11

Tranquillity Base
1969

THE *EAGLE* LANDS

The world news in most of July 1969 included a typical mix of singular and persistent items. A car occupied by Senator Edward Kennedy and his companion, Mary Jo Kopechne, went into the water off Chappaquiddick Island, Massachusetts, and only the senator came out alive. The Vietnam War and the protests against it raged on, but "peace was in sight." A British entry into the six-nation European Common Market was becoming increasingly acceptable to a post–de Gaulle France but was hotly debated by the British themselves. Israel debated how many settlements to build in the Arab territory it occupied. The United States proposed to build new weapons as bargaining chips in arms-reduction talks with the Soviets. Soviet premier Kosygin proposed better relations with the United States. On 13 July his country launched its mystery ship Luna 15 to the Moon, either to bring back a lunar sample before the Americans could or to emplace a rover that would outlast Apollo 11,[1] providing in any case a curious sideshow for the spectacular main event.

The week that began at 1332 GMT on 16 July 1969 may not have been the greatest in the history of the world since the Creation, as President Nixon claimed, but it was close enough in this geologist's view. Exactly 24 years earlier the Trinity test near Alamogordo, New Mexico, had initiated the Atomic Age, and the world assumed that another new age in human history had begun when Saturn 506 roared off from the Kennedy Space Center Moonport, pad 39A. Because the launch went off on schedule Apollo 11 was headed to the easternmost available landing site, ALS 2, in Mare Tranquillitatis.[2]

After a smooth parking orbit and translunar injection; joining of lunar module number 5, now called *Eagle*, to the command module *Columbia;* two trajectory corrections; and an apparently relaxed translunar coast, Apollo 11 with Neil

Armstrong, Buzz Aldrin, and Mike Collins was injected into lunar orbit over the far side of the Moon at 1728 GMT on 19 July. They settled temporarily into orbit as Apollos 8 and 10 had done, snapping photographs and observing visually.

Then came 20 July 1969. First Aldrin and then Armstrong climbed into *Eagle* and undocked from *Columbia* over the far side at 1746 GMT, 100 hours and 14 minutes after launch. After the LM reappeared on the near side, Armstrong reported the maneuver's success with, "The *Eagle* has wings." The two spacecraft, still very close, passed over the near side on their thirteenth revolution of the Moon and exchanged hard numbers about such matters as position and spacecraft status with Houston for the benefit of all parties' computers. Houston gave the go for the next step, and *Eagle's* descent engine fired on the far side to lower its orbit to the 16-km perilune that Apollo 10 had pioneered. The excitement in Mission Control was at fever pitch while the two now widely separated spacecraft were still out of radio contact on the far side. The moment for which everyone in the room and beyond had devoted 8 years of skilled labor was now at hand. An actual descent and landing was the only phase of an Apollo mission that had not yet been performed, and its direction fell to the experienced team led by 32-year-old flight director Eugene Kranz. First *Columbia*, then *Eagle* below it, reappeared at the east limb in the proper positions. Capcom Charlie Duke spoke the dramatic message, "*Eagle*, Houston. If you read [the communications were breaking up], you're go for powered descent initiation" (translation: "You may fire your descent engine and land on the Moon"[3]).

Eagle turned legs forward and fired. "*Eagle*, Houston. You are go. . . . Roger, you are go—you are to go to continue powered descent. You are go to continue powered descent. . . ." But then from Aldrin: "1202, 1202." The flight controllers also heard and saw the 1202 alarm on their consoles. Armstrong: "Give us the reading on the 1202 program alarm." The Apollo computers seemed magnificent back then, but they had less memory than a typical desktop model of today, and *Eagle's* computer was simply overloaded. Fortunately one of the heroes of the mission, Steve Bales, the young (26 years old) LM guidance and navigation officer from MIT, interpreted the cause of the alarms as overload and not something wrong with *Eagle's* hardware. Kranz quickly asked Bales's opinion and got the answer, "We . . . we're go on that, Flight." Kranz: "We're go on that alarm?" Capcom Duke: "We've got . . . we're go on that alarm." *Eagle* continued down and slowly righted itself to a more nearly heads-up position. At eight and a half minutes into the burn and 2,300 m above the surface the braking phase ended and the approach phase began, the point known as high gate. The crew could see their landing site 7 or 8 km ahead. Bales assured Kranz that the elevation read by *Eagle's* radar now agreed with the elevation predicted by the computer. Kranz: "Okay, all flight controllers, go/no-go for landing. Retro?"

"Go!" "FIDO?" "Go!" "Guidance?" "Go!" "Control?" "Go!" "G&C?" "Go!" "Surgeon?" "Go!" "Capcom, we're go for landing."[4] Capcom Duke: "*Eagle,* Houston. You're go for landing." At about 600 m elevation Armstrong checked in with, "1201 alarm." Kranz again, his voice strained: "Guidance?" Bales: "Go!" Duke: "Hang tight, we're go." *Eagle* kept descending and its crew ignored another alarm. Aldrin has said that if this had been another simulation at the Cape, they probably would have aborted.

The alarms prevented Armstrong and Aldrin from studying their landing site on the way down and locating the landmarks they had studied for many hours on the Apollo 8 and 10 photographs. Armstrong did not like what he saw when he looked out his triangular LM window at the place the computers were taking them: blocks "the size of Volkswagens" ejected from a crater about 180 m across named West. He took over the controls of *Eagle* and kept flying, slowly descending and steering between West's blocky rays and beyond a 250-m-wide zone with the largest blocks. As Aldrin called out altitudes and horizontal speeds, the excited capcom Duke apparently added so much chatter that he received a rap on the arm from Deke Slayton with the advice, "Shut up!" But Duke had to call out "Sixty seconds," meaning that fuel remained for only one more minute of flight. Nevertheless, Armstrong let *Eagle* down with agonizing slowness. Duke: "Thirty seconds." But then Aldrin: "Forward. Drifting right. Contact light. OK, engine stop," followed by more technical words and then Neil Armstrong's dramatic phrase: "Houston, ah, Tranquillity Base here. The *Eagle* has landed." Duke: "Roger, Twank . . . , Tranquillity, we copy you on the ground. You've got a bunch of guys about to turn blue. We're breathing again." Buzz and Neil shook hands. So did Slayton and Kranz. As the hubbub continued in Mission Control, Armstrong asked, "Do we get to stay, Houston?" The moment when the first humans landed on the Moon was 20.17.42 GMT on Sunday, 20 July 1969.

The combined forces of Houston, Armstrong, Aldrin, and Collins failed to locate *Eagle's* exact position. I was in a television studio in Hamburg, having been enlisted as a scientific commentator by the German "second channel," Zweites Deutsches Fernsehen (ZDF). I sat there with my slide rule (we still used those things then) trying to convert all the numbers coming down from the Moon into a spot I could point to on a chart. But Tranquillity Base was not located exactly until after the astronauts began their return to Earth.[5] As Armstrong said while still in *Eagle,* "Houston, the guys that said we wouldn't be able to tell precisely where we are are the winners today. We were a little busy worrying about program alarms and things like that in the part of the descent where we would normally be picking out our landing spot." He had wisely followed the aviator's rule of thumb, "When in doubt, land long." *Eagle* had overshot the center of the prime landing ellipse by 7 or 8 km downrange and 2 km crossrange, and ended up at 0.67° N, 23.49° E, beyond the Orbiter 2 high-resolution coverage that had "certified" the landing suitability of the region. Inaccurate data on the LM's position had shifted the computer-chosen landing point west of the originally intended one, and Armstrong's understandable distaste for the boulder field of the sharp-rimmed and rayed (Copernican) West crater had taken *Eagle* another 400 m beyond it.

Only 10 minutes after landing, while still in the LM, Aldrin began the geologic description of the Moon: "It looks like a collection of just about every shape, angularity, granularity, about every variety of rock you could find."[6] He also described something later astronauts would repeatedly notice: lunar colors depend on which direction you look relative to the Sun. The astronauts then rested, ate, and made the many complicated preparations for the EVA. Aldrin asked every person listening to pause and contemplate the events of the last few hours, and gave thanks for "the intelligence and spirit that had brought two young pilots to the Sea of Tranquillity" by sipping a few drops of sacramental wine from a small silver chalice.

In the wee hours of 21 July in Europe, but prime time of the 20th in the United States, Neil Armstrong emerged from *Eagle.* On the way down the ladder he pulled a lanyard to deploy a television camera aimed at him. Now we no longer saw rigid metal on the Moon, as we had all through the Surveyor program, but the complex articulation of a living being from Earth. It has been said that Johannes Kepler would have understood what was happening, having himself written about a Moon voyage, but would have been flabbergasted by the ability of hundreds of millions of people on Earth to *watch* the event as it happened. Armstrong stepped on the Moon's surface at 0256 GMT of 21 July, uttering the most famous and I think best-thought-out (though not best-delivered) punctuation mark in the history of space exploration. He had meant to say, "That's one small step for a man, one giant leap for mankind," but it came out without the "a" before "man."

Although Congress insisted that the Stars and Stripes, and not the United Nations flag, be planted on the Moon, Apollo 11's landing was indeed an international event. My host country had produced Wernher von Braun and the (lethal) ancestors of the Saturn 5 (of which a colleague of von Braun once said, "Well, it's the same old cucumber").[7] I was left with no doubt about the world's interest, as every magazine and newspaper on every newsstand I saw in France, Holland, and Germany carried banner headlines and expertly written feature articles about the great event.[8] The USSR delayed the coverage by six hours, but only the people of China, Albania, North Korea, and North Vietnam missed seeing it altogether. Everyone else was witness to the greatest shared adventure in human history. I watched and listened, enthralled, like any other citizen, and my silence disappointed my German hosts, who thought I should be drowning out the historic occasion by jabbering about geology or something as commentators usually do.[9]

Let the also normally laconic Armstrong and Aldrin talk about the geology. Armstrong's first words after his small step began his field geologist description of the once-mysterious surface: "Yes, the surface is fine and powdery. I can kick it up loosely with my toe. It does adhere in fine layers like powdered charcoal to the sole and sides of my boots. I only go in a small fraction of an inch, maybe an eighth of an inch, but I can see the footprints of my boots and the treads in the fine, sandy particles."

The capcom, Bruce McCandless now, replied, "Neil, this is Houston. We're copying." Armstrong continued, "There seems to be no difficulty moving around, as we suspected. It's even perhaps easier than the simulations at one-sixth g that we performed . . . on the ground. It's virtually no trouble to walk around. The descent engine did not leave a crater of any size. . . . We're essentially on a very level place here, I can see some evidence of rays emanating from the descent engine, but a very insignificant amount."

Ten minutes after descending, Armstrong collected, only 1.5 m from *Eagle,* a 1-kg contingency sample whose purpose was to get some Moon rock even if the mission had to be cut short. But no problem; he was able to stay on the surface for two hours and 13 minutes. He commented that Tranquillity Base "has a stark beauty all its own. It's much like the high desert of the United States. It's different but it's very pretty out here." He reported that the hard rock samples are pitted by what appear to be vesicles and that some seem to have some sort of phenocrysts. Not all test pilots knew those terms.

Aldrin, whose EVA lasted an hour and 45 minutes, descended 15 minutes after Armstrong, a sequence that seems later to have deeply depressed him.[10] He did not seem depressed at the time, however, joking that he would make sure not to lock the hatch on the way out and exclaiming "beautiful view" and "magnificent desolation." The field geology team and the operations people had carefully prepared an elaborate plan with a precise time line, most of which was abandoned by the astronauts. No matter; the two skilled observers whom their and our good fortune had placed on the Moon gathered the subjective and physical data that everyone wanted. What about Gold's tales of horror and woe? *Eagle's* engine had hardly disturbed the surface, and Armstrong and Aldrin found a firm footing beneath a soft, resilient layer only about 5–20 cm thick (it varied from place to place). What about the fearful blinding sunlight reflected back at zero phase? There was indeed a surge of brightness exactly opposite the Sun, but they could see detail in all directions, though best while looking cross-sun. The Sun itself looked white rather than yellow. The lunar colors paled beside the brilliant black, silver, and orange yellow of *Eagle.* Earth was hard to look at because it was almost overhead at this near-equatorial location. The curvature of the horizon was obvious. They could not even see features as close as West crater. These first lunar astronauts quickly learned that normal jogging in the exotic low surface gravity (one-sixth that of Earth) would carry them farther than they wanted to step, so they developed a sort of kangaroo hop that soon became familiar to the fascinated television audience. Their heavy backpacks offset their center of gravity so that a slight lean forward was their equilibrium standing position. Even though neither man was talkative by nature, both continued a running commentary in accurate geologic terms.

Six minutes after he emerged, Aldrin remarked, "Neil, didn't I say we might see some purple rock?" He saw some "very small, sparkly fragments" on this rock's surface and noted, "I would make a first guess of some biotite. I will leave that to the further analysis." Geoscientists immediately noticed a problem because the mineral biotite contains hydroxyl (OH) and the Moon was already believed to be dry; I mentioned this to my German audience when Aldrin said it. (The next landing crew was terrified of making a similar mistake and watered down their terminology.) But Aldrin said he was guessing and would leave that for later analysis. He was just using a shortcut description.

After 20 minutes on the surface Aldrin set up a simple experiment to capture solar wind particles: a piece of aluminum foil called the "Swiss flag" because of the nationality of the experiment group that would boil out the particles back in the laboratory. He noted that sprays of dirt he kicked up continued to sail on ballistic trajectories and landed together; no atmospheric winnowing or gravitational sorting here. A little more than an hour into his EVA, Armstrong collected a bulk sample of rock and soil within about 8 cm of the surface. Meanwhile, Mike Collins was still trying in vain to spot *Eagle* from above.

The foil was going to be returned to Earth after 77 minutes of exposure, but two other experiments saved for Apollo 11 by Wilmot Hess[11] and set up by Aldrin 20 minutes before the end of his EVA were left on the Moon. One was a seismometer — the only ALSEP-type experiment that had survived the planning for this first mission — that constituted the Early Apollo Surface Experiment Package. Aldrin had some trouble leveling the seismometer but finally succeeded. The second instrument was a square array of 100 optical reflectors that would reflect a laser beam sent from a telescope on Earth to measure the Earth-Moon distance with the incredible precision of a few centimeters; this was the Laser Ranging Retroreflector, whose accurate but unpronounceable name was usually converted into "LR Cubed" (LRRR = LR^3).

While Aldrin was setting up the geophysical and astronomical instruments, Armstrong was geologizing. He described boulders up to 2 feet across that "look like basalt, and they have probably 2% white minerals in them, white crystals. And the thing that I reported as vesicular before, I don't believe I believe that any more. I think that small craters — they look like little impact craters where B-B shot has hit the surface." He was describing glass-lined "zap pits" that were indeed dug by small impacts, as expectable on a surface unprotected by any atmosphere.

Aldrin set about collecting core samples near the solar wind foil. He had some difficulty driving in the core tube with his geologic hammer (the hammer's only use on this mission), yet the tube would not stand by itself. This firming up of the Moon's regolith a short distance beneath its surface was observed repeatedly by every Surveyor and Apollo lander. Aldrin's hammer blows showed up in the early seismometer signals sent back to Earth.

Toward the end of the EVA, time got a little short for the sample that was supposed to be carefully "documented" by description and photography before and after collection. Capcom McCandless expressed the general idea at that point as follows: "Neil, this is Houston. After you've got the core tubes and the Solar Wind, anything else that you can throw into the box would be acceptable."

Neil picked up "several pieces of really vesicular rock" and managed to collect what he referred to as "about 20 pounds of carefully selected, if not documented, samples" in the last three and a half minutes before he had to quit. He packed them into the box, passed both rock boxes up to Aldrin, who was already in the LM, and called it a day. That it was. They closed the hatch of the LM and repressurized it, at which time the charcoal-colored Moon dust that had adhered to everything so tenaciously came loose and filled the cabin with a smell like gunpowder. The two moonwalkers answered technical and geological questions forwarded by the capcom, and worked or rested almost sleeplessly for more than 12 hours in the cold and noisy *Eagle.*

The next "day" they expertly answered more questions. Armstrong described the craters at Tranquillity Base as a field of circular secondaries and the soil as like powdered graphite. He correctly suspected that the boulder field they were in was part of the raylike ejecta of West crater (he did not use the name West). West was both a hazard and a sampling drill hole. It is about 30 m deep and easily penetrates the regolith, whose thickness was later estimated by Gene Shoemaker and his team of geologic advisers and observers as about 3–6 m, bringing 5-m (Volkswagen) blocks from the underlying bedrock to the surface. Thanks to Armstrong's maneuvering, the blocks at the more distant actual landing site were a more manageable maximum of about 80 cm across.

At 1754 GMT — two hours after Luna 15 crashed ignominiously in Mare Crisium[12] — Armstrong and Aldrin launched the ascent stage of *Eagle.* About three and a half hours later they rejoined Collins in *Columbia,* rendezvousing and docking on the far side of the Moon out of sight of Earth on the strength of their onboard computers and their pilots' eyeballs. Remaining behind on the Moon were the flimsy descent stage of *Eagle* (looking like the cheap Hollywood imitation the skeptics believed it was) and a variety of discarded equipment worth about $1 million in 1969 money. One of the LM's legs bears a plaque that reads: "Here men from the planet Earth first set foot upon the Moon, July 1969 A.D. We came in peace for all mankind." The plaque and the rest of the expensive junk will outlast all of man's works now on the corrosive surface of Earth, from the Egyptian pyramids to the skyscrapers of New York City.

The Soviets graciously congratulated the Americans. After seven and a half hours more in orbit the SPS fired at 0456 GMT on 22 July, and three men headed home bearing the first 22 kg of rock and soil ever collected from another world.

THE SCIENTISTS POUNCE

At 1650 GMT on Thursday, 24 July, *Columbia* splashed down in the early-morning Pacific, eight days, three hours, and 19 minutes after she left Cape Kennedy along with *Eagle* and the giant Saturn 5 stack. The big screen in Mission Control bore the words, "'I believe that this nation should commit itself to achieving the goal, before the decade is out, of landing a man on the Moon and returning him safely to Earth'—John F. Kennedy, 25 May 1961." Another screen read, "Task accomplished—24 July 1969." So it was, in eight years and two months, and with time to spare.

The historic cargo of Moon rocks and film was carefully returned to Houston via USS *Hornet* (USS *John F. Kennedy* having been vetoed as the recovery ship by Nixon or someone on his infamous staff) and arrived at the Lunar Receiving Laboratory on 25 July, ahead of the astronauts. Needless to say, the assembled petrologists and geochemists of the LSPET were eager to see what was in the two sealed aluminum rock boxes (Apollo Sample Return Containers in official NASA-ese). But first the alien Moon made itself felt. Quarantine paranoia had reached ridiculous levels during planning for the LRL; even the film that had been on the Moon was carefully sterilized. The rock boxes were sterilized by ultraviolet light and paracetic acid, dried with nitrogen, and finally punctured to remove remnants of the gruesome lunar atmosphere. All human contact with the objects from the Moon was mediated by rubber gloves mounted in the walls of glass cases.

P. R. Bell and Elbert King of LRL, Ed Chao of USGS Astrogeology, Harvard mineralogist Cliff Frondel, and former USGS geologist-geochemist Robin Brett provided running commentary for the grand opening. Bell had raised a scare about a "pyrophoricity" phenomenon that would cause the lunar soil to burst into flame when it contacted oxygen. After an eternity, the first box was opened at 3:49 P.M. Then the first Teflon bag was slit open. There was no fire. All eyes focused on what looked like: the Rosetta Stone? primordial chondrites? sparkling pegmatites? No; dirty coal. Astronomers had been saying that the Moon is really dark and not off-white as it seems in the night sky, and obviously they were right.

After a little cleaning some of the larger pieces of rock began to reveal their character as basalts. At a press conference about a week after splashdown, Harold Urey admitted, "On the basis of the evidence presented today, I should consider revising my opinion. These rocks, as they look at present, could be lava flows." *New Yorker* writer Henry Cooper recorded with dry amusement Urey's personal battle with lavas, and other skirmishes in the tug-of-war between scientists' emotions and the facts.[13] During the EVA he had heard Urey say, "Oh, hurry up and get the samples!" And, "The astronauts know very well what pumice looks like, yet they're not reporting any pumice!"[14] This hopeful comment made the cold Moon seem safe a little longer, even though it was uttered after one mention of vesicles and before another. Now he was beginning to show grace in the face of reality again, although he still held out hope that the lavas were created by impacts.

While LSPET was attacking the samples, debriefers were attacking the astronauts' memories while they were fresh. Armstrong, Aldrin, and Collins arrived at LRL on 27 July and were immediately quarantined for three weeks; with nowhere to go, they were at the mercy of questioners. As soon as possible they spoke their memories into tape recorders and later went over the same ground with the experts. On 6 August (the day after Mariner 7 flew by Mars taking pictures and six days after Mariner 6 did), I joined a group emphasizing the photographic and sampling aspects of Apollo 11. MSC photography specialists, Tom Gold, Elbert King, Hal Masursky, Gene Shoemaker, Gordon Swann, Bob Sutton, Harold Urey, and many others I do not remember also peered through the strong glass-Plexiglas partition at Armstrong, Aldrin, and Collins. Only the photo people and science experimenters were allowed to speak, and many questions went unasked. Details such as the collection sites of individual rocks could not be established. However, the astronauts conveyed many items of general interest about the tools, rock boxes, sampling procedures, and the like that would benefit later missions. Aldrin described the uncertainties of walking on the variable-thickness surface material as like walking on snow, as Gerard Kuiper had predicted. They told us that distances and the nature of distant features were hard to estimate while on the surface. They could not see any stars, though Armstrong saw one bright planet (I think he meant Earth). He apologized for not being able to document the samples better, saying, "I'm sorry, maybe next time." Armstrong told Gold, whose experimental camera was used to take 17 closeup stereoscopic photographs of the surface, that if the handle of his camera were not redesigned, "we're in danger of having someone throw it over a nearby crater." They went on to discuss small, shiny droplets of something looking like liquid solder which the camera had photographed and which, Armstrong observed, were always splattered on the bottoms of small raised-rim craters. A mystery worthy of Gold's imagination! He later suggested they are melt rock caused by a novalike surge in solar heating and concentrated by the parabolic shape of the crater.[15] (He also said he did not favor geologists studying the Moon any more than he favored them studying the Sun.)[16] Jack Green thought the droplets are semiliquid volcanic bombs.[17] But they are almost certainly impact splashes.[18] Armstrong did not have the opportunity to collect any of the blobs and complained in general about the lack of time, the impossibility of photographing and sampling at the same time, and the difficulty of inspecting and collecting rocks while standing (their space suits, stiff as an inflated football, kept them from bending over very far). There was much to correct on later missions.

Collins told us that his orbital photography depended not on following the target-of-opportunity chart but on what was out the window when he could spare a few minutes to snap pictures. The following quote by one of the crew summarizes pretty well the feelings of all Apollo crews about the orbital photography:[19]

> I'm sure you would have been amused if you could have seen inside the cockpit during an exercise in which we were trying to do a very simple thing like looking out toward Aristarchus [for transient phenomena] or taking a picture of crater 320 or something. You have camera backs and a couple of lenses; then you get the 16-millimeter camera out and a couple of magazines; then you try to decide which kind of film you are supposed to be using. The monocular and the recorder are there. In addition, you are probably trying to eat lunch at the same time; and about 20 different kinds of food packages, a lot of other books, and claptrap are floating around. It really looks very much like two guys eating lunch in the window of a camera store.

One impression stands out in my memory from the debriefing: Armstrong's competence. Although his intelligence and alertness had always been evident on the geology field trips, he had not seemed more interested than the average astronaut. But here he showed that he had observed everything and remembered everything that could possibly interest the scientists and engineers. When asked whether the many partly buried rocks that were observed were being covered or uncovered, he gave the sophisticated answer that they seemed to be in a steady state. It turned out that he had wandered off on his own to investigate a 25-m crater without anyone knowing it, a seemingly impossible feat for someone monitored by a Mission Control chock full of expert flight controllers and watched on television by hundreds of millions more. Aldrin and Collins performed very well as observers, too, but Armstrong, in one of the astronauts' favorite terms, was outstanding.

I learned later that this was the only scientific debriefing of the crew, though I still have trouble believing it. Maybe somebody will correct me. If not, you have a fine illustration of NASA's attitude toward science. Another is that the first surface pictures seen by Shoemaker, the geology team leader, were duplicates given to him by a newsman. NASA also wavered in its public-affairs promotion for the most monumental undertaking of the industrial age. The television pictures transmitted from the Moon to Earth during the EVA were fuzzy, ghostly images in black and white. George Low, for one, was incredulous that the culmination of this $20 billion program was "to be recorded in such a stingy manner";[20] he was right, of course. The geology team had hoped for a better camera but had no say in the matter.

At the time of the debriefing, geologists visiting the LRL were treated to a preliminary not-for-publication report of the sample analyses by Australian geochemist Stuart Ross Taylor (b. 1925), a member of LSPET then temporarily residing in Houston and attached to MSC. Ross told us in his typical, almost inaudible and seemingly unexcited style that some of the samples are mechanical mixtures of fine regolith particles and rock fragments called breccias or microbreccias. These were certainly to be expected on the much-impacted Moon. The other rock type was expected only by those who knew that impacts were not the whole answer: half of the rocks are crystalline, igneous basalt. Most of the soil fragments are made of this basalt, which is of two similar types. Without question the basalts were erupted as lavas. Their density is about the same as that of the Moon as a whole and they would be denser still if they had been compressed in the Moon's interior; therefore they cannot represent the whole Moon. Nothing wildly alien was found, though the basalts contain much more titanium than do terrestrial basalts. Otherwise they consist of a suite of mostly familiar minerals arranged in mostly familiar textures that could be described by terms already in use on Earth.

The titanium worried Urey; volcanism was a more likely source for that than impacts. But he was temporarily reassured when he got wind of preliminary radiometric dating that suggested ages of 4.5 aeons for some samples—as old as the Moon! I once encountered him in the lobby of the Nassau Bay "Resort" Hotel across from MSC (unofficial hangout of Moon scientists and the site of many an indiscretion by otherwise serious and respectable scholars, but hardly a resort). Urey, bent over and hands behind his back, was pacing stiffly back and forth muttering, "damn geologists!" (Well, I am not sure he swore, but that was the idea.) Only a nincompoop geologist could have thought that the maria are younger than the Moon itself!

THE FIRST ROCK FEST (JANUARY 1970)

But the facts continued to roll in. LSPET's examination ended in September and its results were made public.[21] Dating of the rocks based on isotopes of argon was indicating ages between three and four aeons. So, at least one part of Mare Tranquillitatis consists of volcanic rocks erupted between half a billion and one and a half billion years after the Moon formed. Urey gave in; he had been wrong, and the geologists had been right. Gilvarry, however, was not ready to change his opinion that the maria consisted of water-laid sediments. He acknowledged that the returned rocks were basalt but said they had been transported to the site from the highlands by flowing water.[22]

The preliminary examination was quickly succeeded by minute scrutiny at the home institutions of some 142 principal investigators and hundreds of coinvestigators. The Lunar Analysis Planning Team (LSAPT, unkindly pronounced "less apt"), some of whose members were also on LSPET, had the job of distributing the precious samples. The investigators then worked furiously and under an embargo against reporting their results until the week of 5–8 January 1970, when they assembled at MSC for the first annual "Rock Fest" to announce their findings, along with some preliminary ones from Apollo 12.[23] *Science* magazine pounced on the 143 resulting papers as eagerly as the analysts had on the samples, processed the manuscripts on the spot, and made the basic facts available to the scientific community in exquisite detail only three weeks later. Even more elaborate descriptions followed later in the year in the three-volume conference proceedings.[24]

The samples were tortured by every sophisticated analytical technique known to science, including some invented just for them. The time elapsed since crystallization of their source units and the time individual rocks had lain on the surface were determined by painstaking analyses of chemical isotopes in a dozen ultraclean laboratories in the United States, Australia, Canada, Britain, Germany, and Switzerland. Dozens of other tests tracked down every last trace element and isotopic variation of the major elements. Solar wind gases and effects of cosmic rays were detected in the rock surfaces, soil particles, and the Swiss flag. There were tests for complex organic compounds that would have detected 10 parts in a billion; none of lunar origin were found — only the microorganisms that had leaked out of the astronauts' space suits. The same goes for volatiles; not the slightest trace of water either now or at any time in the Moon's past could have come near the returned samples until Armstrong and Aldrin got there. The Moon is and always has been ultradry and, until the astronauts arrived, totally devoid of life.

A few new minerals were found, the most famous of which is *armalcolite*, a titanium-bearing mineral named for the astronauts *Arm*strong, *Al*drin, and *Col*lins. The chemistry of the basalts is a little exotic compared with that of terrestrial basalts but is not really extraordinary. Most noticeable is a relative paucity of volatile elements such as sodium but a great abundance of titanium. A striking peculiarity is the relative paucity of one of the rare earth elements, europium, compared with the others. The lack of volatiles and this "negative europium anomaly" would play major roles in later megathinking about the Moon.

The origin of armalcolite and the paucity of oxidized iron point to one of the lavas' exotic features: they were formed under highly *reducing* conditions — that is, in the near absence of oxygen. They are unearthlike in additional ways. They show no hydrothermal alteration or weathering whatsoever because of the absence of water, and so look fresher than terrestrial basalts that erupted yesterday. Also, their surfaces are drilled by the zap pits. Armalcolite, however, has turned out to be not quite so unique as we thought in 1969; it has since been discovered at the Ries and elsewhere on Earth, also formed under reducing conditions.[25]

The discovery of the titanium led to the solution for another set of thorny problems dating from before the Ranger flights: the meaning of the colors and albedos of the maria. In an article dated two weeks before the Apollo 11 launch, Anthony Turkevich interpreted the readings by his Surveyor 5 alpha-scatterer to mean that Mare Tranquillitatis is rich in titanium, and he was right.[26] Relatively bluish maria are rich in titanium; redder maria are generally poorer in titanium.

The basalts' composition also explains their great fluidity, something already inferred by Ralph Baldwin. Low silica and low alkalis such as sodium make for low viscosity.[27] This is why few flow fronts are visible in telescopic and Lunar Orbiter photographs; once erupted, a lunar basalt flows far and fast.

Probably the most important data extracted from the rocks were their ages — or is that just my geologist's bias? At the time of the Rock Fest the ages temporarily settled down at about 3.65 aeons.[28] Unfortunately, records of air pressure changes believed caused by meteors entering Earth's atmosphere had recently misled Don Gault and Gene Shoemaker into estimating ages that were significantly younger than 3.65 aeons (and younger than they themselves had predicted in calmer earlier times).[29] Ralph Baldwin had estimated 2 to 3 aeons in 1964 but also went down the garden path in 1969 with an estimate of less than 640 million years.[30] Fortunately for Bill Hartmann, he was in print predicting 3.6 aeons and had not recanted.[31] But all was not well with the ages. The Lunatic

Asylum of Caltech, the best darn geochronology laboratory in the world by their own account (and probably in reality), had calculated an age of 4.5 or 4.6 aeons for the soil, 900 million years older than the rock it covers! Even nongeologists knew this was a bit peculiar.[32] At the time of the Rock Fest, the "chief inmate" of the Lunatic Asylum, Gerry Wasserburg, thought the soil ages might represent an average of the Moon's materials. Later, the Asylum suggested that some "magic component" might be raising the ages of the regolith particles. Subsequent sampling missions would be needed to find out.

The 3.65-aeon age had profound implications for the history of the Moon and the Solar System. Crater densities show that the maria are relatively young in the lunar scheme of things, but 3.65 aeons is far from young by any earthly standards. The early Solar System must have been a *Star Wars* zone of bombardment to produce terrae so much more heavily cratered than the maria in the comparatively short time since the Moon originated—if 850 million years is short.

The careful study of every fragment turned up something unexpected that unfolded into whole new lines of thinking about the Moon. Although most of the soil particles are similar in composition to the mare basalts, about 4% are light in color and consist of more than 70% *plagioclase.* Plagioclase is among the most common minerals on Earth or Moon because its major elements (oxygen, silicon, aluminum, and calcium) are abundant, and because it forms at temperatures and pressures common in magmas. Many terrestrial plagioclases also contain considerable sodium instead of some of the calcium, but the plagioclase of the sodium-poor Moon is highly calcic. A rock composed of more than 90% calcic plagioclase is called *anorthosite.* A few of the lunar soil particles fit the definition of anorthosite, and others contain enough magnesium- and iron-bearing (mafic) minerals to be called *anorthositic gabbro.* The anorthosite shook up the analysts. It was the one rock that had not been predicted in the lunar crust until Surveyor investigator Shoemaker suggested anorthositic gabbro as a possible material at Tycho. Anorthosite is rare on Earth and in its massif form characterizes Earth's ancient (pre-Cambrian) terrains. What was it doing on the Moon? What was it doing in regolith developed on basalt?

The propensity of impacts to throw some ejecta long distances answered the second question. Tranquillity Base is only 41 km north of the nearest highlands and, as Maurice Grolier's mapping showed, lies near rays from the crater Theophilus, which straddles a contact between mare and terra 320 km south of the landing site. Apparently, Theophilus or another impact tossed a little terra material onto the mare. Meteoriticist-turned–lunar petrologist John Wood of the Smithsonian Astrophysical Observatory remembered that Shoemaker had predicted that about 4% of Apollo 11 soil should come from the highlands.[33] So why are the lunar terrae, at least in the Theophilus region, composed of anorthosite?

The element-by-element probing of lunar materials suggested an answer. Relative to europium, the terra plagioclase has less of the other rare earths than does the mare-basalt plagioclase. Plagioclase likes to take up europium if any is available in the melts from which it crystallizes. These "europium anomalies" suggested that the europium had been extracted from some common ancestral melt and taken up in the plagioclase before the parent material of the mare basalts segregated from the melt. So, the Moon's materials definitely had differentiated and had done it very early.

Much was left to learn about the Moon after January 1970. But the basic outline had been sketched: it is an ancient body consisting of differentiated, generally earthlike but totally waterless materials whose surface-shaping activity was concentrated in the first aeon of the Solar System's existence. The craters near Tranquillity Base, at least, were formed by impacts. The maria are basaltic lava flows, so at least parts of the Moon had once been hot. The lavas are covered with a locally derived, fragmental but firmly supportive regolith on the order of meters thick. There is not much meteoritic material in the soil. Dust does not migrate by electrostatic transport to form thick deposits. Tektites do not come from the Moon.

Bevan French has given us a dramatic perspective on the Moon's antiquity by following the history of one rock that the astronauts picked up from the regolith.[34] It formed from molten lava about 3.6 aeons ago, almost the age of the oldest known Earth rocks. An impact finally broke it off its parent bedrock and threw it out on the surface about 500 million years ago, not long after the first complex animals began to appear on Earth. It was nudged and flipped over a few more times by random meteorite impacts and finally came to rest 3 million years ago, about the same time that part of the primate line in Africa began to show humanoid qualities. Three million years later a remote descendant of that line "dressed in a spacesuit, landed on the Moon, picked up rock 10017, and brought it back to Earth."