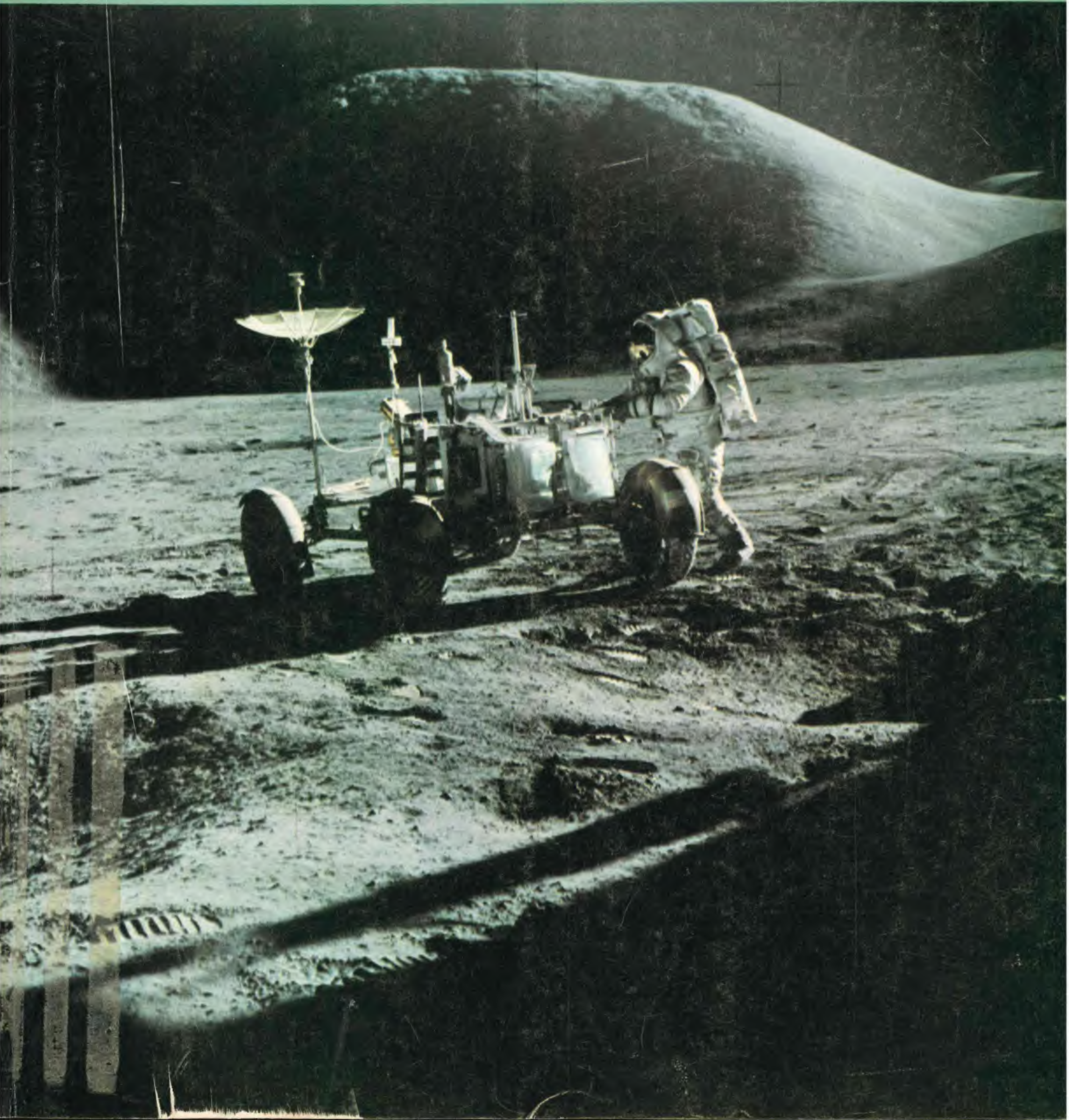
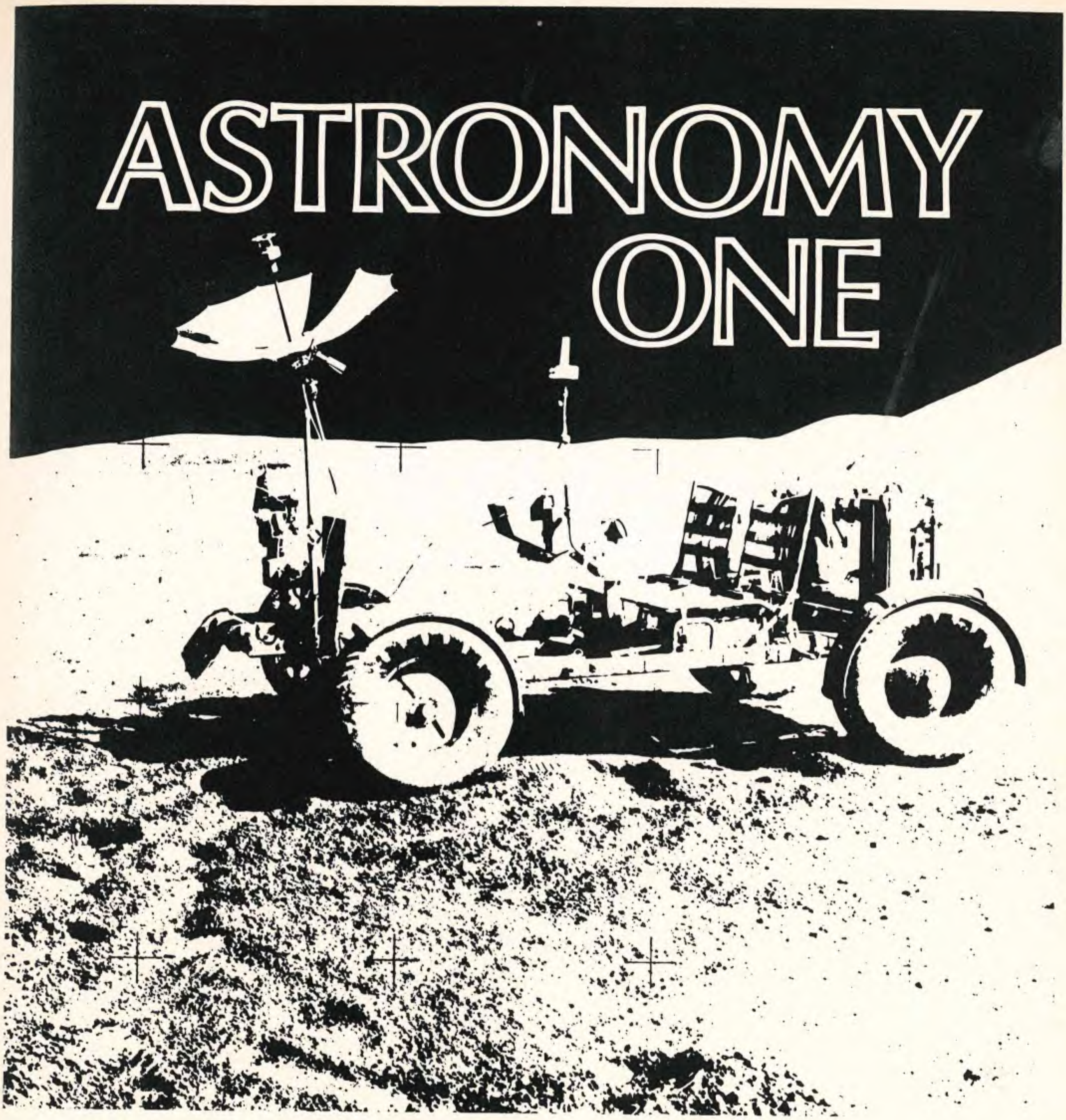
March-April 1972
Volume 60
Number 2

American Scientist




ASTRONOMY
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Joseph P. Allen

Apollo 15: Scientific Journey to Hadley-Apennine

The stunning beauty of the most recent lunar landing site is surpassed by the rich scientific harvest which it yielded

On July 30, 1971, the Apollo 15 lunar module *Falcon*, with commander D. R. Scott and lunar module pilot J. B. Irwin, descended along a steep trajectory over the 5,000 meter Apennine mountain front and landed just inside this towering range on the hummocky plain of Mare Imbrium some 800 km north of the lunar equator. The safe landing marked the beginning of the scientific phase of the most ambitious expedition yet undertaken to explore and systematically study the moon. Although the mission itself ended formally when the command module *Endeavour*, piloted by A. M. Worden, splashed into the Pacific eight days later, the scientific adventure continues unabated as the returned samples and photographs are examined, and as the data which continuously stream from the emplaced experiments on the moon and from the subsatellite now orbiting the moon are analyzed.

From the outset the objectives of the Apollo 15 mission were distinctly different from those of the three successful lunar-landing missions that preceded it. The reliability of the launch vehicles, the spacecraft, and the associated support systems, including earlier versions of the spacesuits to be used on the lunar surface, had been proved; and the capability of the mission teams and astronaut crews to achieve safe, pinpoint landings had been extensively tested in previous missions. Consequently, the course of Apollo 15 had been determined almost exclusively by the experimental goals the program scientists wished to attain. These scientific objectives dictated that Apollo 15 be different from its predecessors in four major ways: (1) the *Falcon* carried with it an electrically powered lunar roving vehicle (the Rover) which could increase the traverse distance of the crew up to ten times that possible by walking, (2) both spacecraft, *Falcon* and *Endeavour*, had the capability of remaining on and around the moon considerably longer than the spacecraft of previous missions because of the increased consumable supplies carried on board, (3) the command-service module carried with it a complement of special instruments—the scientific instrument module (the SIM bay)—designed to study the lunar surface from orbit, and (4), perhaps most important, the mission was targeted into a landing site chosen for its potential for new scientific results and insight.

Scientific objectives

The scientific objectives of the Apollo 15 mission to Hadley-Apennine can be divided into three distinct categories: (1) to carry out orbital measurements; (2) to deploy and activate a series of lunar surface experiments; and (3) to accomplish a comprehensive geological exploration of the complex Hadley Rille, the Apennine mountain front, and the mare surface accessible from the selected landing site.

The orbital experiments (Esenwein et al. 1971) carried in the SIM bay of the service module, shown in Figure 1, included two large cameras for comprehensive mapping of the sunlit surface, a mass spectrometer, a laser altimeter, a remote-sensing geochemical package containing X-ray, gamma-ray, and alpha-particle spectrometers, and a small subsatellite to be placed in lunar orbit just before the homeward journey began. The subsatellite housed an S-band transponder to allow accurate tracking of its orbit from earth and subsequent determination of the moon's mass distribution, a flux-gate magnetometer to study the induced and permanent magnetic fields of the moon, and a series of charged-particle detectors to map the plasma flux around the moon as it moves in and out of the earth's magnetosphere and magnetopause.

Space limitations preclude discussion of the design, the operation, and the specific objectives of the SIM bay instruments; suffice it to say that their basic objective was to provide synoptic mapping and geochemical data for the large areas of the moon seen from orbit 60 nautical miles above its surface. From these data it will be possible to deduce correspondingly large-scale characteristics of this planet. Detailed knowledge returned from the various Apollo landing sites gives us extremely important calibration points for the interpretation of these remotely made measurements.

The surface instruments emplaced upon and into the lunar surface included a magnetometer, a seismometer, a cold-cathode ion gage, a solar-wind spectrometer, a suprathermal-ion detector, a lunar-dust detector, a laser reflector, a solar-wind composition experiment, and a heat-flow experiment. Except for the heat-flow experiment, units similar to each of these instruments were already in operation at one, and in some cases at two, of the three previous landing sites. In fact, for the seismometer, cold-cathode ion gage, suprathermal ion detector, lunar-dust detector, and laser reflector, the Apollo 15 package of surface experiments provided the all-important third corner for a triangle of experimental stations operating on the moon, a fact that had been weighted heavily in the selection of the landing site so far from the lunar equator.

Joseph P. Allen, an astronaut at the Manned Spacecraft Center in Houston, Texas, obtained his undergraduate degree at DePauw University, in Greencastle, Indiana. After completing his doctoral studies at Yale University, he was a research associate in nuclear physics at the University of Washington, in Seattle. He was selected for astronaut training in 1967 and has since logged over 1,000 flying hours in jet aircraft. During the past two years he has served as a support crewmember for the Apollo 15 mission, working as the mission scientist, with responsibility as a liaison between the many Principal Investigators with experiments on the mission and the flight crew who would perform these experiments. He was the capsule communicator while many of the experiments were carried out on the lunar surface. Address: NASA-Manned Spacecraft Center, Houston, TX 77058.

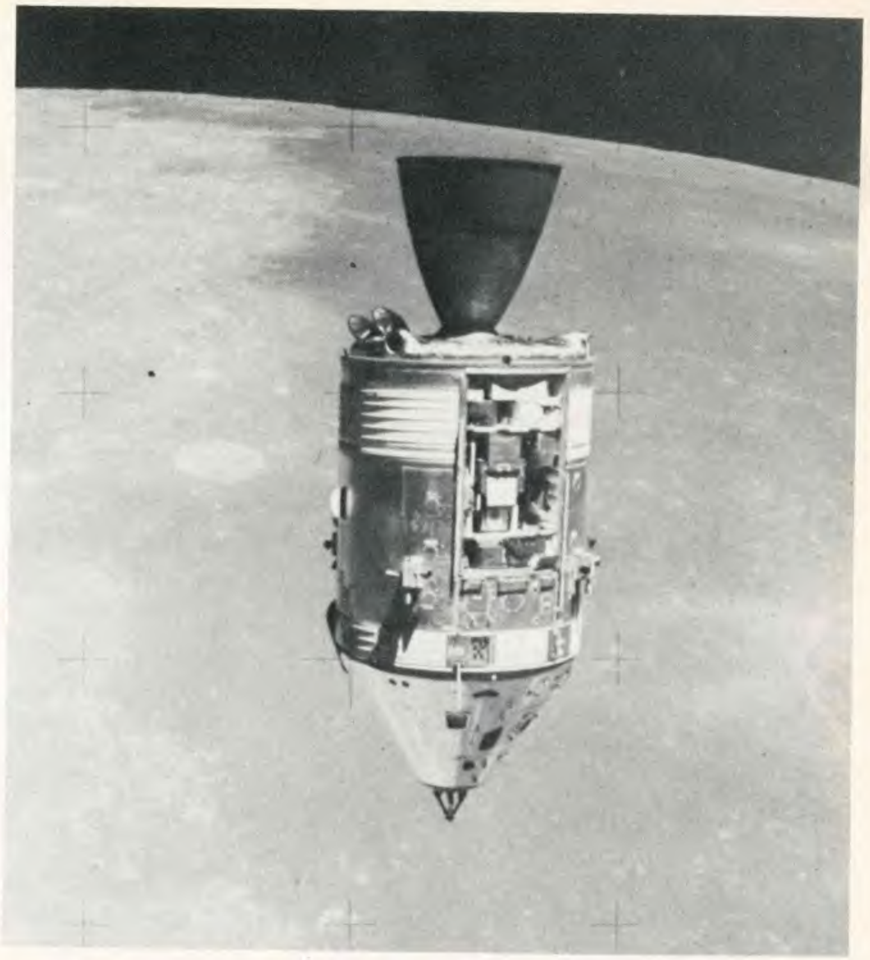

Figure 1. Photograph of the Apollo 15 command-service module *Endeavour* taken from the lunar module *Falcon* after their rendezvous in lunar orbit. The SIM-bay instruments, clearly visible here, are initially exposed when the protective panel of the service module is jettisoned just before the spacecraft are placed into lunar orbit. The docking probe is extended from the nose of the command module in preparation for the spacecraft docking, which will follow shortly.

The geologic investigation of the landing site was designed to collect data needed for a comprehensive understanding of the geological history of the Hadley-Apennine region, important in itself, but of further importance to the other surface experiments because much of their data must necessarily be interpreted within the framework provided by the regional geology. Earth-based photographs and lunar orbiter photographs available to the planning teams prior to the flight show the Apennine Mountains rising some 5 km above the mare surface which they partially encompass. As shown in Figures 2 and 3, these mountains, which form the southeastern boundary of Mare Imbrium, the largest and second-youngest circular basin on the moon, are thought to be large fault blocks uplifted as part of the system of concentric rings resulting from the Imbrium impact. These massive mountains are thus assumed to be composed of pre-Imbrian crustal rocks, perhaps mantled by ejecta from the impact event which produced the Imbrium basin (these ejecta were sampled by the Apollo 14 crew at the Fra Mauro site) and perhaps by ejecta from the older Serenitatis basin.

Hundreds of canyon-like formations, known as rilles, are found on the moon, many of them concentrated around the edges of the circular basins. They are particularly enigmatic features (Baldwin 1963). Although some meander like rivers and some show straight fault-like walls, in most cases their sheer size sets them apart from any possible terrestrial equivalents. Of these, Hadley Rille is thought to be one of the youngest and freshest sinuous rilles on the moon. It meanders from its probable source, an elongate depression south of the landing site, through the mare surface, and occasionally touches the mountain massifs.

The mare region between the rille and the mountains is a gently rolling, dark plain at the margin of Mare Imbrium. Lying on the mare plain just north of the landing site is a series of low, irregularly shaped hills (the North Complex) that may consist of ejecta from nearby large craters, or may be landforms of volcanic construction that occurred during the last stages of mare-basin filling. The secondary crater cluster located just south of the landing site lies on an ejecta ray that is traced back to either of the two Copernican-age craters Autolycus or Aristillus found in Mare Imbrium 150 and 240 km to the northwest, respectively.

The major objectives of the geological exploration were to visit, photograph, and sample as thoroughly as possible (in order of decreasing priority) the Apennine mountain front, Hadley Rille, the mare plain, the North Complex, and the secondary crater cluster. These objectives were recognized before the mission to be extremely ambitious, overly optimistic even; yet they were very nearly met during the three geology traverses of the mission in spite of several surprises encountered along the way.

It should be emphasized at this point that the complex task of flying a mission to the moon has evolved to where it can be viewed as comprising two major phases. The difficult, but nonetheless coldly predictable (and nearly perfect, we hope), phase of the journey itself is reflected in the precise trajectories of the spacecraft and in the exact timetables of the rocket burns, attitude changes, pyrotechnic detonations, etc., all of which are laid out in great detail prior to the mission. In contrast, the correspondingly unpredictable exploration phase of the mission starts when the traverses and the experiments themselves begin. In

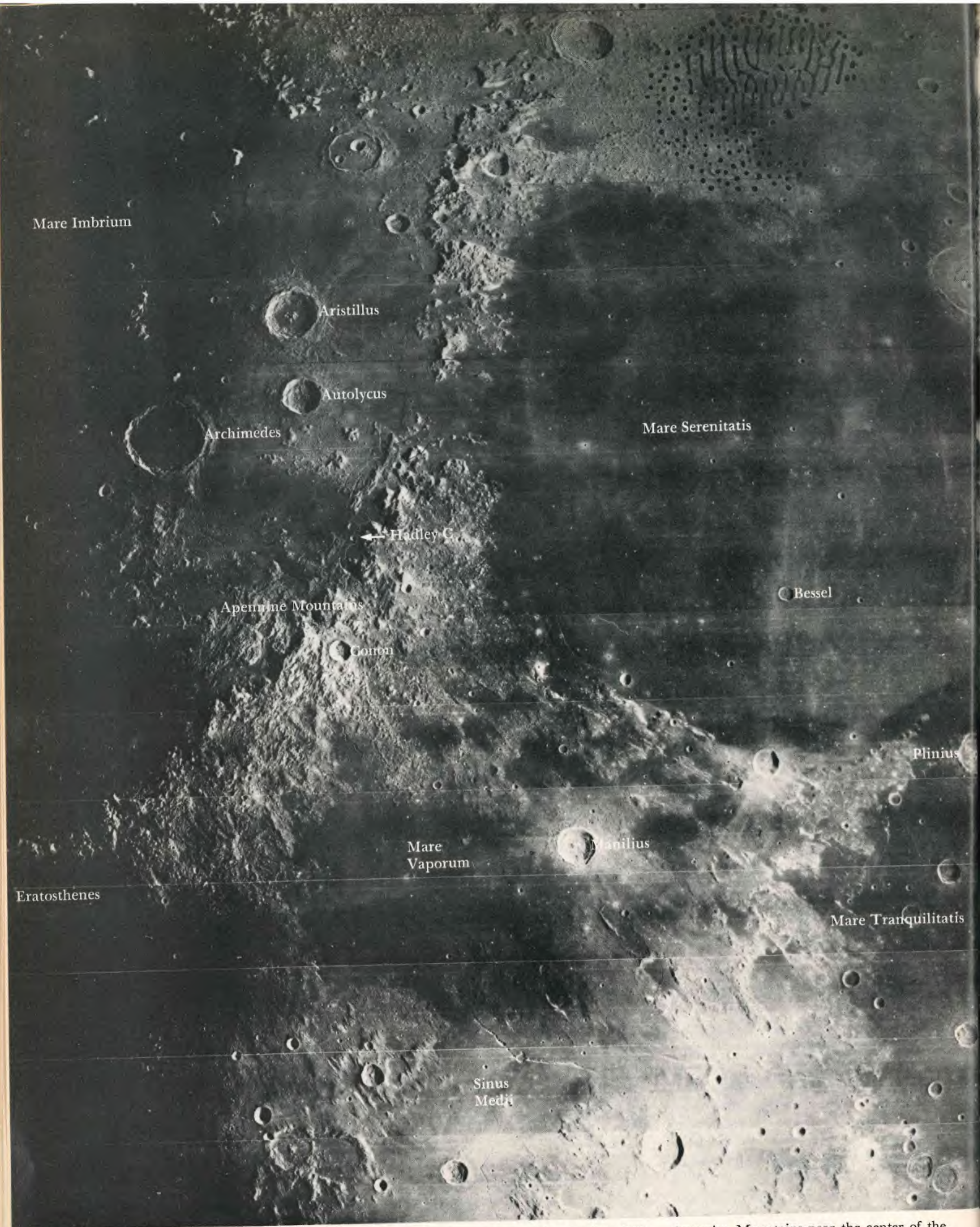

Figure 2. Lunar orbiter photograph of the major features comprising the north-central region of the moon's near side. Although tiny at this scale, Hadley Rille and the crater Hadley C can be seen in the Apennine Mountains near the center of the photograph.

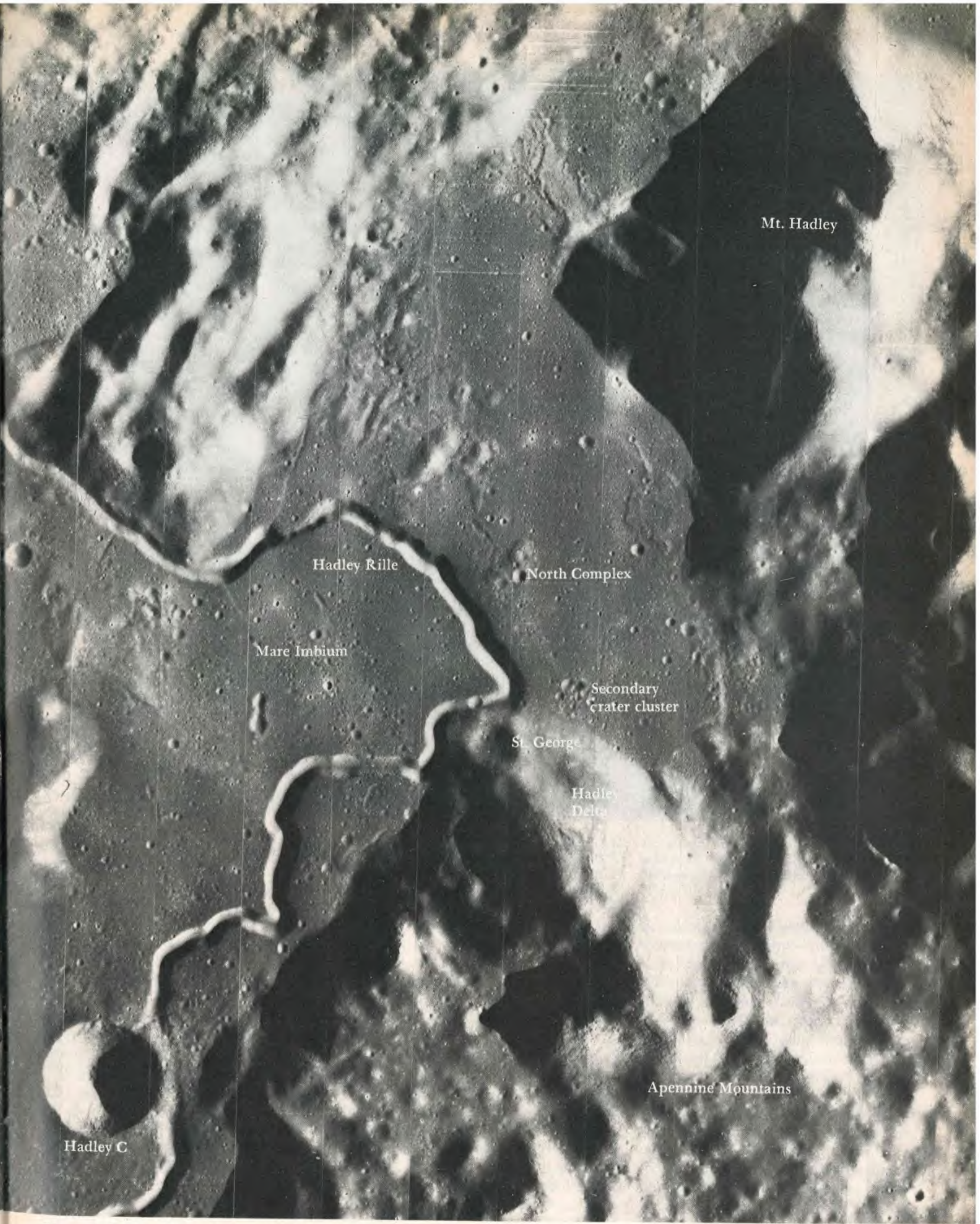

Figure 3. Lunar orbiter photograph of the regional features surrounding the Hadley-Apennine landing site.

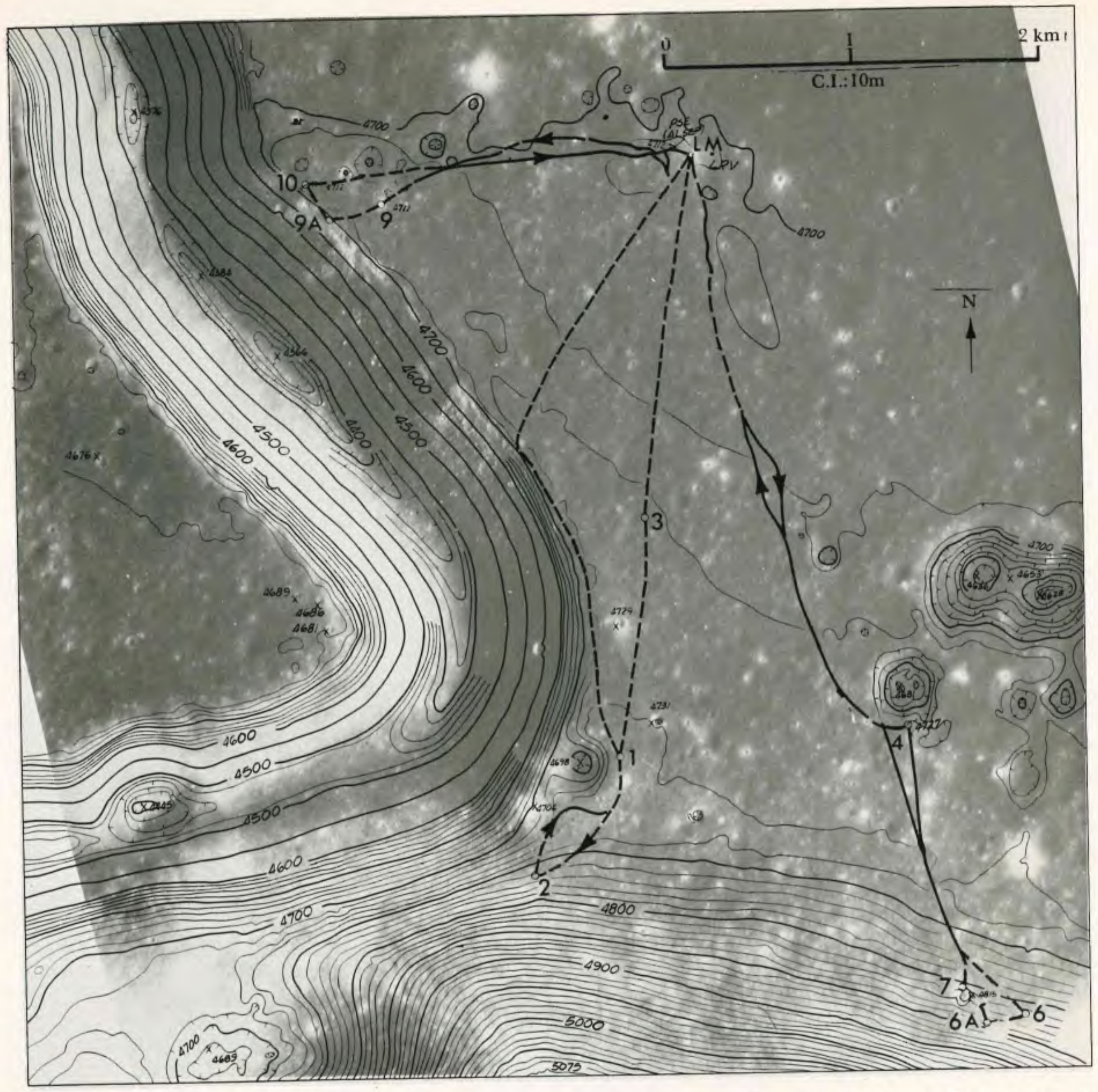

Figure 4. Photograph of the Apollo 15 landing site taken from orbit overhead. The routes followed during the three geology traverses are shown (from Swann et al. 1971), together with topographic lines given in meters above a reference plane. Traverse stop #1 is beside Elbow crater, #4 is beside Dune crater.

short, the journey through space is accurately predictable; the journey of exploration across the surface of a foreign planet is not. The basic mission philosophy for both phases is to plan for, and to be prepared for, whatever surprises may come. We hope not to encounter surprises during the space journey itself; but, indeed as with all scientific experiments, we anxiously await surprises during the traverses and the experimental activities, tempered of course with the hope that the unexpected will be properly recognized and can be accommodated suitably by the ingenuity and flexibility of the explorers and their ground-support team.

During the exploration phase of the mission, the scientific goals the new data suggest we should seek must always be prudently balanced with the many parameters that describe the capability of the crewmen and the equipment available to them. For instance, if during a traverse the geological observations being made indicate that the exploration should continue farther from the lunar module than had been originally planned, the team directing the traverse from Mission Control must answer a number of questions: for example, Is the increased travel time (which must ultimately be taken from experiments yet to be done) outweighed by the possibly higher scientific return from the more distant sampling location? More important, do the projected consumables-usage rates in the astronauts' portable life-support systems, coupled with the computed average speed the Rover has made so far and is expected to make across the surface ahead, and then combined with a postulated Rover failure at the most distant point, permit the crew to walk safely back to the lunar module before they or their life-support systems are exhausted?

Many more parameters than these are involved at each decision point during the actual lunar traverses; consequently, the efforts of scientists and systems experts must be carefully and effectively combined in Mission Control while the traverses, and the estimated scientific returns of the traverses, unfold on the moon. The final goal of the mission direction, of course, is to maximize the total scientific return from all the experiments being performed. Such direction is a difficult task at the very best, because much of the actual scientific return is not fully realizable until months, or even years, after the mission ends.

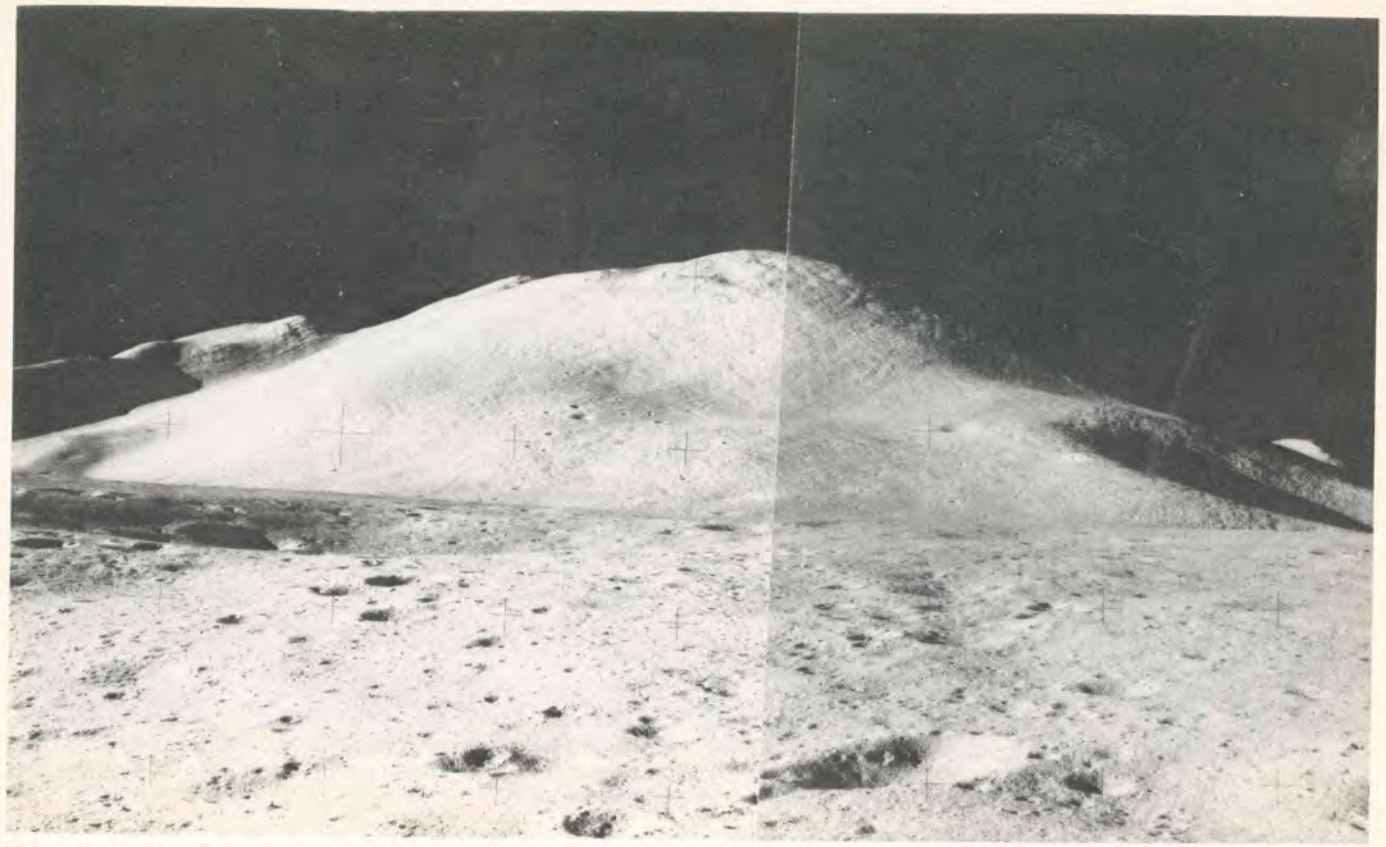

Figure 5. Hadley Delta with the features Silver Spur to the left and St. George crater to the right. This composite photograph was taken from the lunar module shortly after the successful landing. A mountain near the crater Hadley C, south of the landing site, is the bright peak above St. George crater. Note particularly the east-dipping lineations in Silver Spur and Hadley Delta.

In the case of Apollo 15, several major changes and hundreds of smaller modifications were made in the carefully pre-planned traverses as hardware problems (such as the difficulty in extracting the deep corestem from the lunar surface) were met, and as scientific surprises (such as the absence of obvious lateral variations in material along the Apennine front) were encountered. Likewise, during the two days in lunar orbit after ascent-stage lift-off, similar changes were made to the pre-mission plan for the utilization of the SIM bay experiments as initial data were analyzed and as the operating characteristics of the instruments became better understood.

Summary of surface geology

As stated above, the major scientific objectives of the Apollo 15 expedition were to carry out extensive geological exploration of the Apennine front, Hadley Rille, and the mare plain; to set up the lunar surface instruments near the landing site; and to perform the SIM bay experiments from lunar orbit. I have not mentioned a number of ancillary experiments and tests (medical experiments, for example); and, indeed, space does not permit even a brief discussion of initial results from all the major geological, surface, and orbital experiments that have been indicated here. Instead, I shall discuss initial results from just a few selected experiments and attempt to point out possible interpretations that the new data may suggest. Because many of the results are still preliminary, these interpretations may change as analyses continue.

The mobility provided by the lunar Rover permitted Scott and Irwin to explore an extensive area around Hadley Base. As shown in Figure 4, the crew was able to accomplish four of the major objectives established prior to the mission. During the three traverses they investigated the Apennine front along the mountain Hadley Delta, south of the landing site, Hadley Rille at locations west and southwest of the landing site, and the mare plain at various locations. From the stop at Dune crater information was also obtained about the secondary crater cluster. Finally, because of the unanticipated loss of time in recovering and stowing the deep corestem, the North Complex was not visited; even so, some information was collected by photographing, with a telescopic lens, the south-facing exposures of this intriguing feature.

An extensive geological description of the major features in the Hadley area has been constructed (Swann et al. 1971) from the data returned. In general, the Apennine Mountains show gentle-to-moderate slopes, with very subdued, rounded outlines, in sharp contrast to many of the fresh and rugged mountain ranges found on earth. Large blocks are scarce on the mountainsides, even near the few fresh craters, suggesting that most of the debris thrown out by the cratering process has been subsequently transported downhill, leaving only a thin debris cover on the upper slopes. Quite surprisingly, sets of stark, clearly etched, parallel linear patterns appear on most of the mountain faces, an observation totally unexpected before

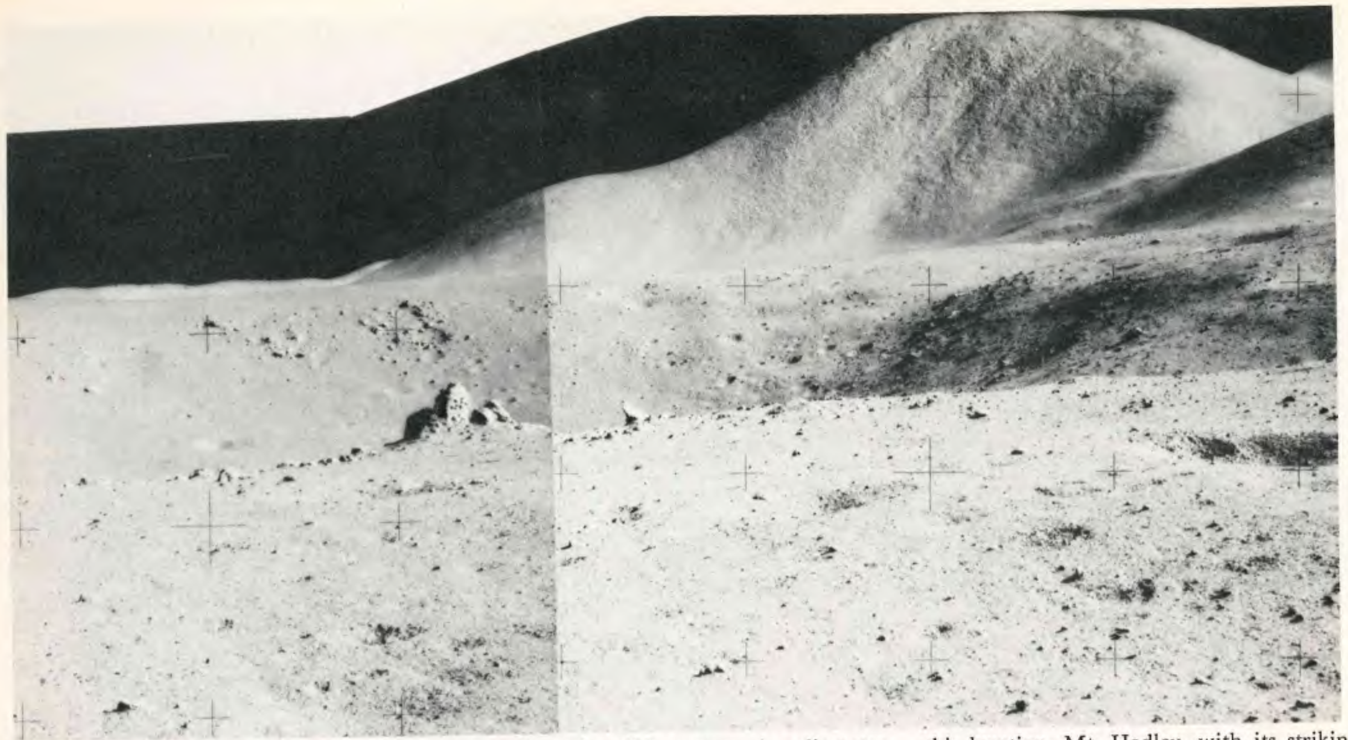

Figure 6. Composite photograph taken across Dune crater to the northeast during the second geology traverse. Dune crater is approximately 400 meters in diameter. The vesicular boulder on the edge of the crater marks the area that was sampled at this location. Mt. Hadley, with its striking linear patterns, dominates the skyline.

the mission. Typical examples of these features are shown in Figures 5 and 6. These major lineaments may represent the expressions of sets of compositional layers, or sets of regional fractures showing through the regolith cover of the slopes; or, in the cases of the very finely spaced lineaments, they may be an optical illusion caused by the unscattered sunlight falling at low angle on the randomly irregular surfaces of these slopes. Although an unequivocal interpretation of these striking patterns has not been possible in the initial analyses of all the photographs, it seems clear that some of the parallel patterns contain exciting clues to the processes which formed the premare lunar surface.

Hadley Rille, shown in Figure 7, was visited during the first and third traverses. Several massive outcrops of bedrock on the near side of the rille rim were sampled. They represent what are perhaps the first genuine bedrock samples returned from the moon, a particularly important identification if the fundamental stratigraphy of the local regolith is to be understood (Goles 1971). In addition, the exposed rille walls on both the near and the far sides were photographed in detail. The bedrock strata visible in these many photographs have thicknesses as great as 60 meters, are distinctly layered along the horizontal or near-horizontal, show evidence of columnar jointing, and exhibit varying surface textures and albedos. All these features are typical of individual lava flow units.

Thus, we now have clear evidence that the Hadley plain, and perhaps all mare plains, are underlain by a series of lava flows similar to those found in many lava fields here on earth. An unequivocal explanation of the origin of the rille itself is not so easily made. However, initial studies (Howard et al. 1971) of the depth-to-width ratios derived from the Apollo 15 surface and orbital photography of this mysterious feature give tentative support to the theory that it may be the result of incomplete collapse of a buried lava tube of a size that is enormous by terrestrial standards.

The dark plain of the mare surface is generally smooth to gently undulating, heavily cratered, and hummocky. Except for the rougher ejecta blankets around the numerous craters, rocks cover only some one percent of the surface. (This fact, determined only after the landing, was crucial to the planned traverse distances, because the average driving speed attainable by the Rover is critically dependent on surface roughness.) Initial study of the photographs of the landing site indicates a probable subdivision of the mare into four geological units characterized by differences in crater populations and surface textures. The morphology of the craters in the mare suggests its age to be late Imbrian to early Eratosthenian (Mutch 1970), and the specific sampling sites visited by the crew span this age range. For example, a particular 15 meter-diameter crater with a widespread glassy ejecta blanket probably represents the youngest surface feature yet sampled on the moon. Age dating of these samples is awaited with high anticipation.

A total of 77 kg of lunar samples was returned by the Apollo 15 crew. These samples comprise rocks that weigh from 1 g to 9.5 kg (the largest sample was scooped up by Scott near the rille rim and is now called the "Great Scott Rock," much to his consternation), three core tubes, a deep corestem, and a variety of soil samples taken from numerous sampling locations including the hillside of Hadley Delta, the rim of Hadley Rille, and across the mare plain. In general, the samples reveal (Lunar Sample Preliminary Examination Team 1971) the immense variety of materials that were accurately recognized and described by Scott and Irwin while they selected the materials. In spite of the awkward sampling procedures made necessary by the bulky spacesuits, the astronauts located, described, documented, and returned samples representative of the area, including anorthosite; vesicular basalts with phenocrysts of plagioclase, pyroxene, and olivine; complex breccias with an assortment of well-defined clasts; rocks in various stages of shock metamorphism; rounded and angular glass fragments; soils of different textures and granularities; and samples displaying color differences, hints of surface coatings on fractures, slickensides, glass coatings, and a variety of fracture patterns.

Figure 7. A view to the north along Hadley Rille, taken by Irwin during the first geology traverse. Scott is unloading equipment from the Rover, parked south of Elbow crater.

Even a brief summary of the some 350 individual rock samples is clearly beyond the scope of this article. However, a twofold classification of the returned materials shows a simple relationship between the major rock types and the major geological units. Many of the samples from the mare are basalts roughly similar in composition to the basalts returned from the Apollo 11 (Mason et al. 1970), the Apollo 12, and the Luna 16 mare sites. In particular, these basalts are high in iron, with a correspondingly high iron-to-magnesium ratio, and low in sodium, in notable contrast to typical terrestrial basalts. On the other hand, the majority of samples from the Hadley-Apennine mountain front are breccias that contain clasts of basalts, but basalts which are distinctly different in both appearance and chemical content from the mare basalts. Specifically, these basalt clasts are considerably richer (by up to a factor of 2) in aluminum than the typical mare-type basalt. The possibility of finding aluminum-rich material in the lunar highlands had been pointed out (Wood et al. 1970) prior to the Apollo 15 landing, but it was generally felt that this material would be in the form of anorthosite, a rock of high aluminum content.

Scott and Irwin did indeed return a beautiful specimen of anorthosite (the 269-gram sample #15415, also dubbed the "Genesis Rock"), but we now suspect that this sample is not characteristic of the material from the upper sections of the Apennine Mountains around Hadley; rather it is probably an interloper thrown from some distance onto the mountain slope by some traumatic event in its history. In any case, the discovery of an aluminum-rich igneous rock as an abundant constituent of lunar highlands raises a perplexing question. Why do the highland rocks, formed perhaps around $4^1/_2$ billion years ago, differ in make-up so strongly from the mare rocks, formed around $3^1/_2$ billion years ago? Obviously these two types of igneous rock, so fundamental to the moon, were derived from very different magma sources. Could the moon have accreted in inhomogeneous zones that were never thoroughly mixed?

The soils returned from Hadley Base are similar in most respects to soil samples returned from previous missions (Wood 1970) except for a peculiar component in these samples of green glass spheres never before reported in lunar soils. Interestingly enough, the chemical composition of the soil samples, particularly from the mare regions, is distinctly different from the composition of the rocks from the same locales. However, a linear correlation involving the iron and the aluminum constituents of the soils suggests very convincingly that lunar soils may be derived from a range of rock materials, with the two end-members of this range being the iron-rich basalt so typical of the mare and the aluminum-rich basalt found so abundantly at the Apennine front.

A total of 4.6 kg of material was returned from the Hadley site in the form of core samples. Three of the core tubes were hammered into the lunar surface during the traverses. Initial X-radiographs of the lunar material within these core tubes reveal distinct layering delineated by discontinuities in the spectrum of soil textures, fragment sizes, and material densities. The fourth core was drilled 2.4 meters into the surface with the percussive drill that was also used to

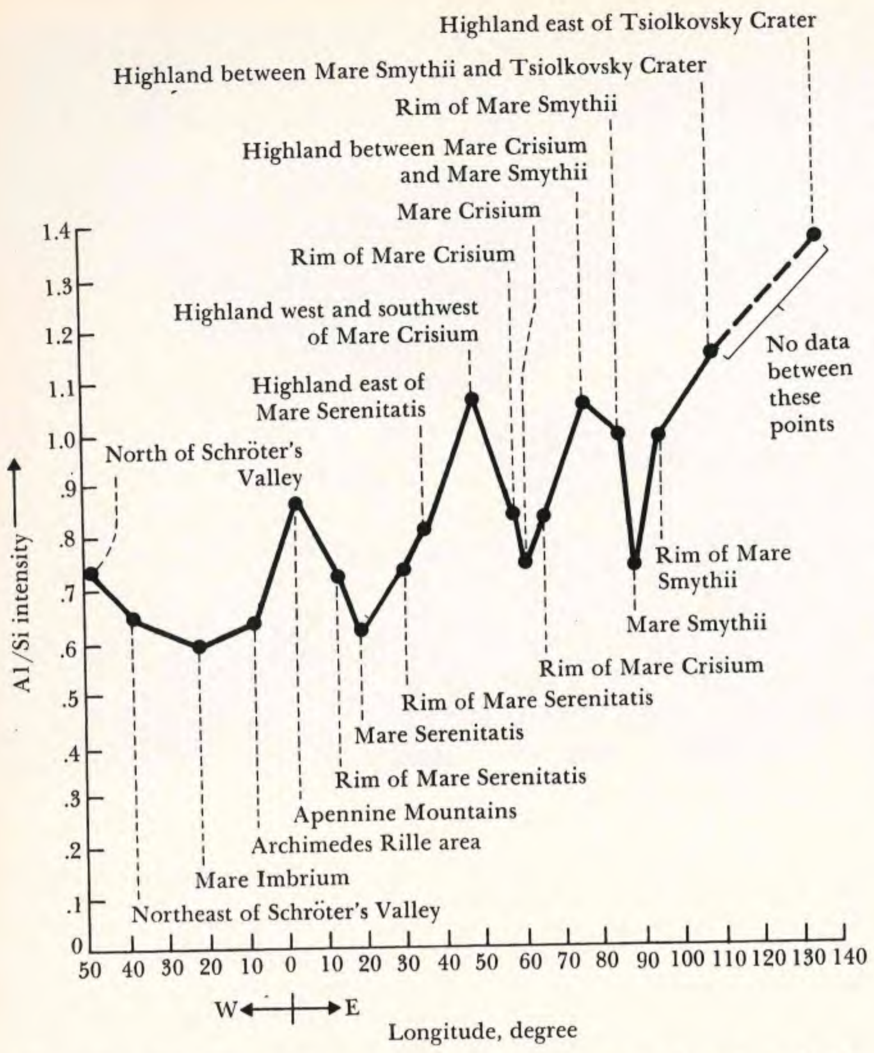

Figure 8. Plot of Al/Si intensity ratios along a northerly ground track (from Adler et al. 1971), derived from data from the X-ray spectrometer experiment.

emplace the heat-flow probes. The upper layers of the surface regolith were far more resistant to this drilling operation than had been anticipated before the mission. The resulting mechanical problems with the drilling, the extraction, and the subsequent separation of the sections of this deep corestem into lengths which would fit into the spacecraft were among the most exhausting faced by the crew during their surface operations.

These problems also posed difficult questions, requiring immediate answers, to the science team guiding the surface activities from Mission Control. In spite of the difficulties, the deep corestem was ultimately recovered and returned; and the X-radiographs of it show more than 50 individual layers with thicknesses from 0.5 to 21 cm, a truly remarkable stratigraphic record. In fact, the episodes represented by these layers may be a significant fraction of the post-volcanic history of Mare Imbrium.

A study of the layers should provide valuable insight into the only erosional process of apparent current importance on the moon, that of micrometeorite "gardening." Additionally, a study of the various isotopes within these strata could provide a history of solar activity that stretches back hundreds of millions of years into the past. The potentially rich scientific return from this corestem is gratifying in view of the agonizing moments spent by the mission team and the astronaut crew in deciding to give up a portion of the third geology traverse in favor of a last attempt to recover the corestem, even when it seemed at the time to be irretrievably stuck in the lunar surface.

Relative concentrations of noble-gas isotopes measured in the samples from Hadley Base are similar to the abundances and abundance ratios previously found in lunar materials. Amounts of the spallation-produced isotopes, resulting from cosmic-ray bombardment, such as neon-21, krypton-80, and xenon-126, can be used to calculate exposure ages (not to be confused with crystallization ages) of the rocks. The measured exposure ages lie in the range of 50×10^6 to 500×10^6 years. Thus some of the samples picked up at Hadley Base had been lying on the surface, more or less undisturbed, since the beginning of the Cambrian period on earth.

Summary of surface experiments

The purpose of the seismic experiment (Latham et al. 1971b) is to study the lunar-surface vibrations, from which interpretations of the internal structure and the physical state of the moon can be determined. Sources of seismic energy may be internal (from moonquakes) or external (from impacts of either meteoroids or spent space hardware). Regardless of whether the source is internal or external, a straightforward determination of source location requires at least three instruments, suitably spaced, monitoring the event of interest. The Apollo 15 seismometer station represents the third in the network of seismometers now operating on the lunar surface; thus the deployment of this unit marked a vitally important step in the investigation of this unique planet.

It was well established from earlier data that seismic energy deposited at the surface by an impacting object is confined by efficient surface scattering for a surprisingly long time within a shallow surface layer. Nevertheless, the energy slowly dissipates through interior propagation to more distant parts of the moon, and probably all but the smallest of impact signals from all parts of the moon are detected at the operating stations. As expected, the impact of the third stage of the Apollo 15 launch vehicle was recorded by both the Apollo 12 and Apollo 14 seismometers, and the much smaller impact of the abandoned ascent stage of *Falcon* was recorded by all three instruments. The seismic refractions from these two impacts provided the first clear-cut evidence for pronounced sound-velocity differences in the lunar subsurface, suggesting the presence of a lunar crust and mantle analogous to what is found on earth.

The thickness of the lunar crust is between 25 and 70 kilometers in the region of the Apollo 12 and 14 landing sites, and the velocity of the compressional waves in this crustal material is between 6.0 and 7.5 km/sec, which is a range that spans the velocities expected for the rocks found on the lunar surface. The transition from the crustal material to the mantle material may be gradual, starting at about 25 km depth, or rapid, with a sharp discontinuity at a depth near 70 km. In either case, the compressional-wave velocity reaches about 9 km/sec in the mantle material, and the contrast in elastic properties of the materials making up these two major layers is at least as great as the contrast that exists between the rocks which make up the crust and mantle of the earth.

The major part of the natural lunar seismic energy detected by the network is in the form of periodic moonquakes that occur near times of perigee and that originate from ten or more separate locations. However, a single source located approximately 600 km south-southwest of the Apollo 12 and 14 sites, at a depth of approximately 800 km, accounts for 80 percent of the seismic energy detected. From the nearly identical signature of the events originating at this focal zone, it is concluded (Latham et al. 1971b) that the source region is confined to just a few kilometers in extent. Furthermore, the release of seismic energy from this great depth (slightly greater than for any known earthquake sources) indicates that the lunar interior, almost halfway to the center of the planet, must still be rigid enough to support appreciable stress. This fact places strong constraints on thermal models of the moon.

Besides the periodic moonquakes, episodes of frequent small moonquakes (Latham et al. 1971a) have been discovered. Individual events may occur as frequently as every two hours for periods lasting up to several days. The source of the moonquake swarms is at present unknown, but they may result from continuing minor adjustments to stresses in the outer shell of the moon. Even with the periodic moonquakes and the moonquake swarms, the average rate of seismic energy released within the moon is still far below that of the earth; it follows that the outer crust and mantle of the moon must be relatively cold and stable as compared to the crust and mantle of the earth.

The Apollo 15 magnetometer (Dyal et al. 1971) was deployed to study intrinsic remanent magnetic fields at the lunar surface and to observe the global response of the moon to large-scale magnetic fields imposed upon it. Such fundamental properties of the lunar interior as electrical conductivity, magnetic permeability, and internal temperatures can be derived from these magnetic measurements. The three flux-gate sensors of the Apollo 15 instrument show a steady magnetic field of approximately 5 γ ($1\ \gamma = 10^{-5}$ gauss) at the Hadley site, which is considerably smaller than the 38γ field measured at the Apollo 12 site, and the 50-to-100γ fields measured at the Apollo 14 site. Far more surprising, however, is the fact that the majority of the samples returned from all the sites show remanent magnetic fields so large that they must have formed in the presence of magnetic fields several orders of magnitude greater than we now measure at the surface. What was the original source of this magnetism—the earth in close proximity to the moon, or the interior of the moon itself?

The response of the moon to the externally imposed variable magnetic fields of the sun and the earth yields data that can be interpreted in terms of a spherically symmetric, three-layer model of the moon with a thin outer crust (of approximately 80 km thickness) of temperature about 440°K, an intermediate layer of temperature about 800°K, and an inner core (of approximately 1,000 km radius) of temperature around 1,100°K, where one assumes that the chief constituent of the interior is olivine, a mineral of possible abundance within this planet.

The third and largest U. S. retroreflector for laser ranging from earth (Faller et al. 1971) was deployed at the Hadley site during the first traverse and now provides the crucial north-south baseline separation with the Apollo 11 and the Apollo 14 reflectors. Successful range measurements to this 300-corner-cube array were made shortly after the *Falcon* lifted off several days later. The better signal-to-noise ratio available with this larger reflector enables more frequent ranging measurements to be made, and it will enable measurements to be carried out by telescopes of smaller aperture than heretofore possible. It is encouraging to note that none of the reflectors on the lunar surface seem to be suffering any deterioration of their optical properties as they are exposed to the space environment. This durability is important since ranging measurements to these benchmarks in space over many years will be required to accumulate the data for the planned astronomical, geophysical, and general-relativity investigations.

Emplacement of the first heat-flow experiment (Langseth et al. 1971) into the lunar surface was begun during the first surface extravehicular activity period and, because of difficulties encountered with the emplacement operation, was finally finished at the end of the second extravehicular activity. The drilling of the 3-meter-deep holes into which to drop the two slender temperature-sensing probes proved to be far more demanding than had been anticipated. In spite of the problems encountered, one of the two probes is now placed at about 1.5 meters and the other at about 1.0 meters into the lunar soil, and the subsequent measurements of the temperature gradients and the thermal conductivity of the lunar regolith have provided a remarkably accurate value of the heat flux from the interior of the moon.

The heat loss of a planet is, of course, related directly to its rate of internal heat production and to its internal temperature profile; hence, a heat-flow measurement gives information about the abundances of long-lived radioisotopes within a planet and, in turn, leads to an increased understanding of its thermal evolution. In the case of the moon, we now know that the lowest temperature anywhere within it exists just 70 cm below the surface because of the impressive insulating properties of the upper few centimeters of soil. The temperature increases from this depth at the rate of 1.75 ± 2% °K/m, and the thermal conductivity of the regolith increases with depth as well. These results yield a heat flow from below Hadley Base of $3.3 \times 10^{-6} \pm 15\%$ watts/cm^2, a value very close to one-half the average heat flow from the planet earth. The most fashionable models of the moon to date predict a heat-flow value at least a factor of two below what is now being measured. Consequently, this surprising number, if it is representative of the whole moon and not just a local anomaly, implies a radioactive content for the moon considerably higher than previously assumed and, more important, considerably higher than the radioactive content usually accepted for earth.

In spite of the severe demands placed on the crew in the final minutes of the last traverse period, a quick demonstration experiment was conducted just before they left the lunar surface. Making good use of the superb vacuum and the weak gravity unique to the lunar environment, Scott released simultaneously, from shoulder height, a suitably heavy object (a metal geology hammer) and a suitably light object (the tail feather of a falcon, donated out of molting season under strong objection) while in clear view of the TV camera. These two objects were observed to undergo the same acceleration and to strike the lunar surface simultaneously, a result which has been verified in the instant-replay TV tapes to within the accuracy of the simultaneous release of the objects. The result had been long predicted by well-established theory, but it was nonetheless gratifying, considering the number of viewers that witnessed the experiment, and particularly reassuring, considering the fact that the homeward journey was based critically on the validity of the gravitational principle being demonstrated.

Summary of orbital experiments

The purpose of the X-ray experiment (Adler et al. 1971) carried in the SIM bay was to map the elemental constituents (specifically aluminum, silicon, and magnesium) of the upper layer of the lunar surface by measuring the fluorescent X rays produced by the interaction of incident solar X rays with the lunar surface material. Starting with the first hours of data return, this experiment has given very exciting information. In general, the long-suspected major compositional differences between the two fundamental lunar features, the maria and the highlands, are confirmed; and more subtle compositional differences within both the maria and the highlands are strongly indicated.

For example, as shown in Figure 8, the aluminum-to-silicon intensity ratio is highest over the highlands, lowest over the maria, and, as would be expected, intermediate over the boundary regions between these major units of the moon. The extremes for this ratio vary from about 0.6 to 1.4, with a tendency for the value to increase from the western mare to the highlands of the eastern limb. Furthermore, a striking correlation exists between the aluminum-to-silicon intensity ratio and the values of surface albedo along the ground track surveyed by the X-ray experiment. In essence, the data confirm the idea that the maria and the highlands are indeed chemically different. The distinguishing albedo differences between these major lunar features, easily seen from earth by anyone who has examined the face of the "man in the moon," must be, in part at least, the signature of this chemical difference.

The high aluminum component of the samples returned from the Hadley-Apennine front is certainly related to the high aluminum content measured across all the highland regions, and the correspondingly low aluminum content of the mare basalts returned from all the mare sites is consistent with the low aluminum values measured across all the mare regions. It is interesting to note that the sharp change in the aluminum-to-silicon ratio between the highland and the mare areas places stringent limitations on the amount of horizontal displacement the highland materials could have undergone after the aluminum-poor lavas flooded into the enormous mare basins. This strongly rules out certain theories which invoke large-scale horizontal transportation mechanisms to explain mare filling. Finally, the X-ray data support very convincingly the theory that the moon developed a well-differentiated, aluminum-rich crust shortly after its formation.

The gamma-ray spectrometer (Arnold et al. 1971) was designed to measure from lunar orbit the gamma-ray activity of the lunar-surface materials over which the spacecraft flies. It is well known that the near-surface abundance of naturally occurring radionuclides is a sensitive function of the degree of chemical differentiation undergone by the moon, and thus their measured abundances relate directly to the origin and evolution of this planet. The gamma-ray data show notable regional differences in the amounts of radioactive elements across the surface of the moon. Specifically, the typical mare regions have a higher radioactive level than the average highland regions; and, although there seems to be a wide range of radionuclide content across the highlands, the average highland radioactivity content is considerably lower than that inferred from the few samples returned on previous missions, which were thought to have originated in highland areas. This is particularly true in the case of the Apollo 14 samples. Their high radioactivity, with respect to the level that seems best to represent highland material in general, throws open to question the interpretation of these samples as ancient highland rocks that were excavated and thrown onto the Fra Mauro site by the Imbrium impact.

Local mass concentrations (Sjogren et al. 1971) and local magnetic field anomalies (Coleman et al. 1971) are being systematically mapped by the small subsatellite that was launched from the orbiting command-service module just before the homeward journey began. The strongest of the measured magnetic anomalies, which are thought to be due to the remanent magnetization of surface rocks, ironically is found over the crater Van de Graaff, suggesting to electrostatic accelerator physicists at least that other electromagnetic anomalies should be found over the large craters Gauss and Weber!

Systematic study of the more than 10,000 photographs returned from the landing site and taken from lunar orbit by the high-resolution cameras has only just begun. About 12 percent of the lunar surface is covered by this photography. An enlarged frame of the Hadley Base area is shown in Figure 9 to illustrate the detail available for examination in these photographs.

Conclusions

It is certainly premature to offer, at this stage, any far-reaching theories for the origin, evolution, and present condition of the moon, much less to indicate major revisions required in these theories based on the newly returned Apollo 15 data. Nevertheless, over the past few years an enormous increase in our understanding of this fascinating planet has occurred (for an excellent review of current lunar knowledge and theories, see Hinners 1971). Data collected from the detailed analyses of lunar samples returned by all the Apollo missions (and by the Luna 16 mission), data taken from the Apollo-emplaced science stations operating on the lunar surface, and data received from the unmanned spacecraft placed on and into orbit

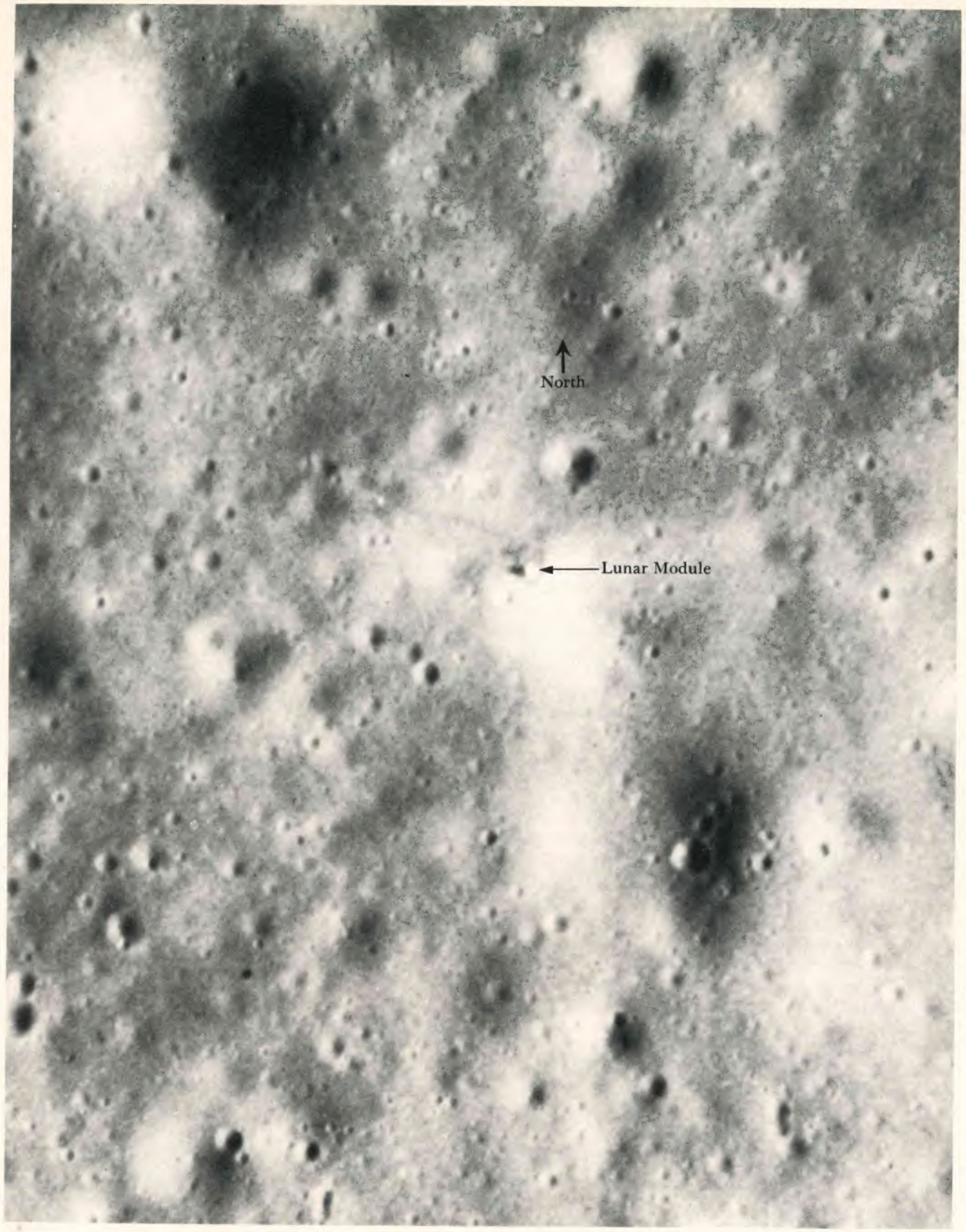

Figure 9. Enlargement (28 times) of the Apollo 15 landing site. The photograph was taken by the high-resolution SIM-bay camera from 87 nautical miles (slant range) between the second and third geology traverses. The arrow indicates the lunar module sitting on the surface. The light-colored area southeast of *Falcon* is thought to be a surface pattern left by the blast of the descent engine. The slightly darker key-shaped pattern running west of the lunar module consists of Rover tracks and footprints made as the surface experiments were deployed.

around the moon, when coupled with the framework built earlier from earth-based observations, give us a set of fundamental facts about our only natural satellite.

We now know that the moon was formed about 4.6 billion years ago during the beginning of the solar system. It is a heterogeneous planet, as reflected both in the wide spectrum of materials it comprises and in the enormous variety of landforms it exhibits. Furthermore, we have a general idea of the fundamental chapters that make up its early history, including its accretion, the formation of its initial crust showing pronounced chemical differentiation, the construction of its vast circular basins by massive impact events, the volcanic flooding of these basins to form the maria, and the subsequent modification of its surface by continued volcanic activity and impact events.

The moon harbors no life and apparently none of the complex organic molecules that serve as the building blocks of the forms of life familiar to us. The rocks we find on the surface of the moon are of igneous origin. Perhaps more important, they are extremely old, with the oldest going back to the very first days in the birth of the moon and with the youngest corresponding in age (as sheer good fortune would have it) to some of the oldest rocks found on the surface of the earth; thus, an essentially unbroken record of the history of the solar system has been left within the materials of these two planets together. The birth and early adolescence of the solar system is written in the lunar samples; the late adolescence and adulthood of the solar system is written in the terrestrial and the lunar samples. How completely we will be able to decipher this record remains to be seen. In any case, the knowledge that the record exists, and the hope that much of it can be unraveled, provides an intriguing challenge to the ingenuity of man.

The moon is only the second planet that man has been able to study in situ and later at great lengths in earthbound laboratories. This is an obvious, yet vitally important, fact because, just as a nuclear physicist studies the widest possible spectrum of nuclear isotopes in order to understand any one particular nucleus more clearly, so must a planetologist study in detail as many examples of planets as possible in order to understand the planet earth more clearly.

In these days when environmental science has finally found a new and much needed relevance, it is becoming increasingly obvious that nothing will contribute more to the continued life of man on earth, and to the continued quality of this life, than a comprehensive understanding of the vulnerable planet on which he lives. Our study of the primitive moon, in relation to the complex earth, is contributing significantly to this comprehensive understanding. Ironically, despite this, there is no doubt that the initial sense of excitement and adventure involved in the space journey to the moon has diminished greatly in many quarters. (See Mendelssohn 1971, for an interesting discussion of another major national effort with a far less obvious final goal.)

Nevertheless, the scientific adventure of these missions continues to increase markedly as the present surface explorations unfold, and as the resulting samples and returning data are received and studied on earth. The study of the moon is a great adventure in thought. A comprehensive understanding of the origin and evolution of the earth's only natural companion in space will be a milestone in the history of man. It is particularly satisfying to realize that the scientific contributions of the Apollo 15 expedition have provided an enormous quantum jump in the information available to this continuing adventure.

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