing their interiors (forming wrinkle ridges). They could not sink completely, hence the mascons. Add the presence of a mantle uplift beneath the mare suggested later by Don Wise, geophysicist Bill Kaula, and others, and you have the current model of lunar and planetary mascons.[59]

After the three Ranger successes, some scientists and engineers had predicted that 30 or 40 more precursor missions would be needed before man could land on the mysterious lunar surface. But the five successful Surveyors and five Lunar Orbiters were followed by no more unmanned precursors.