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Surveyor and the Regolith
1966–1968

HOPEFUL PLANS (1960 – 1965)

The Rangers and early Zonds and Lunas provided only preliminary glimpses of previously unknown terrain. Better views were needed if scientific understanding of the Moon was to be improved and if man was going to land on its mysterious surface. "Better" meant both much broader and much closer; that is, the views that could only be obtained by orbiters and "soft" landers — those that did not destroy themselves while landing.

Which should come first was not clear. In fact, the two types overlapped chronologically in both the Soviet and American programs. They even had the same names in the Soviet program, Luna, and also for a while in the American program, Surveyor. When the Surveyor program was initiated at JPL in May 1960 and approved in July 1960, it included orbiters as well as soft landers.[1] Both kinds of craft would use common hardware to the extent possible and would rely on the same launch vehicle, the kerosene/liquid-oxygen Atlas first stage and liquid-hydrogen liquid-oxygen Centaur second stage. JPL worked on both types of spacecraft for more than two years, but Ranger and one type of Surveyor proved to be all they could handle. Also, the Centaur was plagued with problems. NASA decided in favor of the lander as the surviving Surveyor component. The Surveyor orbiter was pretty well dead by October 1962.

JPL had originally conceived of Surveyor primarily as a scientific exploration tool in its own right and not as Apollo support; May 1960, when Surveyor began, preceded May 1961, when Apollo was given its mission. Seven "engineering" Surveyors would come first to test the flight systems and the lunar soil, followed by 13 "scientific" Surveyors, each a flying Christmas tree hung with 160 kg of instruments, including a camera for taking pictures during descent and two more for taking surface panoramas after landing. There would be seismometers, magnetometers, gravity meters, radiation detectors, X-ray diffractometers and spectrometers, drills, and a soil processor that would receive materials from a sampler. There were even hopes for a microscope based on the ones with which petrologists and petrographers study thin sections of rocks in their laboratories. The roving vehicle discussed in chapter 4 was considered for a while. But when the Centaur seemed unable to lift all this weight, the instruments and the spacecraft "bus" itself were whittled down more and more. The launch date for Surveyor continued to slip, whereas that of Apollo, for the time being, did not. For a long time Surveyor suffered severely from shifting estimates of Centaur's thrust, changing mission objectives, and friction and misunderstandings among JPL, NASA Headquarters, and the spacecraft's designer and builder, the Hughes Aircraft Company.[2] For example, as late as July 1964 and until admonished by Homer Newell, JPL Director William Pickering considered Surveyor a low-key project that could be kept on the back burner.[3]

In January 1963, after much debate among its factions, NASA tentatively decided to cancel the "scientific" Surveyors. The painful decision was confirmed in November 1963, then reconfirmed in June 1965. One final attempt to upgrade the Centaur was made in 1965, but all hope vanished in the fall of that year. The seven engineering Surveyors were modified by dropping the instruments for testing the surface and adding some "scientific" instruments. After 101 modifications or change orders the original 160 kg became 30 and the total weight injected into Earth orbit dropped from 1,140 to 950 kg before climbing again to 1,025 kg for the first four spacecraft.[4] Except for a nonusable approach camera retained on Surveyors 1 and 2,[5] the cameras were reduced to one to take pictures on the surface.[6] The seven modified "engineering" landers constituted the Surveyor program.

The main object of interest to Surveyor was the thin layer of debris covering the lunar surface — what I have been calling surficial material, near-surface fragmental material, or other terms to that effect. The news media reported speculations that the layer was composed of either (1) deep dust, (2) permafrost just beneath the surface, (3) lava frothed in vacuum, (4) melted and mixed earthlike materials, or (5) a primordial rock surface. (Gold and Kuiper were obviously the publicity hounds of the day.) The pre-Surveyor assessment based on the photometric, polarimetric, infrared, radio, and radar properties was almost unanimous: the surface material was very porous. This was why the rugged Bonito flow near Flagstaff was chosen to test the Surveyor cameras. Still, the depth and scale of the porosity were uncertain. Gold lambasted Don Gault for the design of Surveyor, claiming that even the antenna would sink out of sight.[7] A more common guess was that the debris consisted of particles smaller than a millimeter though with a component of larger rocks. Some of these estimates were right, some were wrong, and none of the remotely sensed properties really showed what the surface is like. Oran Nicks thought it was fortunate that the engineering model of the lunar surface on which the Surveyor design was based "was prepared by engineers not emotionally involved in the generation of scientific theories."[8] Nicks also expressed his "warm pride" in Surveyor, an emotion shared by others associated with the project (I was not).

Kuiper had been the principal experimenter of the Ranger television experiment, but for Surveyor it was to be Gene Shoemaker for the entire active life of the project (1963–1968). Gene had long been interested in the surficial material as a record of lunar and Solar System history and recognized Surveyor as the means to decipher it. He devoted more energy to Surveyor than to any other class of mission, including Apollo, and would bring home the goods when five of the craft landed safely.

LANDING SITES (1965)

Surveyor, Lunar Orbiter, and Apollo were intimately intertwined as the time of the first launches approached. Their needs were to be balanced by Bellcomm and the Surveyor/Orbiter Utilization Committee (SOUC), but the first grunt work on the landing sites was performed by USGS and JPL geologists.

Shoemaker had recommended sites to JPL as early as January 1964 and, with Elliot Morris, submitted an upgraded list of 5 sites for Surveyor "mission A" in January 1965. In June 1965, after Ranger 8 and 9 data were in hand and just before the Woods Hole–Falmouth conference, the Surveyor project asked Jack McCauley to apply his terrain studies in preparing a list of the safest sites. Jack enlisted the help of Morris, Larry Rowan, Joe O'Conner, and Henry Holt, and the group quickly turned out a list of 74 sites.[9] The landing sites were within target circles 25, 50, and 100 km in radius because the landing accuracy of Surveyor was uncertain. Some of the circles were concentric, whereas others were eccentric because the different landing accuracies called for different aim points. JPL and Bellcomm submitted lists at the same time, so Morris, Holt, and Alan Filice of JPL collaborated in preparing a consolidated and shorter list. The correct trajectory and lighting constraints were incorporated at a meeting at JPL, and the target circles were reduced to two sizes, 25 and 50 km radius. The final list was readied with amazing speed for presentation by McCauley to the SOUC at that committee's first meeting on 20 August 1965.[10]

The list included 24 mare sites with 50-km radius and 7 "highland" and 13 "science" sites with 25-km radius that later Surveyors might dare to approach. Large craters visible telescopically were avoided to distances of one crater diameter even if their rim-flank material was not visible; experience had taught that the ejecta deposit was there unless mare flooding was seen. Visible peaks and ridges were avoided, though a certain minimum number had to be accepted. Rays were avoided. Dark spots on the maria were preferred because they were believed to be sparsely cratered. No site received an unqualified A rating from both the terrain and scientific standpoints, but all the sites that were eventually visited by Surveyors (except Surveyor 7) and that were trod by the Apollo 11 and 12 astronauts were identified in this early study. The rest was up to the SOUC. They added such considerations as the most favorable launch times and MSC's requirements, and Surveyor was ready to go to the Moon.

SUCCESS AND FAILURE (MAY 1966 – JANUARY 1968)

Seven Surveyors were launched between 30 May 1966 and 7 January 1968.[11] Two failed, but five successfully returned the impressive total of almost 88,000 high-resolution surface pictures,[12] three chemical analyses, and valuable tests of the mechanical properties of the lunar surface.[13]

To the surprise of JPL engineers steeled by Ranger, the first launch led to the first success. Surveyor 1 left Cape Kennedy at 1441 GMT on 30 May 1966, Memorial Day, and almost two days and 16 hours later sensed the surface with its radar and touched down gently at 3–4 m per second, then bounced a few inches (0617 GMT, 2 June 1966, late on 1 June at JPL).[14] Jack McCauley, Larry Rowan, and other terrain analysts and Surveyor people gathered in a house in Flagstaff felt not so much elation as relief that nothing they had done had scuttled the mission. The landing point was in Oceanus Procellarum at 2.5° S, 43.2° W,[15] within the almost-buried 112-km crater Flamsteed P, usually referred to as the Flamsteed ring. The cameras could see the Flamsteed P "mountains" on the horizon. The mare surface turned out to be the youngest ever visited by any spacecraft, unmanned or manned, Soviet (probably) or American; but more about that in later chapters. The first transmitted picture showed one of the collapsible footpads, which proved by the slight impression it made that the surface was easily strong enough to bear not only Surveyor 1 but probably anything else. By means of a filter wheel with four positions the camera could show lunar color if there was any; there were only grays, but the color wheel mounted on one of the three legs for calibration showed up nicely on color television sets back home. Grains and other details as small as half a millimeter were visible.

The "unbelievably successful" achievement (which coincided with Geminis 9 and 10) generated more public interest than any other lunar mission between Ranger 7 and Apollo 8, and the press rose to the occasion. There was the usual chauvinistic media crowing about how many more pictures were transmitted from the Free World's Surveyor (more than 11,000 ultimately) than from the Communists' Luna 9 four months earlier. Ours had succeeded on the first try whereas They had required at least half a dozen.[16] Ours was powered by solar panels rather than Their batteries, and landed softly on its own rather than being dropped from a carrier rocket and allowed to roll as was Theirs. Contrary to expectations, Ours even triumphed unexpectedly over the long, cold lunar night and awoke on 6 July, eight Earth days after sunrise on the Moon, to transmit more data, and in fact kept doing so every lunar day until 7 January 1967. Ray Batson and his crew, who had developed the procedures during the arduous tests at the Bonito flow, assembled the many, many 5-by-5-cm prints of narrow-angle pictures into mosaics and stuck them on the inside of hemispheres to make up panoramas. Possibly the experimenters came to secretly hope that Surveyor 1 would finally expire.[17]

The prolonged life of Surveyor 1 did not delay the next launch. Surveyor 2 left the Cape on 20 September 1966 on a trajectory toward Sinus Medii, which was regarded as a prime Apollo landing site. A problem during the midcourse correction caused the spacecraft to tumble, though, and it could not be saved. This unfortunate outcome (balanced by the concurrent success of Gemini 11) at least alleviated one problem: the communication frequencies had not been changed from those used for Surveyor 1, and the geriatric Surveyor 1 would have responded to commands sent to Surveyor 2.

Surveyor 3 brought another success as it landed four minutes after midnight GMT on 20 April 1967 (late afternoon of the 19th at JPL), at 3.0° S, 23.3° W, in a part of Oceanus Procellarum that since 1976 has officially been called Mare Insularum (at my suggestion).[18] Before settling down on a crater wall that would later be trod by the two Apollo 12 astronauts, it jumped twice because its vernier control engines did not shut off immediately. Surveyor 3 brought a new tool into use on the Moon, officially called the soil-mechanics surface sampler and unofficially the "scratcher arm." This was a scoop mounted on a pantograph arm that could reach out about 1.5 m and dig trenches, break rocks with its blade as a geologist would with a geologic hammer, and generally pick up or shove rocks and scrape the surface for the benefit of watchers back at JPL's mission control center, the Space Flight Operations Facility (SFOF).[19] It could test the bearing strength of the surface by recording the power required to push the shovel blade into it, and could weigh rocks in the same way. This versatile contraption had been conceived by Ronald Scott, a professor of engineering at Caltech who had been involved with the Surveyor rover. Scott and the first actual operator of the sampler, JPL engineer Floyd Roberson, reported that they developed a "feel" for the lunar soil despite the intercession of some 400,000 km, the need to control the sampler electronically in steps, and the camera mirror dirtied by dust raised by the verniers.[20] They compared their vantage point to that of a nearsighted person viewing the soil from four feet away. They could "feel" the increase in resistance about a centimeter below the surface that the Apollo astronauts also later noted. Surveyor 3 survived only one lunar night (to 4 May GMT) and transmitted "only" about 6,000 pictures, yet it dug four trenches in 18 hours of operation and supplied key data for the soil-properties and television teams' efforts to decipher the surface material.

Surveyor 4, with the same instruments as Surveyor 3, tried again on 14 July for Sinus Medii and made it to the target. It ceased transmitting two and a half minutes before touchdown, though, and was never heard from again. The final resting place and fate of Surveyor 4 were never determined. Either Sinus Medii or even numbers seemed to be unlucky for Surveyor.

Surveyor 5 was destined for the honor of making the direct determination of the Moon's composition. Anthony Turkevich, a nuclear chemist at the University of Chicago, had led in devising a method of doing chemical analyses by remote control without an excessively heavy instrument. Alpha particles emitted from bits of the recently discovered radioactive transuranium element curium in his alpha back-scattering instrument were scattered or bounced back from the surface with an energy proportional to the mass of the nuclei they hit.[21] Homer Newell was amused to comment that Surveyor 3 had the "scratcher" and Surveyor 5 the "alpha back scratcher." Happily, this ingenious "alpha-scat" worked directly for five elements expected to be especially abundant in Moon rocks (oxygen, silicon, aluminum, magnesium, and sodium) and indirectly for three more (calcium, iron, and titanium) on the assumption that they were the main contributors to element groups detected by the instrument. Only the uppermost surface skin was analyzed, but one could reasonably suppose that its fragments were derived from the underlying bedrock.

Despite a zigzag trajectory reflecting frantic and ingenious measures taken by the engineers to compensate for a helium leak, Surveyor 5 landed on target with its analytical minilab on 11 September 1967 GMT (10 September in the United States). The target this time was in Mare Tranquillitatis, at 1.4° N, 23.2° E, only 60 km from the Ranger 8 impact point and 25 km from the future Tranquillity Base. The Surveyor skidded down the 20° slope of an elongated crater (probably a secondary, though interpreted by the investigators as a collapse crater) and could barely see over its rim. Fortuitously, the slide piled soil on a magnet intended to estimate the amount of meteoritic iron in the soil — an amount (less than 1%) that proved smaller than most people expected on a surface exposed to cosmic space. The vernier engine of the spacecraft was fired once, after 18 hours of data had been obtained, to move the alpha-scatterer to a second spot.

John O'Keefe tells a story about picking up Harold Urey at the Los Angeles airport just after the first results from the alpha-scatterer were decoded. As O'Keefe was excitedly enumerating the probable elements and their abundances, Urey commented glumly, "It's basalt, isn't it," and added, "You are a very poor driver." Don Gault remembers Urey remaining silent during a presentation by Turkevich and for about two days more. Then he admitted, "Maybe Mother Nature knows best." Hal Masursky remembers him saying, "If this happens again, I'm in trouble."[22] It is indeed basalt, and of a type commonly found on Earth. O'Keefe could adjust to this reality by displacing the source of Earth's tektites to the lunar terrae. Urey, who was by this time speaking again to lava advocate Kuiper, later adjusted to Surveyor's assay and Apollo's findings by dropping his entire original concept that the Moon had never experienced much internal heating. John Gilvarry had another interpretation: the alpha-scatterer confirmed his 1960 idea that the maria are desiccated water-laid sediments because the analyses matched mudstones better than any other rock.[23] Surveyor 5 also sent back almost 19,000 pictures of what later was determined to be the oldest mare surface visited by any Surveyor.

The release of Surveyor 6 to perform the original objective of the Surveyor project, scientific exploration, was considered for a while. Gene Shoemaker, John O'Keefe, Harold Urey, Hal Masursky, and several others all came out strongly for a terra site, each for his own reason. Shoemaker's favorite was the Fra Mauro Formation.[24] Other science sites were suggested at a June 1967 meeting of the Surveyor Scientific Evaluation Advisory Team chaired by JPL project scientist[25] Len Jaffe (whose possibly excessive desire to exert control over the project was hampered on some occasions by his refusal to fly, which caused him to arrive late for meetings in the East if the trains were late). Two unsurprising entries were Copernicus and the perennial candidate Alphonsus. A newer but also long-lasting candidate was the Marius Hills, brought to the attention of lunar scientists by Jack McCauley. The crater Aristarchus was there, and Hal Masursky added to the list the special-feature favorites Aristarchus Plateau and Hyginus Rille. Less "special" but more suited to Surveyor's landing accuracy were the relatively smooth and level floors of the craters Julius Caesar and, especially, Hipparchus, a favorite for a Surveyor and early Apollo mission at least since the Falmouth conference because it offered a big (150-km) nonmare target. Keith Howard, an able field geologist hired for the Menlo Park USGS office in April 1966, proposed a similar terra-plains site inside the 75-km crater Flammarion, which he had been studying while mapping his LAC quadrangle, Ptolemaeus. The voting at a 24 September 1967 meeting of the advisory team favored Hyginus, Copernicus, Aristarchus Plateau, and Hipparchus, in that order; Masursky was very persuasive.

For the time being, the targeting exercise was futile. NASA Headquarters sent the word that Surveyor 6 had to try again for Sinus Medii to please the manned program. On 10 November 1967 (GMT) it finally broke the double jinx by landing safely in Central Bay, at 0.5° N, 1.4° W, next to a mare ridge. In its lifetime of one Earth month it transmitted almost 30,000 pictures, a third of the project's total. The SFOF controllers refired its engines to hop it 2.5 m to a new spot. Surveyor 6 carried another alpha-scatterer, which found more basalt. It had "happened again," upsetting Urey's convictions even further. Shoemaker turned the primary reporting responsibility for Surveyor 6 over to his faithful colleague on the Surveyor project, Elliot Morris. Polarization measurements had survived into the spacecraft era as an objective because they are easily performed; Surveyor 6 carried polarizing instead of color filters, and Henry Holt, the inheritor of the study begun by me at Meudon and continued by Newell Trask, interpreted the meager results.

Even the ravenous Apollo project was satiated by four successes in the potential Apollo landing zone on the maria. NASA, possibly embarrassed by their caution, now threw it to the winds.[26] Surveyor 7, the last of its program, would be devoted to science. The list of scientific landing sites was reviewed again. The Surveyor 5 and 6 analyses had confirmed the long-held majority view that the mare rock is basalt, implying that the Moon had differentiated. Urey's long-sought primitive, undifferentiated, presumably chondritic material had therefore not yet been found. Dick Eggleton suggested that this primitive rock, or at least residues left by the partial melting that created the basalt, might have been brought to the surface from depths as great as 70 km in the Fra Mauro Formation. He picked a point where a Surveyor had a good chance of landing safely even without great accuracy.

But an even bolder suggestion, apparently arrived at almost unanimously among the experimenters, finally won: the north rim of the crater Tycho in the southern highlands. Here at last was pure terra and Pure Science. There was little chance an Apollo could ever land at Tycho, and none ever did. Surveyor 7 would be the first, and, of course, the last, to combine all three sophisticated devices: the camera, the alpha-scatterer, and the scoop. Tycho was obviously an impact crater to all but people like Jack Green, and yet Lunar Orbiter 5 revealed some material with flat, fractured, sparsely cratered surfaces "ponded" or "pooled" in depressions in the rim. Some of the pools were fed by leveed channels and clearly were formed by a very fluid material. In the spirit of the times the knee-jerk interpretation was hybridization of the crater by volcanism.

The popular media have left us a record of the enthusiasm for Surveyor of the "ebullient, articulate, flamboyant" Shoemaker and three of his nine or so USGS Surveyor henchmen—photogrammetrist Ray Batson and geologists Elliot Morris and Henry Holt.[27] Just after midnight (EST) on 7 January 1968 they came roaring up in an automobile only a few thousand feet away from launch pad 36A where an Atlas-Centaur was waiting to fire Surveyor 7 toward the Moon. It was their last chance to see a launch of their favorite machine, and the most scientific one to boot. Security guards made sure they saw it from a safer place. They would have plenty of opportunity to vent their enthusiasm in the Space Flight Operations Facility at JPL during mission operations and more than plenty in the long-drawn-out process of preparing reports, which for the interesting Surveyor 7 were particularly voluminous.

A word about those mission operations. Almost all lunar scientists I know considered their participation in the operations conducted at SFOF or at Mission Control in Houston while their experiments were orbiting or sitting on the Moon as among the most exciting and rewarding times of their lives. "Mission ops" are indeed dramatic. People are dashing about while never-before-seen views of outer space are flashing onto the monitors. In the 1960s and 1970s the central room in SFOF and its Apollo equivalent at MSC were full of highly competent engineers knowingly contemplating their computer screens. The back rooms were equally full of scientists speculating on the meaning of it all. The rooms were windowless; night and day were identical, and the excitement went on 24 hours a day as in a Nevada casino. Churchill's war room beneath London must have had a similar atmosphere. I know of only one scientist who disliked mission operations: me. I enjoyed being present during the missions but not having to work while there. To me, work is best done in the observatory, at home, or in a relatively tranquil office, and not in collaboration with others in the midst of all the clamor and confusion inevitable at mission ops.

Surveyor 7 touched down safely to general jubilation and some surprise, considering the roughness of the target, at 0106 GMT on 10 January 1968 (early evening of the ninth at JPL). The touchdown point was about 30 km north of the rim of Tycho at 40.9° S, 11.4° W, only 2.5 km from the target, a wonderful feat in itself and the best accuracy yet achieved. Pictures started streaming back from the rocky Tycho rim, whose rough appearance was enhanced by the low Sun elevation of 13°. But the alpha-scatterer was stuck. Dirt had gotten into its ratchet gear and it failed to drop onto the surface. The Turkevich team called on the Scott team for help. Over five and a half hours, Scott and Roberson sent 600 commands to the surface sampler soil scoop to move out, in, up, down, and sideways until it had nudged the alpha-scatterer onto the surface. Later they moved the alpha-scatterer two more times, once onto a rock and once onto an area stirred up by the surface sampler. They also dug seven trenches, one 15 cm deep. The one-at-a-time rectangular motions made the operation seem like a "square meal" administered during military basic training or fraternity hazing, with the added fillip of looking in a mirror, and provided a taste of what the original plan for remote control of the scientific Surveyors would have been like. But except for two Soviet Lunokhod rovers, humans would conduct future hands-on science operations on the Moon in person.

THE REGOLITH DECODED

Surveyor easily did its primary job of assessing the surface properties for Apollo. The fact that five craft landed successfully and barely dented the surface proved that the astronauts would be safe on the Moon. Even when the attitude-control jets spurted nitrogen gas at the surface to try to stir it up, not much happened; no Gold dust again. The famous porous surface wasn't there either, as it was not in the Luna 9 and 13 pictures. Whatever it is at microscopic scales, it is trivial at the scale of a spacecraft or an astronaut. Users of remote sensing beware.

Surveyor did much more.[28] Shoemaker said that it characterized the surficial debris layer better than did Apollo. During an intensive study of the field of view of Surveyor 3, he finally gave the layer the name it has borne ever since: *regolith.*[29] The term had been used for decades to describe the fragmental material that covers Earth's surface, including the soil, bedrock weathered or otherwise loosened up in place, and material of any origin transported from somewhere else. Thus the term is perfectly applicable to the Moon.[30] Lunar regoliths have evolved over long times, have been generated by innumerable random impacts, and consequently are finely structured.[31]

Competent interpretations of mere pictures—without drills, seismometers, or black magic—also confirmed the supposition that the regolith increases in thickness with age. Impacts eject blocks of basalt or other cohesive material from beneath the regolith. The subregolith material gets harder and harder to reach as the regolith thickens with time. A crater big enough to penetrate the regolith will have blocky ejecta, and a crater too small to penetrate it will not. A scientist or educated technician can therefore measure the smallest blocky crater and the largest nonblocky crater and set limits to the regolith's thickness. Also, earlier blocks get broken down by repetitive reworking by impacts, so an experienced observer can guess the age of a regolith, therefore of its substrate, just by looking at the number and size of blocks. The regolith on the old lavas of Sinus Medii is more than 10 m thick; the regolith on the rim of Tycho is perhaps only 2–15 cm thick.[32] The steady-state size of craters, as measurable on Ranger or orbital photos, also increases with age of the bedrock unit.[33] All these relations boil down to a simple and satisfying way of estimating the age of a lunar geologic unit if you have a good photograph (and compensate for Sun illumination differences): big soft craters and small fragments, old unit; many small sharp craters and many large sharp blocks, young unit. Old sites, despite their greater total number of craters, are smoother and therefore more favorable for landings than the block-littered young sites. This lesson was crucial to Apollo planning.

Individual fragments seen in the pictures directly showed something of the processes that produce regolith. Upper surfaces rounded by impact erosion and small pits attributed to small impacts were visible.[34] Blocks at all Surveyor landing sites seemed to be about equally bright, and brighter than the fine soil particles.[35] This is why slopes on the Moon are brighter than the plains: soil particles tend to be shed from the slopes and accumulate on the plains. Tycho is bright because it is blocky and composed of terra material. Surveyor was answering many long-standing questions.

THE BIGGER PICTURE

In the spirit of its original purpose, Surveyor delivered more than an analysis of the regolith. The chemical analyses made by the alpha-scatterers on the last three Surveyors[36] provided first looks at the compositions of both the maria and the terrae. Surveyor 7, less directly, also provided the opportunity for a dialogue about what proved to be a critical type of geologic unit for the understanding of lunar processes: the smooth pools and leveed channels on the Tycho rim. In both cases, later confirmation of the results based on Surveyor data were needed. Nevertheless, the right answers were available in 1968.

Even before the Apollo 11 *Eagle* landed, the Turkevich team established that Surveyors 5 and 6 almost surely sat on iron-rich basalts in Mare Tranquillitatis and Sinus Medii, respectively.[37] The Tycho rim material analyzed by Surveyor 7 has a similar distribution of major elements detectable by the alpha-scatterer and early on was often called high-aluminum basalt. Working together in Menlo Park, Dale Jackson and Howard Wilshire even wrote that light spots visible in the pictures were large crystals (*phenocrysts*) of the type found in basalts.[38] The petrologic skills of Dale and Howie are undisputed, but there is too little iron for a typical basalt. And to Gene Shoemaker, the fragments appeared more diverse than the basaltic fragments at the landing sites in the maria. He took the early alpha-scatterer data back from SFOF to his hotel room and calculated what minerals the elements should theoretically compose.[39] The rock name Shoemaker came up with to match the norms is still ringing through the halls of lunar petrology and geochemistry: *anorthositic gabbro.* He furthermore proposed an origin of the Tycho target rock in layered intrusions, another still-current interpretation for the ancestry of lunar terra rocks.

The density of anorthositic gabbro is consistent with the density of a rock "weighed" by the scratcher arm and is too low for this rock to compose the whole

Moon. Since basalts are also present, lunar differentiation was almost certain. The alpha-scatterer data were also incompatible with the lunar origin of tektites and all other meteorites, except, perhaps, basaltic achondrites, stony meteorites consisting of basalt rich in plagioclase (but these do not come from the Moon either).

Interpretations of the Tycho fluid-flow features depended on Lunar Orbiter photos but were inspired by the concentrated attention paid to the Surveyor 7 site. The Lunar and Planetary Laboratory, represented by Kuiper on Gault's team, believed the liquid or liquefied flow material was volcanic lava. Gilbert Fielder was at LPL on leave from the University of London and collaborated with Bob Strom in suggesting an extensive postimpact volcanic history for Tycho.[40] To Shoemaker, however, the larger fragments derived from the flows looked more like the suevite found at the Ries. The volcanic idea seemed more straightforward because the pools are less densely cratered than the surrounding fragmental rim material at the landing point; the volcanic magma delayed its extrusion onto the surface until some time had passed after the impact. To explain the crater density difference, Shoemaker called on a rain-back of ejecta after the fragmental debris was emplaced but before the melt rock solidified. At the time this impact-melt notion seemed contrived to cling to a pure impact model for Tycho and, by extension, craters in general.

Impact melting was slowly becoming understood on Earth. At the time of the Surveyor 7 flight, investigators were not even in accord about the origin of the best terrestrial examples: dense rocks with igneous textures found in the large craters Manicouagan and Clearwater in Canada. The rocks *looked* volcanic even when examined closely. Pools superposed on fresh craters were still widely thought to be volcanic even by impact-minded astrogeologists of the USGS—Jack McCauley and me, for example.[41] However, the enormous energies released by cosmic impacts were going to win one more argument during the relatively leisurely post-Apollo contemplation of Orbiter and Apollo photos (see chapter 18). If impacts could dig big craters, they could and did melt great volumes of rock that looks very volcanic.

In his mostly prescient *American Scientist* article of 1962 Shoemaker had predicted an orderly progression from orbiter photography to Surveyor landings to manned landings.[42] Surveyor might even guide the Apollos to their landings by means of a beacon. This was not to be. The first Lunar Orbiters came after the first Surveyor. Only one Surveyor site, 3, was visited by astronauts, and that mainly to prove the point-landing capability of the Apollo system and secondarily to examine the results of a 30-month exposure of Surveyor to the lunar environment.[43] Surveyor, like Ranger, came along too late to affect the design of the Apollo lunar module. Nevertheless, at a cost of $469 million for the spacecraft, Surveyor prepared the way for manned landings and anticipated many Apollo findings in considerable detail.[44] The last three Surveyors suggested a general chemical model of the Moon that has now been confirmed. The properties of the regolith are still perceived much as they were through the remote Surveyor observations. Like dry beach sand, the regolith could support heavy loads even though its particles did not stick together. A safe landing of the lunar module and its precious human occupants had moved one long step closer to reality.