Two service propulsion system firings were required for rendezvous. The first firing, a corrective combination maneuver, was necessary to achieve the proper phase and altitude offset so that the second firing would result in an orbit coelliptic with that of the S-IVB. The two firings achieved the desired conditions for rendezvous terminal phase initiation. The terminal phase initiation maneuver was performed with an onboard computer solution based on optical tracking of the S-IVB stage with the sextant. A small midcourse correction was then made, followed by braking and final closure to within 70 feet of the S-IVB. Stationkeeping was performed for approximately 20 minutes, after which a 2-foot-per-second service module reaction control system posigrade maneuver removed the spacecraft from the vicinity of the S-IVB stage. The next 24-hour period was devoted to a sextant calibration test, a rendezvous navigation test, an attitude control test, and a primary evaporator test. The crew used the sextant to track the S-IVB visually to distances of as much as 320 miles.

The service propulsion system was fired six additional times during the mission. The third firing was a 9.1-second maneuver controlled by the stabilization and control system. The maneuver was performed to increase the backup deorbit capability of the service module reaction control system. The fourth firing was performed to evaluate the minimum-impulse capability of the service propulsion engine. The fifth firing was performed to position the spacecraft for an optimum deorbit maneuver at the end of the planned orbital phase. To assure verification of the propellant gaging system, the firing duration was increased from that planned originally. The 67.6-second maneuver produced the largest velocity change during the mission, 1693 feet per second, and incorporated a manual thrust-vector-control takeover approximately halfway through the maneuver. The sixth maneuver, performed during the eighth mission day, was a second minimum-impulse maneuver. The seventh firing, performed on the 10th mission day, placed the spacecraft perigee at the proper longitude for entry and recovery. The eighth firing was performed to deorbit the spacecraft.

Tests performed during the mission included a rendezvous radar transponder test and a test to determine whether the environmental control system radiator had degraded. The radar test was performed during revolution 48, and lockon was accomplished by a radar site at the White Sands Missile Range at a range of 415 miles. The radiator test was also successfully conducted, and operation of the system was validated for lunar flight.

The final day of the mission was devoted primarily to preparations for the deorbit maneuver, which was performed at 259:39:16. The service module was jettisoned, and the entry was performed using both the automatic and manual guidance modes.

The parachute system effected a soft landing in the Atlantic Ocean near the recovery ship, U.S.S. *Essex*. On landing, the spacecraft assumed a stable II flotation attitude, but was successfully returned to the normal flotation position by the inflatable bag uprighting system. The crew was retrieved by helicopter, and the spacecraft was later taken aboard the recovery ship. Mission duration was 260 hours 9 minutes 3 seconds.

All spacecraft systems operated satisfactorily, and all but one of the detailed test objectives were met. Additional information is given in reference 2-11.

2.4.3 Apollo 8 Mission

Apollo 8, the first flight to take men to the vicinity of the moon, was a bold step forward in the development of a lunar landing capability. Also, Apollo 8 was the first manned mission to be launched with the three-stage Saturn V vehicle. Figure 2-12 shows the vehicle being transported to the launch pad. The crewmen were Frank Borman, Commander; James A. Lovell, Jr., Command Module Pilot; and William A. Anders, Lunar Module Pilot. The mission, originally planned as an earth orbital flight, was changed to a lunar orbital flight after an evaluation of all aspects of the progress of the program. To accommodate this change, crew training and ground support preparations were accelerated.

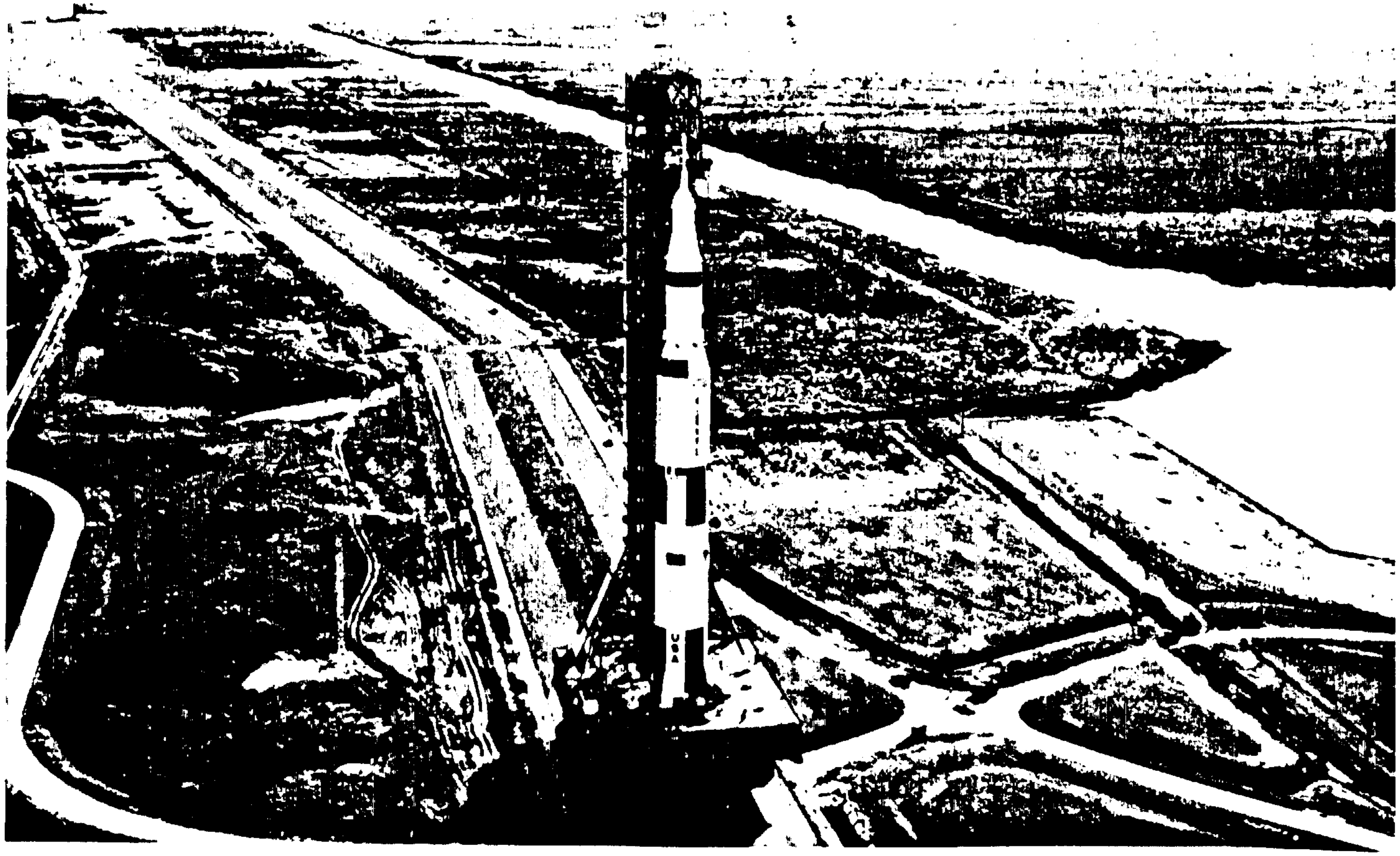

Figure 2-12.- Space vehicle for Apollo 8 mission being transported to Launch Complex 39A.

The primary objectives for the Apollo 8 mission were to demonstrate the combined performance of the crew, space vehicle, and mission support team during a manned Saturn V mission using the command and service module and to demonstrate the performance of nominal and selected backup lunar-orbit-rendezvous procedures. The spacecraft was a Block II command and service module. A lunar module test article was installed for mass loading purposes in the spacecraft/launch vehicle adapter in place of an actual lunar module.

The space vehicle was launched from Kennedy Space Center Launch Complex 39A at 07:51:00 a.m. e.s.t. (12:51:00 G.m.t.) on December 21, 1968, and the spacecraft was inserted into a 103- by 98-mile earth parking orbit. After the spacecraft had been in earth orbit almost 3 hours for inflight systems checks, the translunar injection maneuver was performed. The spacecraft was separated from the S-IVB approximately 25 minutes later using the service module reaction control system and was turned around to permit observation and photography of the S-IVB stage. The crew then performed two reaction control system maneuvers to increase the separation distance. A ground-commanded liquid oxygen dump provided impulse for targeting the S-IVB stage to fly past the moon and into solar orbit.

The translunar injection maneuver was so accurate that only one small midcourse correction would have been sufficient to achieve the desired lunar orbit insertion altitude of approximately 65 miles. However, the second of the two maneuvers that separated the spacecraft from the S-IVB altered the trajectory so that a large midcourse correction at 11 hours was required to achieve the desired trajectory. For this midcourse correction, the service propulsion system was used to reduce the altitude of closest approach to the moon from 459 miles to 66.3 miles. An additional small midcourse correction was performed approximately 50 hours later to refine further the lunar insertion conditions. During the 66-hour translunar coast, the crew made systems checks and navigation sightings, tested the spacecraft high-gain antenna (installed for the first time on this mission), and televised pictures to earth.

Lunar orbit insertion was performed with the service propulsion system and the resultant orbit was 60 by 168.5 miles. After approximately 4 hours of navigation checks and ground-based determination of the orbital parameters, a lunar orbit circularization maneuver was performed, which resulted in an orbit of 60.7 by 59.7 miles.

The next 12 hours of crew activity in lunar orbit involved photography of both the near and far sides of the moon, landing-area sightings, and television transmissions. Most remaining noncritical flight plan activities were deleted during the final 4 hours in orbit because of crew fatigue, and this period was devoted to crew rest and preparation for transearth injection. The injection maneuver was performed approximately 89 hours into the flight and resulted in a velocity change of 3517 feet per second.

The transearth coast activities included star/horizon navigation sightings using both moon and earth horizons. Passive thermal control, using a roll rate of approximately 1 revolution per hour, was used during most of the translunar and transearth coast phases to maintain nearly stable onboard temperatures. Only one small transearth midcourse correction, made with the service module reaction control system, was required.

Command module/service module separation was performed at approximately 146-1/2 hours, and command module entry occurred approximately 17 minutes later. The command module followed an automatically guided entry profile and landed in the Mid-Pacific after a flight duration of 147 hours 42 seconds. The transearth injection targeting and separation and the entry guidance were so precise that the command module landed about 1 1/2 miles from the planned target point. The crew were retrieved and taken aboard the U.S.S. *Yorktown* at 17:20 G.m.t. on December 27, 1968.

With only minor problems, all spacecraft systems operated as intended, and all primary mission objectives were successfully accomplished. Crew performance was admirable throughout the mission. The navigation techniques developed for translunar and lunar orbital flight proved to be more than adequate to maintain required accuracies for lunar orbit insertion and transearth injection. Communications and tracking at lunar distances were excellent in all modes. Additional information on the Apollo 8 mission is contained in reference 2-12.

2.4.4 Apollo 9 Mission

The Apollo 9 mission was a 10-day flight in earth orbit to qualify the lunar module for lunar orbital operations. The crewmen were James A. McDivitt, Commander; David R. Scott, Command Module Pilot; and Russell L. Schweickart, Lunar Module Pilot. The primary objectives of the mission were (1) to demonstrate the performance of the crew, space vehicle, and mission support facilities during a manned Saturn V mission using the lunar module and the command and service module; (2) to demonstrate the ability of the crew to operate the lunar module systems for periods of time comparable to those of a lunar landing mission; and (3) to demonstrate some of the nominal and backup lunar landing mission activities, including docking, intravehicular transfer, rendezvous, and extravehicular capability. To meet these objectives, the lunar module was evaluated during three separate manning periods that required multiple activation and deactivation of systems, a situation unique to this mission.

The space vehicle was launched from Launch Complex 39A at the Kennedy Space Center. The launch occurred on March 3, 1969, at 11:00:00 a.m. e.s.t. (16:00:00 G.m.t.), and the insertion orbit was 102.3 by 103.9 miles. After postinsertion checkout, the command and service module was separated from the S-IVB stage, transposed, and docked with the lunar module. At approximately 4 hours, an ejection mechanism, used for the first time on this mission, ejected the docked spacecraft from the S-IVB. After a separation maneuver, the S-IVB engine was fired twice by remote control, and the final maneuver placed the spent stage into a solar orbit.

Crew activity on the second day was devoted to systems checks and to three service propulsion system maneuvers while docked. On the third day, the Commander and the Lunar Module Pilot entered the lunar module to activate and check out the systems and to fire the descent engine with the vehicles still docked. Attitude control with the digital autopilot and manual throttling of the descent engine to full thrust were demonstrated.

Extravehicular operations were demonstrated on the fourth day of flight. The actual operations were abbreviated from those of the flight plan because of a minor inflight illness experienced by one crewmember on the preceding day and because of the many activities required for rendezvous preparation. Wearing the extravehicular mobility unit, the Lunar Module Pilot egressed the depressurized lunar module and remained near the hatch for approximately 47 minutes. During this same period, the Command Module Pilot, dependent on the command and service module systems for life support, partially exited through the command module hatch for observation, photography, and retrieval of thermal samples (fig. 2-13). The Lunar Module Pilot also retrieved thermal samples from the spacecraft exterior. A planned extravehicular transfer from the lunar module to the command module was not conducted because of the abbreviated operation.

On the fifth day, the Commander and the Lunar Module Pilot again transferred to the lunar module, this time to perform a lunar-module-active rendezvous. The lunar module primary guidance system was used throughout the rendezvous; however, mirror-image backup maneuver computations were made in the command module. The lunar module descent propulsion system was used to perform the phasing and insertion maneuvers, and the ascent engine was used to establish a constant differential height after the coelliptic sequence had been initiated. After redocking and crew transfer back into the command module, the lunar module ascent stage was jettisoned and the ascent engine was fired to oxidizer depletion.

The sixth service propulsion maneuver, to lower the perigee, was performed successfully during the sixth day. In the final 4 days, a series of landmark tracking exercises and a multispectral photography experiment were performed. The service propulsion system was fired for the seventh time at approximately 169-1/2 hours as a test and for the eighth time at 240-1/2 hours to deorbit the command and service module. This last maneuver was performed one revolution later than planned because of unfavorable weather in the planned recovery area. After a normal entry using the primary guidance system, the command module landed within 2.7 miles of the target point in the Atlantic Ocean after 241 hours 54 seconds of flight. The crewmen were recovered by helicopter and were aboard the primary recovery ship, the U.S.S. *Guadalcanal*, 49 minutes after landing. Further details of the Apollo 9 mission are given in reference 2-13.

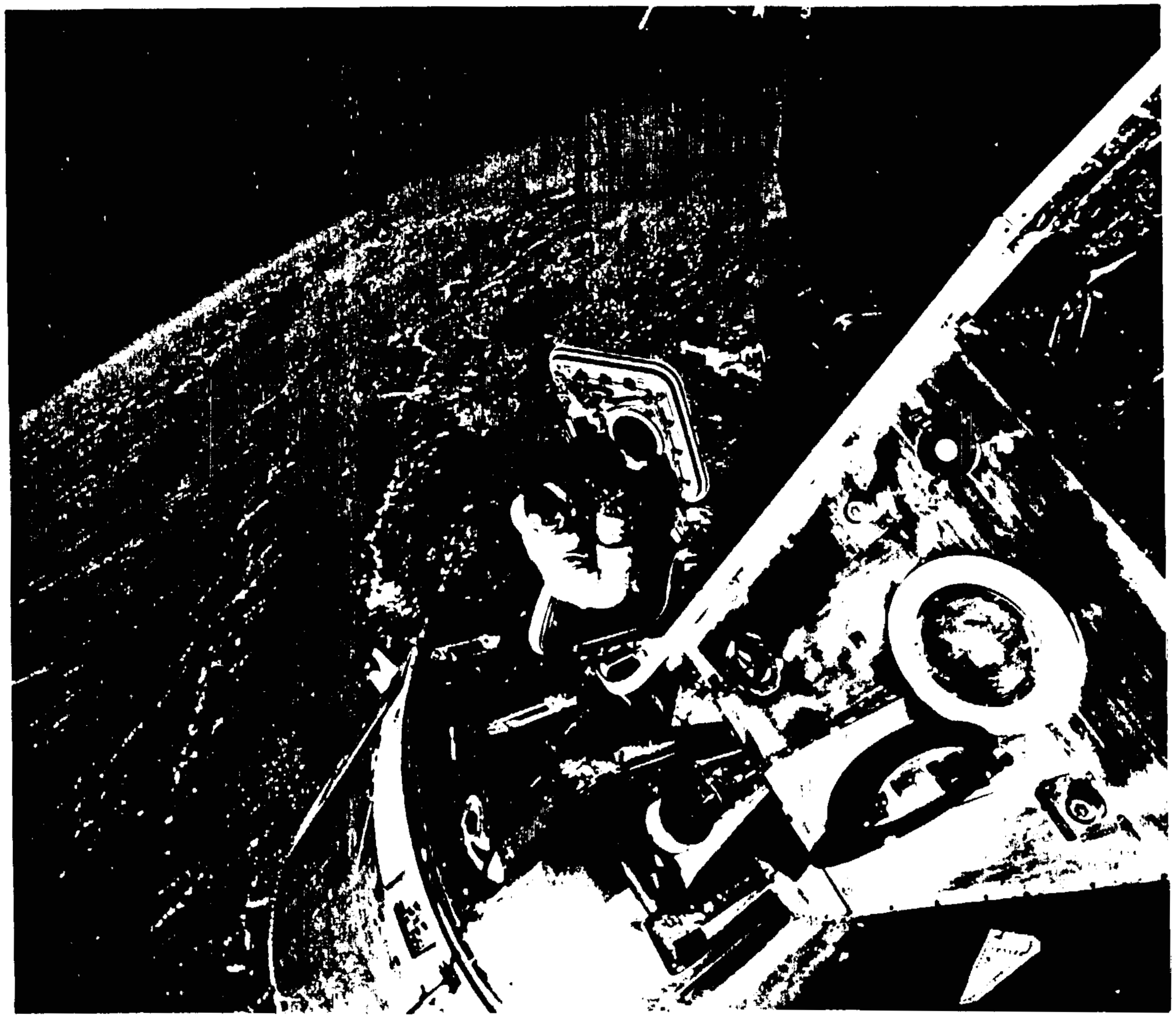

Figure 2-13.- View of Command Module Pilot during Apollo 9 extravehicular activity.

2.4.5 Apollo 10 Mission

Apollo 10 was an 8-day mission to qualify the combined spacecraft in the lunar environment. Particular primary objectives were to demonstrate the capability for rendezvous and docking in the lunar gravitational field and to evaluate docked and undocked lunar navigation. The mission events simulated those for a lunar landing mission. In addition, visual observations and stereoscopic strip photography of Apollo Landing Site 2, the planned location of the first lunar landing, were accomplished.

The Apollo 10 space vehicle, with crewmen Thomas P. Stafford, Commander; John W. Young, Command Module Pilot; and Eugene A. Cernan, Lunar Module Pilot; was launched on May 18, 1969, from Kennedy Space Center Launch Complex 39B at 11:49:00 a.m. e.s.t. (16:49:00 G.m.t.). The spacecraft and S-IVB stage combination was inserted into an earth parking orbit of 102.6 by 99.6 miles. After onboard systems were checked, the S-IVB engine was ignited at 2-1/2 hours elapsed time to place the spacecraft on a translunar trajectory.

At 3 hours after lift-off, the command and service module was separated from the S-IVB stage and then transposed and docked with the lunar module. The docked spacecraft were ejected 40 minutes later, and a separation maneuver was performed. The S-IVB stage was placed into a solar orbit by ground command for propulsive venting of residual propellants.

A preplanned midcourse correction executed at 26-1/2 hours adjusted the trajectory to coincide with a July lunar landing trajectory. The passive thermal control technique was employed to maintain desired spacecraft temperatures throughout the translunar coast except when a specific attitude was required.

At 76 hours mission elapsed time, the spacecraft was inserted into a lunar orbit of 60 by 171 nautical miles. After two revolutions of tracking and ground updates, a maneuver was performed to circularize the orbit at 60 nautical miles. The Lunar Module Pilot entered the lunar module, checked all systems, and then returned to the command module for the scheduled sleep period.

Activation of the lunar module systems began at 95 hours, and the spacecraft were undocked approximately 3 hours later. Figure 2-14 shows the command and service module as viewed from the lunar module. After stationkeeping, the lunar module was inserted into the descent orbit. An hour later, the lunar module made a low-level pass over Apollo Landing Site 2. The pass was highlighted by a test of the landing radar, by the visual observation of lunar lighting, by stereoscopic strip photography, and by the execution of the phasing maneuver using the descent engine. The lowest measured point in the trajectory was 47 400 feet above the lunar surface. After one revolution in the phasing orbit of approximately 8 by 194 miles, the lunar module ascent stage was separated from the descent stage and the ascent engine was used to perform an insertion maneuver. The rendezvous that followed was representative of one that would follow a normal ascent from the lunar surface. The rendezvous operation commenced with the lunar module coelliptic sequence initiation maneuver approximately one-half revolution from insertion, followed by a small constant differential height maneuver and the terminal phase initiation maneuver. Docking was complete at 106-1/2 hours, and the lunar module crew transferred into the command module. The lunar module ascent stage was jettisoned, and the ascent engine was fired by remote control to propellant depletion at 109 hours. After a rest period, the crew conducted landmark tracking and photography exercises. Transearth injection was performed at 137-1/2 hours.

The passive thermal control technique and the navigation procedures used on the translunar portion of flight were also used during the earth return. Only one midcourse correction of approximately 2 feet per second was required; this correction was made 3 hours before command module/service module separation. The command module entry was normal, and the spacecraft landed near the primary recovery vessel, the U.S.S. *Princeton*, after an elapsed flight time of 192 hours 3 minutes and 23 seconds. At daybreak, the crewmen were retrieved by helicopter.

All systems in the command and service module and the lunar module were managed very well. Although some problems occurred, most were minor and none caused a constraint to completion of mission objectives. Valuable data concerning lunar gravitation were obtained during the 60 hours in lunar orbit.

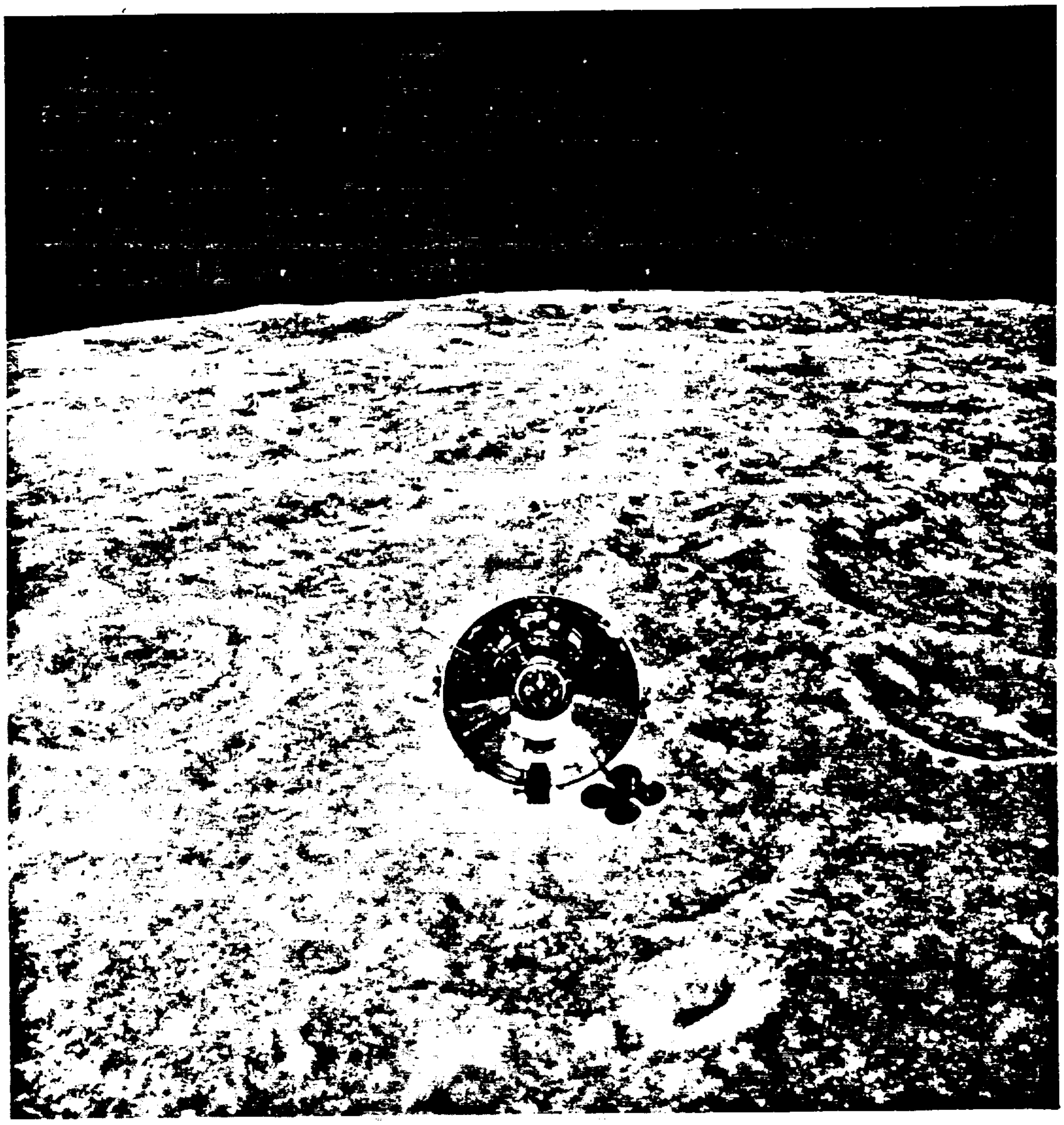

Figure 2-14.- Apollo 10 command and service module as viewed from lunar module after undocking.

Spacecraft systems performance was satisfactory, and all mission objectives were accomplished (ref. 2-14). All detailed test objectives were satisfied with the exception of the lunar module steerable antenna and relay modes for voice and telemetry communications.

2.4.6 Apollo 11 Mission

The Apollo 11 mission accomplished the basic objective of the Apollo program; that is landing two men on the lunar surface and returning them safely to earth. Crewmembers for this historic mission were Neil A. Armstrong, Commander; Michael Collins, Command Module Pilot; and Edwin E. Aldrin, Jr., Lunar Module Pilot.

The Apollo 11 space vehicle was launched from Kennedy Space Center Launch Complex 39A on July 16, 1969, at 08:32:00 a.m. e.s.t. (13:32:00 G.m.t.). The spacecraft and S-IVB stage of the launch vehicle were inserted into a 100.7- by 99.2-mile earth parking orbit. After a 2-1/2-hour checkout period, the spacecraft/S-IVB stage combination was injected into the translunar coast phase of the mission. Trajectory parameters after the translunar injection firing were nearly perfect. A midcourse correction of 20.9 feet per second was made during the translunar phase. During the remaining periods of free-attitude flight, passive thermal control was used to maintain spacecraft temperatures within desired limits. The Commander and the Lunar Module Pilot transferred to the lunar module during the translunar phase to make the initial inspection and preparations for the systems checks that would be made shortly after lunar-orbit insertion.

The docked spacecraft were inserted into a 60- by 169.7-mile lunar orbit at approximately 76 hours after launch. Four hours later, the lunar-orbit circularization maneuver was performed to place the combined spacecraft in a 65.7- by 53.8-mile lunar orbit. The Lunar Module Pilot entered the lunar module at approximately 81 hours after launch for initial powerup and systems checks. After a planned sleep period was completed at 93-1/2 hours elapsed time, the lunar module crewmen transferred to the lunar module and made final preparations for descent to the lunar surface. The lunar module was undocked from the command and service module at a mission time of approximately 100 hours. The lunar module descent orbit insertion maneuver was performed with the descent propulsion system at 101-1/2 hours into the mission, and the powered descent initiation occurred 1 hour later. The lunar module was maneuvered manually approximately 1100 feet down range from the preplanned landing point during the final 2-1/2 minutes of descent.

Man first landed on the moon at 03:17 p.m. e.s.t. on July 20, 1969, 102 hours 45 minutes 39.9 seconds mission elapsed time. The spacecraft landed in Mare Tranquillitatis (Sea of Tranquillity) at latitude 0°41'15" N. and longitude 23°26' E. based upon the coordinates of reference 2-15. After a 2-hour postlanding checkout of all lunar module systems, the crew configured the spacecraft controls for lunar stay and ate their first meal on the lunar surface. A crew rest period had been planned to precede the extravehicular activity of exploring the lunar surface but was not needed. After donning the back-mounted portable life support and oxygen purge systems the Commander egressed through the forward hatch and deployed an equipment module from the descent stage. A camera in the equipment module provided live television coverage of the Commander as he descended the ladder to the surface. The Commander made first contact at 09:56:15 p.m. e.s.t. on July 20, 1969, or 109 hours 56 minutes 15 seconds into the mission. The Lunar Module Pilot egressed soon thereafter, and both crewmen used the initial period on the surface to become acclimated to the reduced gravity and the unfamiliar surface conditions. A contingency soil sample was taken from the surface, and the television camera was deployed to include most of the lunar module in the field of view. Figure 2-15 is a photograph of the Commander as he stood beside the deployed United States flag during this part of the extravehicular activity. The crew then activated scientific experiments which included a solar wind detector, a passive seismometer, and a laser retroreflector. The Lunar Module Pilot evaluated his ability to operate and move about, and he was able to do so rapidly and confidently. The crew collected approximately 21 kilograms of lunar surface material for analysis. The surface exploration was concluded in the allotted time of 2-1/2 hours, and the crewmen reentered the lunar module at a mission time of 111-1/2 hours.

After a rest period, ascent preparation was conducted and the ascent stage lifted off the surface at 124-1/4 hours from earth launch. A nominal firing of the ascent engine placed the vehicle into a 45- by 9-mile orbit. After a rendezvous sequence similar to that performed on Apollo 10, the two spacecraft were docked at the mission time of 128 hours. After transfer of the crew and samples to the command and service module, the ascent stage was jettisoned, and the command and service module was prepared for transearth injection.

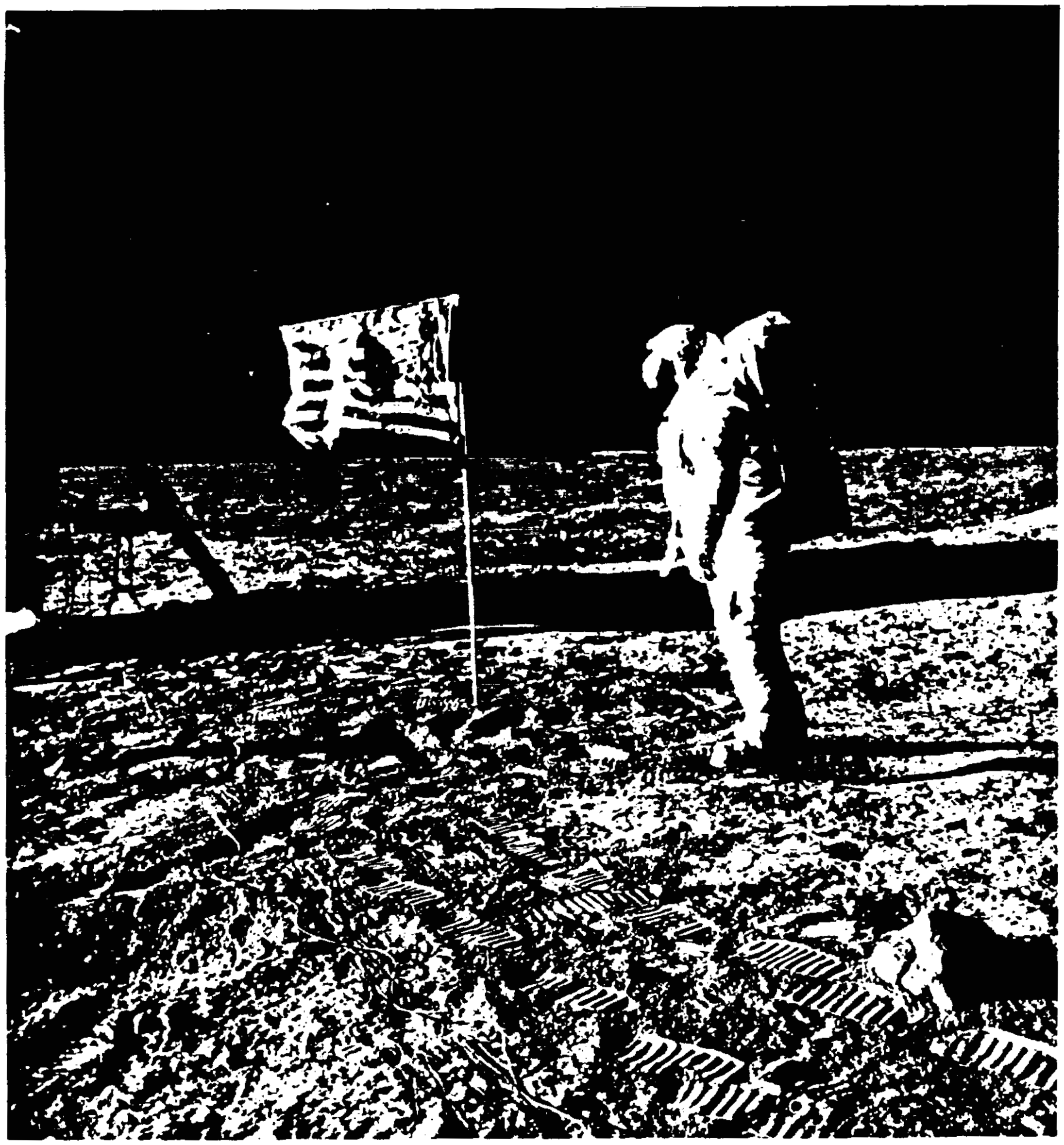

Figure 2-15.- Apollo 11 Commander on lunar surface.

The return flight started with a 150-second firing of the service propulsion engine during the 31st lunar revolution at 135-1/2 hours into the mission. As in translunar flight, only one midcourse correction was required, and passive thermal control was exercised for most of the transearth coast. Because of inclement weather in the planned recovery area, the landing point was moved 215 miles down range. The service module was separated from the command module 15 minutes before reaching the entry interface altitude of 400 000 feet. Following an automatic entry sequence and landing system deployment, the command module landed in the Pacific Ocean after a flight duration of 195 hours 18 minutes 35 seconds. The landing coordinates, as determined from the spacecraft computer, were latitude 13°19' N. and longitude 169°9' W.

After landing, the crew donned biological isolation garments; they were then retrieved by helicopter and taken to the primary recovery ship, the U.S.S. *Hornet*. The crew and lunar material samples were placed in a mobile quarantine facility for transport to the Lunar Receiving Laboratory in Houston.

All spacecraft systems performed satisfactorily and, with the completion of the Apollo 11, mission, the national objective of landing men on the moon and returning them safely to earth, before the end of the decade, was accomplished. Additional information on the Apollo 11 mission is given in references 2-16 and 2-17.

2.4.7 Apollo 12 Mission

Apollo 12, the second lunar landing mission, demonstrated the capability to land at a precise point and on a rough lunar surface. The landing location was in the Oceanus Procellarum (Ocean of Storms) region. The primary objectives assigned were (1) to perform selenological inspection, survey, and sampling in a mare area; (2) to deploy the Apollo lunar surface experiments package; (3) to develop techniques for a point landing capability; (4) to develop further man's capability to work in the lunar environment; and (5) to obtain photographs of candidate exploration sites.

The space vehicle, with crewmen Charles Conrad, Jr., Commander; Richard F. Gordon, Jr., Command Module Pilot; and Alan L. Bean, Lunar Module Pilot, was launched from Kennedy Space Center Launch Complex 39A at 11:22:00 a.m. e.s.t. (16:22:00 G.m.t.) on November 14, 1969. The activities during earth-orbit checkout, translunar injection, and translunar coast were similar to those of Apollo 11, except for the special attention given to verifying all spacecraft systems as a result of lightning strikes on the space vehicle at 36.5 seconds and again at 52 seconds after launch. A non-free-return translunar trajectory profile was used for the first time in the Apollo program.

The docked command and service module and lunar module were inserted into a 168.8- by 62.6-mile lunar orbit at approximately 83-1/2 hours into the mission. Two revolutions later, a second maneuver was performed to achieve a 66.1- by 54.3-mile orbit. At approximately 104 hours after launch, the Commander and the Lunar Module Pilot entered the lunar module to prepare for descent to the lunar surface. About 4 hours later, the two spacecraft were undocked and descent orbit insertion was performed. A precision landing was accomplished through automatic guidance, with small manual corrections applied in the final phases of descent. The spacecraft touched down 110 hours 32 minutes 36 seconds into the mission, with landing coordinates of latitude 3°11'51" S. and longitude 23°23'8" W. (ref. 2-18). One objective of the Apollo 12 mission was to achieve a precision landing near the Surveyor III spacecraft, which had landed on April 20, 1967. The Apollo 12 landing point was 535 feet from the Surveyor III.

Three hours after landing, the crewmen began preparations for egress. As the Commander descended the ladder to the lunar surface, he deployed the modularized equipment stowage assembly which automatically activated a color television camera and permitted his actions to be televised to earth. The television camera was subsequently damaged. After the Lunar Module Pilot had descended to the surface, he erected a solar wind composition experiment. Both crewmen then deployed the first Apollo lunar surface experiments package. On the return traverse, the crew collected a core-tube sample and additional surface samples. The first extravehicular activity period lasted 4 hours.

The second extravehicular activity period began after a 7-hour rest period. Documented samples, core-tube samples, trench-site samples, and gas-analysis samples were collected on a traverse to the Surveyor III spacecraft. The crew photographed and removed parts from the Surveyor (fig. 2-16). After the return traverse, the crew retrieved the solar wind composition experiment. The second extravehicular activity period lasted 3-3/4 hours. Crew mobility and portable life support system operation, as in Apollo 11, were excellent throughout both extravehicular periods. The Surveyor parts and approximately 34 kilograms of lunar material were returned to earth.

The lunar module ascent stage lifted off the lunar surface at a mission elapsed time of 142 hours. After a nominal rendezvous sequence, the two spacecraft were docked at 145-1/2 hours into the mission. The ascent stage, jettisoned after crew and sample transfer to the command module, was maneuvered by remote control to impact on the lunar surface; impact occurred at a mission time of 150 hours approximately 40 miles from the Apollo 12 landing site. Extensive landmark tracking and photography from lunar orbit was then conducted using a 500-mm long-range lens to obtain mapping and training data for future missions. At 172-1/2 hours into the mission, transearth injection was accomplished by using the service propulsion system engine.

Two small midcourse corrections were executed during transearth coast. The entry sequence was normal, and the command module landed in the Pacific Ocean. The landing coordinates, as determined from the onboard computer, were latitude 15°52' S. and longitude 165°10' W. Duration of the mission was 244 hours 36 minutes 25 seconds. After landing, biological isolation precautions similar to those of Apollo 11 were taken. The crew, the lunar material samples, and the spacecraft were subsequently transported to the Lunar Receiving Laboratory.

All spacecraft systems operated satisfactorily, and all primary mission objectives were accomplished. Additional information concerning the Apollo 12 mission is contained in references 2-19 and 2-20.

2.4.8 Apollo 13 Mission

Apollo 13, planned as the third lunar landing mission, was aborted during translunar flight because of the loss of all the oxygen stored in two tanks in the service module. The primary objectives assigned to the mission were (1) to perform selenological inspection, survey, and sampling of materials in a preselected region of the Fra Mauro formation; (2) to deploy and activate an Apollo lunar surface experiments package; (3) to develop further man's capability to work in the lunar environment; and (4) to obtain photographs of candidate exploration sites.

The launch vehicle and spacecraft were similar to those of Apollo 12; however, the experiment complement was somewhat different. The crewmembers were James A. Lovell, Jr., Commander; Fred W. Haise, Jr., Lunar Module Pilot; and John L. Swigert, Jr., who had been the backup Command Module Pilot until the day before launch. Because the prime Command Module Pilot had been exposed to German measles 8 days before the scheduled launch date and was shown during his preflight physical examination to be susceptible to the disease, the decision was made to replace him with the backup pilot as a precautionary measure.

The space vehicle was launched from Kennedy Space Center Launch Complex 39A at 02:13:00 p.m. e.s.t. (19:13:00 G.m.t.) on April 11, 1970. During the launch, the second-stage inboard engine shut down early because of high-amplitude longitudinal oscillations; however, near-nominal trajectory parameters were achieved at orbital insertion. The earth orbital, translunar injection, and early translunar coast phases of flight were normal, and operations during these periods were similar to those of Apollo 11 and Apollo 12 with one exception. On previous lunar missions, the S-IVB stage had been maneuvered by ground command into a trajectory such that it would pass by the moon and go into a solar orbit. For Apollo 13, the S-IVB was targeted to hit the moon so that the vibrations resulting from the impact could be sensed by the Apollo 12 seismic station and telemetered to earth for study. The S-IVB impacted the lunar surface about 78 hours after launch, approximately 140 kilometers west-northwest of the Apollo 12 experiment station. The impact point was very close to the desired target.

Photographs of the earth were taken during the early part of translunar coast to support an analysis of atmospheric winds. After approximately 31 hours of flight, a midcourse correction lowered the closest point of spacecraft approach to the moon to an altitude of approximately 60 miles. Before this maneuver, the spacecraft had been on a free-return trajectory, that is, one

Figure 2-16.- Apollo 12 Commander examining Surveyor III spacecraft with lunar module in background.

on which the spacecraft would have looped around the moon and returned to earth without requiring a major maneuver. At approximately 56 hours, one of the two cryogenic oxygen tanks in the service module failed. (The cause of the failure is discussed in ref. 2-21.) The immediate result was that the oxygen in the failed tank was abruptly lost. Later, it was discovered that the panel had been blown off the bay in which the tank was located (fig. 2-17). The oxygen system with which the second tank was associated also lost pressure, but at a slower rate. These tanks contained most of the oxygen for breathing in the command module and the oxygen for the fuel cells (the primary source of electrical power). Sufficient oxygen remained in the second tank to maintain primary electrical power in the command and service module for approximately 2 hours, which gave the crew time to power up the lunar module, align the inertial reference platform, and shut down the command and service module systems. The docked spacecraft were then maneuvered back into a free-return trajectory using the lunar module descent engine.

From this point on, all systems in both vehicles were powered down except when absolutely required. With no further maneuvers, the command module could have landed in the Indian Ocean at 152 hours mission elapsed time, and the lunar module systems would have been required to support the crew for about 90 hours. However, because consumables were extremely marginal under these conditions and because only minimal recovery support existed in the Indian Ocean, a transearth injection maneuver using the lunar module descent propulsion system was executed to speed up the return to earth after the docked spacecraft had swung around the far side of the moon. Because of this maneuver, the landing was predicted to occur at about 143 hours mission elapsed time in the South Pacific, where primary recovery support was available. Guidance errors during the transearth injection maneuver necessitated a small transearth midcourse correction at approximately 105 hours to bring the projected entry flight-path angle within the specified limits. During the transearth coast period, the docked spacecraft were maneuvered into a passive thermal control mode.

The unprecedented powered-down state of the command module required several new procedures for entry. The command module was briefly powered up to assess the operational capability of critical systems. Also, the command module entry batteries were charged through the umbilical connectors that had supplied any necessary power from the lunar module while the command module was powered down. Approximately 6 hours before entry, the passive thermal control mode was discontinued, and a final midcourse correction was made using the lunar module reaction control system to refine the flight-path angle slightly.

The service module was separated 4-3/4 hours before entry; the separation afforded the crew an opportunity to observe and photograph the damage caused by the failed oxygen tank. The lunar module was retained until 70 minutes before entry to minimize usage of command module electrical power. At undocking, normal tunnel pressure provided the necessary force to separate the two spacecraft. From this point, the events were similar to those of previous flights, and the command module landed approximately 1 mile from the target point. Some pieces of the lunar module survived entry and projected trajectory data indicated that they impacted in the open sea between Samoa and New Zealand. The three crewmen were on board the recovery ship, the U.S.S. *Iwo Jima*, within 45 minutes of landing. Reference 2-22 contains details of the Apollo 13 mission.

2.4.9 Apollo 14 Mission

Apollo 14 was the third mission to achieve a lunar landing. The landing site was located in the Fra Mauro highlands, the same area that was to have been explored on Apollo 13. Although the primary mission objectives for Apollo 14 were the same as those of Apollo 13, provisions were made for returning a significantly greater quantity of lunar material and scientific data than had been possible previously. An innovation that allowed an increase in the range of lunar surface exploration and in the amount of material collected was the provision of a collapsible two-wheeled cart, the modular equipment transporter, for carrying tools, cameras, a portable magnetometer, and lunar samples (fig. 2-18).

An investigation into the cause of the Apollo 13 cryogenic oxygen tank failure led to three significant changes in the command and service module cryogenic oxygen storage and electrical power systems. The internal construction of the oxygen tanks was modified, a third oxygen tank was added, and an auxiliary battery was installed. These changes were also incorporated into all subsequent spacecraft.

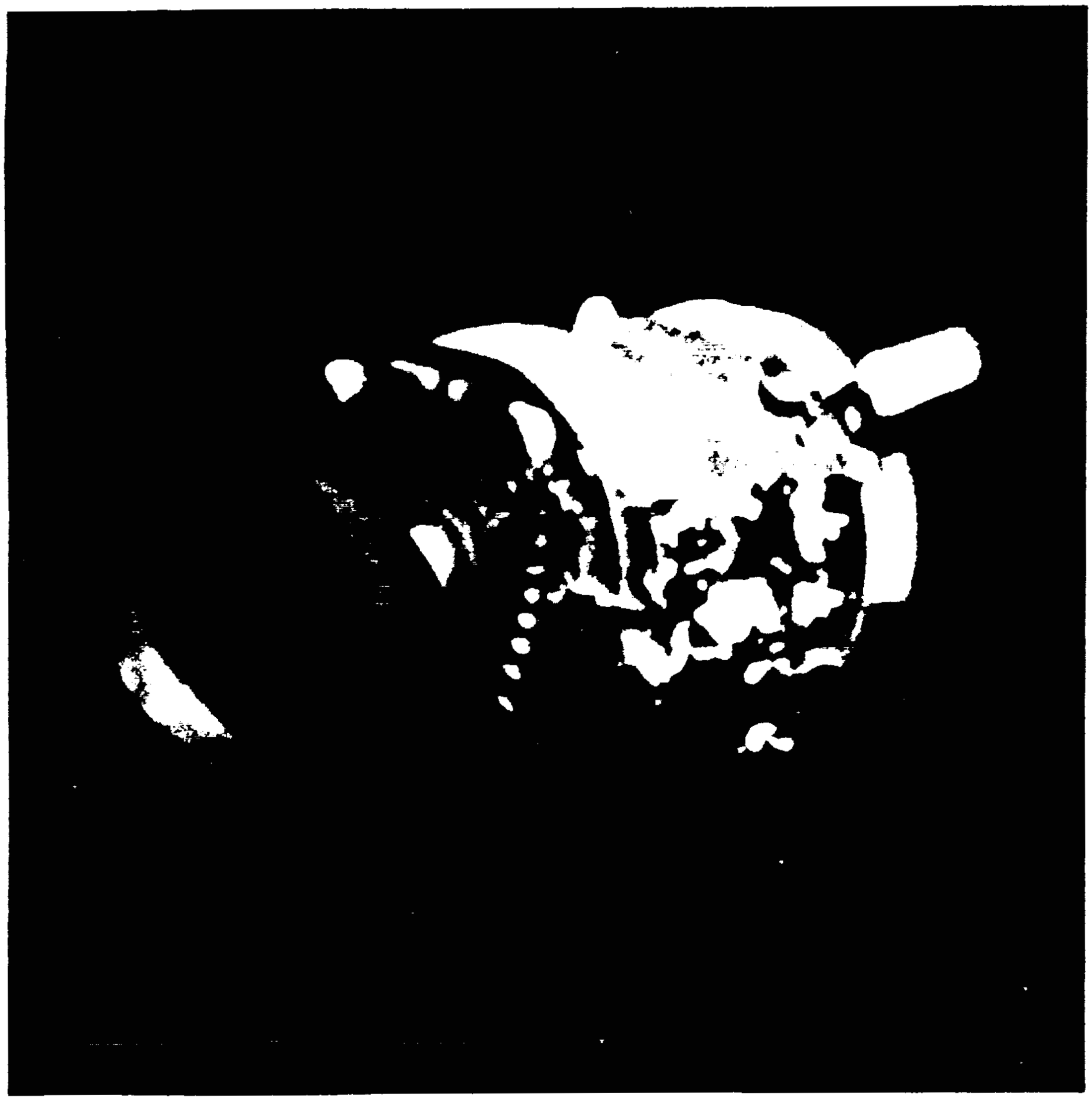

Figure 2-17.- Photograph of damaged service module taken during Apollo 13 mission.

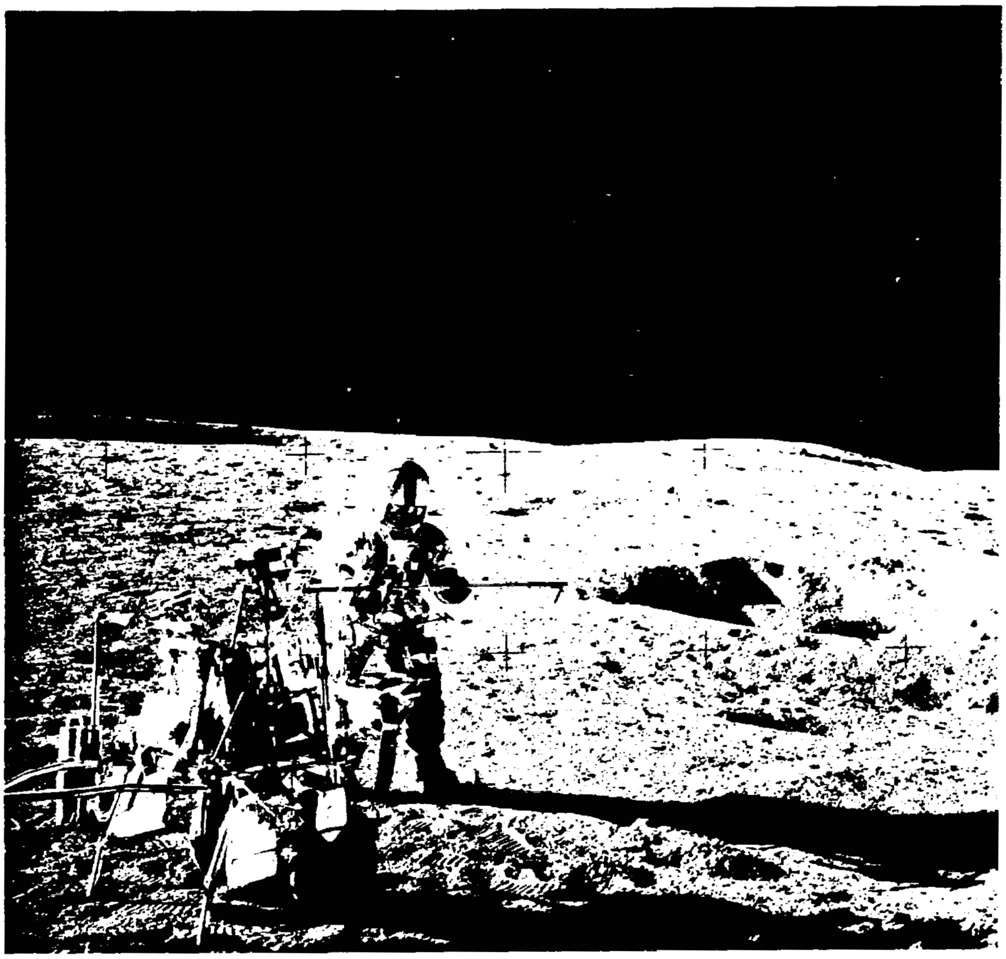

Figure 2-18.- Apollo 14 lunar surface extravehicular activity.

The mission, manned by Alan B. Shepard, Jr., Commander; Stuart A. Roosa, Command Module Pilot; and Edgar D. Mitchell, Lunar Module Pilot, was launched from Kennedy Space Center Launch Complex 39A at 04:03:02 p.m. e.s.t. (21:03:02 G.m.t.) on January 31, 1971. Because of weather conditions which might have triggered lightning, the launch was delayed approximately 40 minutes. The operations in earth orbit and translunar injection were similar to those of previous lunar missions; however, after translunar injection, several docking attempts were made before the command and service module was successfully docked with the lunar module.

As on Apollo 13, the S-IVB stage was targeted to impact the moon within a prescribed area to supply seismic data. The vehicle struck the lunar surface approximately 160 miles from the target, within the desired area, at 82:37:52 mission elapsed time. The Apollo 12 seismic station, located approximately 94 miles southwest of the impact point, recorded the event 37 seconds later and responded to vibrations for more than 3 hours.

Translunar activities included star and earth horizon calibration sightings in preparation for a cislunar navigation exercise to be performed during transearth coast, and dim-light photography of the earth. At approximately 61 hours, the lunar module crew spent approximately 2 hours in the lunar module cabin for housekeeping and systems checkout. While there, the crew photographed a waste-water dump from the command module to obtain data for a particle contamination study being conducted for the Skylab program. Two spacecraft translunar midcourse corrections achieved the trajectory desired for lunar-orbit insertion.

The joined spacecraft were inserted into a 169- by 58-mile lunar orbit with the service propulsion system. After two revolutions, the same propulsion system was used to insert the spacecraft into the descent orbit, which brought the docked vehicles to within 10 miles of the lunar surface. On previous missions, the descent orbit insertion maneuver had been performed with the lunar module descent propulsion system. A change was made on this mission to allow a greater margin of lunar module propellant for landing in a more rugged area.

The Commander and Lunar Module Pilot entered the lunar module, performed systems checks, and undocked during the 12th lunar revolution. After vehicle separation and before powered descent, ground personnel detected the presence of an abort command at a computer input channel although the crew had not depressed the abort switch. The failure was isolated to the abort switch, and, to prevent an unwanted abort, a workaround procedure was developed. The procedure was followed, and the powered descent was performed successfully. The vehicle touched down 12 minutes 45 seconds after engine ignition and came to rest on a slope of about 7 degrees. Sufficient propellant remained for approximately 70 additional seconds of engine firing time. The coordinates of the landing site are latitude 3°40'24" S. and longitude 17°27'55" W. based upon reference 2-23.

After undocking and separation, the command-and-service-module orbit was circularized to an altitude of approximately 60 miles. While the landing crew was on the lunar surface, the Command Module Pilot performed tasks to obtain data for scientific analyses and future mission planning. These tasks included orbital science photography of the lunar surface, photography of the proposed Descartes landing site for site selection studies, photography of the lunar surface under high-sun-angle lighting conditions for operational planning, photography of low-brightness astronomical light sources, and photography of the Gegenschein and Moulton Point regions.

Preparations for the initial period of lunar surface exploration began approximately 2 hours after landing, and the crew egressed about 5-1/2 hours after landing. During the 4-3/4-hour extravehicular period, the crew deployed and loaded the modular equipment transporter; collected samples; photographed activities, panoramas, and equipment; and deployed the second Apollo lunar surface experiments package.

After a rest period of approximately 6-1/2 hours, the crew prepared to travel to the area of Cone Crater, approximately 1.3 kilometers east-northeast of the landing site. Although the crew experienced difficulties in navigating, they reached a point within approximately 15 meters of the rim of the crater, and the objectives associated with reaching the vicinity of this crater were achieved. Various rock and soil samples were collected near Cone Crater, and, on the return to the lunar module, the crew also obtained magnetometer measurements at two sites along the traverse. This second extravehicular period lasted approximately 4-1/2 hours for a total extravehicular time of approximately 9-1/4 hours. Approximately 43 kilograms of lunar samples were collected during the two periods.

The lunar module ascent stage lifted off after a surface stay time of 33-1/2 hours, and the vehicle was inserted into a 51.7- by 8.5-mile orbit. A direct rendezvous was performed (the first use of a direct rendezvous in the Apollo program), and the command-module-active docking operations were normal. After crew and sample transfer to the command module, the ascent stage was jettisoned and a pre-programmed maneuver caused lunar impact approximately 36 miles west of the Apollo 14 landing site. On previous lunar missions, lunar surface dust adhering to equipment being returned to earth had created a problem. Special dust control procedures used on this mission, however, effectively decreased the amount of dust in the cabins.

Transearth injection occurred during the 34th lunar revolution. During transearth coast, one midcourse correction was made using the service module reaction control system. In addition, a special oxygen flow-rate test was performed to evaluate the system for planned extravehicular activities on subsequent flights, and a navigation exercise simulating a return to earth without ground control was conducted using only the guidance and navigation system. Inflight demonstrations of electrophoretic separation, liquid transfer, heat flow and convection, and composite casting under zero-gravity conditions were also performed and televised to earth.

Entry was normal and the command module landed in the Pacific Ocean at 216:01:58 mission elapsed time. The crewmen were retrieved by helicopter and were aboard the primary recovery ship, U.S.S. *New Orleans*, approximately 48 minutes after landing.

As was the case following the Apollo 11 and Apollo 12 missions, the Apollo 14 crew and lunar samples were isolated and tests conducted to assure that they were not biologically hazardous. The test protocols showed no evidence of lunar micro-organisms at the three sites explored, and this was considered to be sufficient justification for discontinuance of the quarantine procedures.

All of the objectives and experiment operations were accomplished satisfactorily except for some desired photography that could not be obtained. Details of the mission are given in reference 2-24 and preliminary scientific results in reference 2-25.

2.4.10 Apollo 15 Mission

Apollo 15 was the first of the three J missions (appendix B) designed to conduct exploration of the moon over longer periods, over greater ranges, and with more instruments for scientific data acquisition than on previous Apollo missions. Major modifications and augmentations to the basic Apollo hardware were made. The most significant change was the installation of a scientific instrument module in one of the service module bays for scientific investigations from lunar orbit. Other hardware changes consisted of lunar module modifications to accomodate a greater payload and permit a longer stay on the lunar surface, and the provision of a lunar roving vehicle (fig. 2-19). The landing site chosen for the mission was an area near the foot of the Montes Apenninus (Apennine Mountains) and adjacent to Hadley Rille. The primary objectives assigned to the Apollo 15 mission were: (1) to perform selenological inspection, survey, and sampling of materials and surface features in a preselected area of the Hadley-Apenninus region; (2) to emplace and activate surface experiments; (3) to evaluate the capability of the Apollo equipment to provide extended lunar surface stay time, increased extravehicular operations, and surface mobility; and (4) to conduct inflight experiments and photographic tasks from lunar orbit.

The space vehicle was launched from the Kennedy Space Center Launch Complex 39A at 09:34:00.6 a.m. e.d.t. (13:34:00.6 G.m.t.) on July 26, 1971. The spacecraft was manned by David R. Scott, Commander; Alfred M. Worden, Command Module Pilot; and James B. Irwin, Lunar Module Pilot. The spacecraft/S-IVB combination was inserted into an earth parking orbit approximately 11 minutes 44 seconds after lift-off. The S-IVB restart for translunar injection was initiated during the second revolution at approximately 2 hours 50 minutes mission elapsed time. The maneuver placed the spacecraft/S-IVB combination on a translunar trajectory that would allow return to an acceptable earth-entry corridor using the service module reaction control system engines. Approximately 27 minutes after injection into the translunar trajectory, the command and service module was separated from the S-IVB and docked with the lunar module. The lunar module was then extracted from the spacecraft/launch vehicle adapter. Shortly thereafter, the S-IVB tanks were vented and the auxiliary propulsion system was fired to target the S-IVB for a lunar impact. The impact of the S-IVB stage was sensed by the Apollo 12 and 14 lunar surface seismometers.

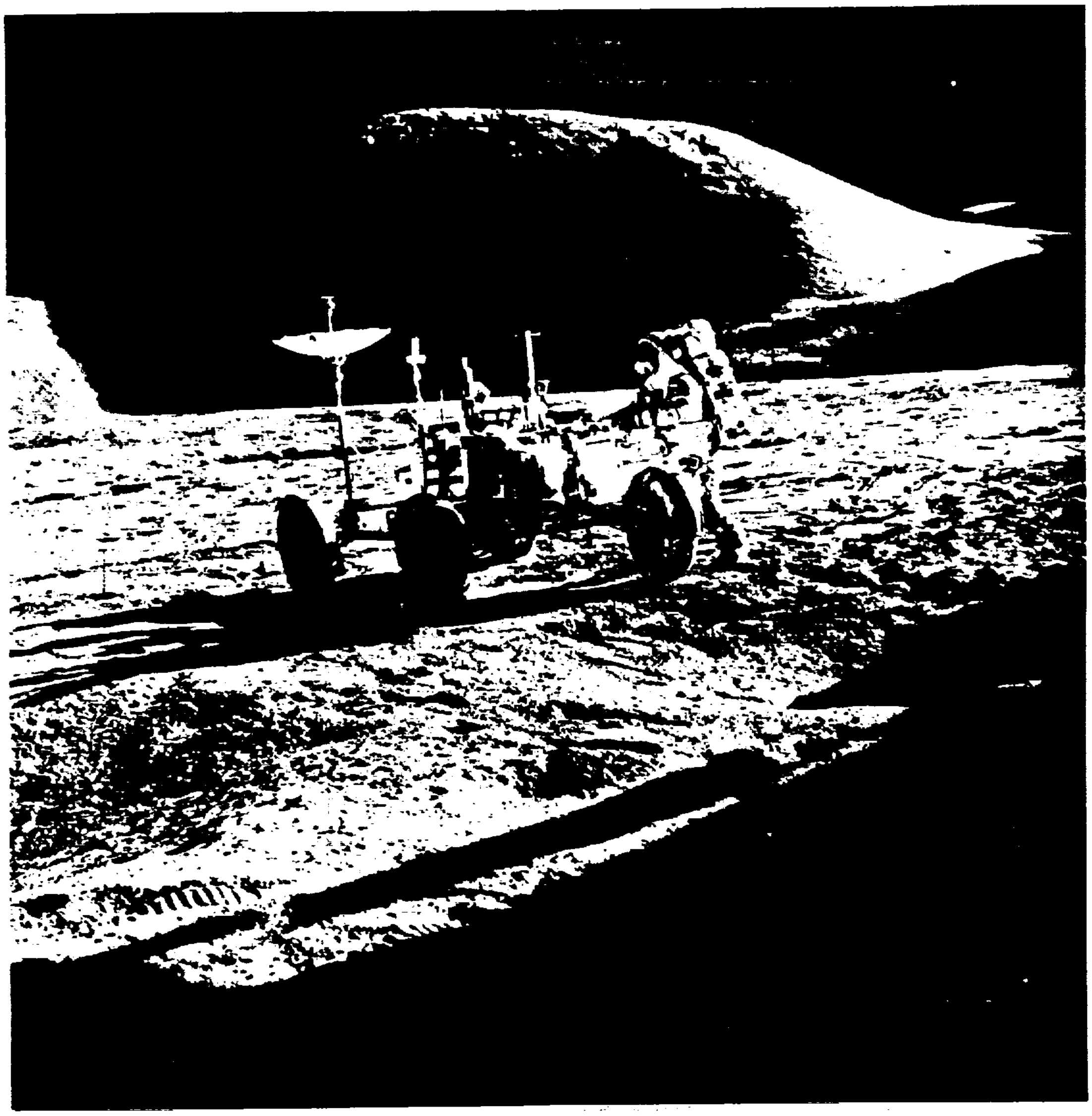

Figure 2-19.- Apollo 15 Lunar Module Pilot working at the lunar roving vehicle.

The docked spacecraft were inserted into a lunar orbit of approximately 170 by 57 miles and about 4 hours later, injected into a 58- by 10-mile orbit. Lunar module undocking and separation were performed at approximately 100 hours 39 minutes into the mission. The command and service module was then placed in a near-circular lunar orbit in preparation for the acquisition of scientific data.

The lunar module touched down on the lunar surface approximately 1800 feet from the planned target point at 104 hours 42 minutes 29 seconds after lift-off. The landing point was latitude 26°6'3" N. and longitude 3°39'10" E. based on the coordinates of reference 2-26. Sufficient descent stage propellant remained after lunar touchdown to have provided a hover time capability of about 103 seconds.

Approximately 2 hours after landing, the Commander photographed and described the area surrounding the landing site by standing in the open top hatch. This extravehicular activity period lasted approximately 33 minutes. The first lunar surface extravehicular activity was initiated about 12-1/2 hours later. During the surface operations, the crew collected and stowed a contingency sample, deployed the lunar roving vehicle, unstowed the third Apollo lunar surface experiments package and other equipment, and configured the lunar roving vehicle for lunar surface operations. Some problems were experienced in deploying and checking out the lunar roving vehicle, but these problems were worked out. The crew then drove the vehicle to Elbow Crater where they collected and documented samples and gave an enthusiastic and informative commentary on lunar features. The Mission Control Center provided television control during various stops. After obtaining additional samples and photographs near St. George Crater, the crew returned to the lunar module using the lunar roving vehicle navigation system. The distance driven was approximately 10.3 kilometers. The crew then proceeded to the selected Apollo lunar surface experiments package deployment site, approximately 110 meters west-northwest of the lunar module. There, the experiments were deployed essentially as planned, except that the second heat-flow experiment probe was not emplaced because drilling was more difficult than expected and the hole was not completed. The first extravehicular activity lasted approximately 6 hours 33 minutes.

The crew spent approximately 16 hours in the cabin between the first and second extravehicular periods. On egress for the second extravehicular activity, the lunar roving vehicle was checked out and prepared for the second traverse. The first stage of the 12.5-kilometer round trip was south to the Apennine front, but east of the first traverse. Stops were made at Spur Crater and other points along the base of the front, as well as at Dune Crater on the return trip. The return route closely followed the outbound route. Documented samples, a core sample, and a comprehensive sample were collected, and photographs were taken. After reaching the lunar module, the crew returned to the experiments package site where the Commander completed drilling the second hole for the heat flow experiment and emplaced the probe. During this period, the Lunar Module Pilot performed soil mechanics tasks. The Commander also drilled to obtain a deep-core sample but terminated the drilling because of time constraints. The crew then returned to the lunar module and deployed the United States flag. The second extravehicular activity ended after approximately 7 hours 12 minutes.

The crew spent almost 14 hours in the cabin after the second extravehicular period. The third extravehicular activity began later than originally planned to allow additional time for crew rest. Because of this delay and later delays at the experiments package site, the planned trip to the North Complex was deleted. The first stop was at the experiments package site to retrieve the deep-core sample. Two core sections were disengaged, but the drill and the remaining four sections could not be separated and were left for later retrieval. The third geologic traverse took a westerly direction and included stops at Scarp Crater, Rim Crater, and the Terrace, an area along the rim of Hadley Rille. Extensive samples and a double-core-tube sample were obtained. Photographs were taken of the west wall of Hadley Rille, where exposed layering was observed. The return trip was east toward the lunar module with a stop at the experiments package site to retrieve the remaining sections of the deep-core sample. One more section was separated, and the remaining three sections were returned in one piece. After returning to the lunar module, the lunar roving vehicle was unloaded and parked for ground-controlled television coverage of the lunar module ascent. A distance of approximately 5.1 kilometers was traveled during the third extravehicular activity, which lasted approximately 4 hours 50 minutes. The total distance traveled with the lunar roving vehicle during the three extravehicular periods was 27.9 kilometers, and the total weight of lunar samples collected was approximately 77 kilograms. The areas traversed on the lunar surface are illustrated in section 3.2.1

While the lunar module was on the surface, the Command Module Pilot completed 34 lunar orbits conducting scientific instrument module experiments and operating cameras to obtain data concerning the lunar surface and the lunar environment. Some scientific tasks accomplished during this time were photographing the sunlit lunar surface, gathering data needed for mapping the bulk chemical composition of the lunar surface and for determining the geometry of the moon along the ground track, visually surveying regions of the moon to assist in identifying processes that formed geologic features, obtaining lunar atmospheric data, and surveying gamma-ray and X-ray sources. High-resolution photographs were obtained with the panoramic and mapping cameras during the mission.

The ascent stage lifted off after 66 hours 54 minutes 53 seconds on the lunar surface. The mission elapsed time of lift-off was 171 hours 37 minutes 23 seconds. A nominal lunar-module-active rendezvous was performed followed by docking at approximately 173 hours 36 minutes.

The lunar module ascent stage was jettisoned at approximately 179 hours 30 minutes into the mission. Jettison had been delayed one revolution later than planned because of some difficulty with verifying the spacecraft tunnel sealing and astronaut pressure suit integrity. Approximately 1-1/2 hours later, the lunar module was deorbited with lunar impact occurring at latitude 26°21' N. and longitude 0°15' E. Impact was approximately 23-1/2 kilometers from the planned point and approximately 93 kilometers west of the Apollo 15 landing site. The impact was recorded by the Apollo 12, 14, and 15 lunar surface seismic stations.

Before the command and service module was maneuvered from lunar orbit, a subsatellite was deployed in an orbit of approximately 76 by 55 miles. The subsatellite was instrumented to measure plasma and energetic-particle fluxes, vector magnetic fields, and subsatellite velocity from which lunar gravitational anomalies could be determined. All systems operated as expected. The transearth injection maneuver was initiated approximately 223 hours 49 minutes into the mission.

At a mission time of approximately 242 hours, a transearth coast extravehicular activity began. Television coverage was provided for the 39-minute extravehicular period during which the Command Module Pilot retrieved film cassettes and examined the scientific instrument module for possible abnormalities. Total extravehicular time during the mission was 19 hours 47 minutes.

A small midcourse correction of 5.6 feet per second was performed at the seventh midcourse correction opportunity. The command module was separated from the service module as planned, and a normal entry followed with the spacecraft being observed on the main parachutes from the recovery ship, U.S.S. *Okinawa*. During the descent, one of the three main parachutes failed, but a safe landing was made. The best estimate of the landing coordinates was latitude 26°7'48" N. and longitude 158°8'24" W., approximately 1 mile from the planned landing point. The crew was brought on board the recovery ship by helicopter about 39 minutes after landing. Duration of the mission was 295 hours 11 minutes 53 seconds.

The mission accomplished all primary objectives and provided scientists with a large amount of new information concerning the moon and its characteristics. References 2-27 and 2-28 provide details on the performance of the systems and the preliminary results of the experiments.

2.4.11 Apollo 16 Mission

Apollo 16 was the second in the series of lunar landing missions designed to optimize the capability for scientific return. The vehicles and payload were similar to those of Apollo 15. Primary objectives assigned were (1) to perform selenological inspection, survey, and sampling of materials and surface features in a preselected area of the Descartes region of the moon; (2) to emplace and activate surface experiments; and (3) to conduct inflight experiments and photographic tasks.

The space vehicle was launched from Kennedy Space Center Launch Complex 39A at 12:54:00 p.m. e.s.t. (17:54:00 G.m.t.) on April 16, 1972. The crewmen for the mission were John W. Young, Commander; Thomas K. Mattingly II, Command Module Pilot; and Charles M. Duke, Jr., Lunar Module Pilot. The launch was normal, and the spacecraft, the launch vehicle third stage (S-IVB), and the instrument unit were inserted into earth orbit for systems checkout before the vehicle was committed to translunar flight. The launch sequence was similar to that described previously for a Saturn V launch.

Translunar injection was initiated during the second revolution in earth orbit. The spacecraft separation, transposition, docking, and ejection operations were performed successfully, and, on ground command, the S-IVB was maneuvered to reduce the probability of recontact with the spacecraft. Approximately 20 minutes later, the propulsive force from a liquid-oxygen dump was used to target the S-IVB for impact on the moon near the Apollo 12 landing site. As on the three previous missions, S-IVB impact was desired to produce seismic vibrations that could be used to study the nature of the lunar interior structure. Although launch vehicle systems malfunctions precluded a planned trajectory refinement, the impact point was within the desired area. However, loss of S-IVB stage telemetry prevented establishment of the precise time of impact, thereby making the interpretation of seismic data uncertain.

During translunar coast, a false gimbal lock warning was issued by the command module computer. To prevent the inertial platform from being caged during critical operations, a procedure was developed to inhibit the computer from responding to the false indications. Activities during translunar coast included a navigation exercise, ultraviolet photography, a demonstration of the effects of zero gravity on the process of electrophoresis, and the first of two sessions to acquire data to be used in trying to determine the mechanisms involved in the production of light flashes seen by some crewmen on previous flights.

The crew inserted the docked spacecraft into lunar orbit by firing the service propulsion system engine in the retrograde direction. The initial 170- by 58-mile orbit was maintained for two revolutions. The crew then inserted the spacecraft into a descent orbit that took them within approximately 10 miles of the surface. After three revolutions the lunar module crew undocked and separated the spacecraft in preparation for the lunar landing. Figure 2-20 shows the lunar module just after undocking.

As the Command Module Pilot prepared to transfer his spacecraft to a circular lunar orbit, oscillations were detected in a secondary system that controlled the direction of thrust of the service propulsion system engine. The spacecraft was maneuvered to place it close to the lunar module while the problem was being evaluated. Tests and analyses showed that the system was still usable and safe; therefore, the vehicles were separated again, and the mission continued on a revised time line. The command and service module circularization maneuver was performed successfully with the primary system.

After devoting approximately 5-3/4 hours to evaluation of the secondary control system problem, powered descent of the lunar module was initiated. The lunar module landed approximately 270 meters northwest of the planned landing site. The location of the landing site is latitude 8°59'29" S. and longitude 15°30'52" E. based on the coordinates of reference 2-29. Propellant for approximately 100 seconds of hover time remained at touchdown.

The first extravehicular activity was started after an 8-hour rest period. Television coverage of surface activity was delayed until the lunar roving vehicle systems were activated because the lunar module steerable antenna, used for initial lunar surface television transmission, remained locked in one axis and could not be used. The fourth lunar surface experiments package was deployed, but accidental breakage of the electronics cable rendered the heat flow experiment inoperative. After completing their activities at the experiments site, the crew drove the lunar roving vehicle west to Flag Crater where they made visual observations, photographed items of interest, and collected lunar samples. The inbound traverse route was just slightly south of the outbound route, and the next stop was Spook Crater. The crew then returned by way of the experiment station to the lunar module, at which time they deployed the solar wind composition experiment. The first extravehicular activity lasted approximately 7 hours 11 minutes, and the crew traveled approximately 4.2 kilometers in the lunar roving vehicle.

The second extravehicular traverse was south-southeast to a mare sampling area near the Cinco Craters on the north slope of Stone Mountain. The crew then drove in a northwesterly direction, making stops near Stubby and Wreck Craters. The last leg of the traverse was north to the experiments station and the lunar module. The second extravehicular activity lasted approximately 7 hours 23 minutes, and the crew traveled 11.1 kilometers in the lunar roving vehicle.

Four stations were deleted from the third extravehicular traverse because of time limitations. The crew first drove to the rim of North Ray Crater where photographs were taken and samples gathered, some from House Rock, the largest single rock seen during the extravehicular activities. The crew then drove southeast to the second sampling area, Shadow Rock. On completing activities there, the crew drove the vehicle back to the lunar module retracing the outbound

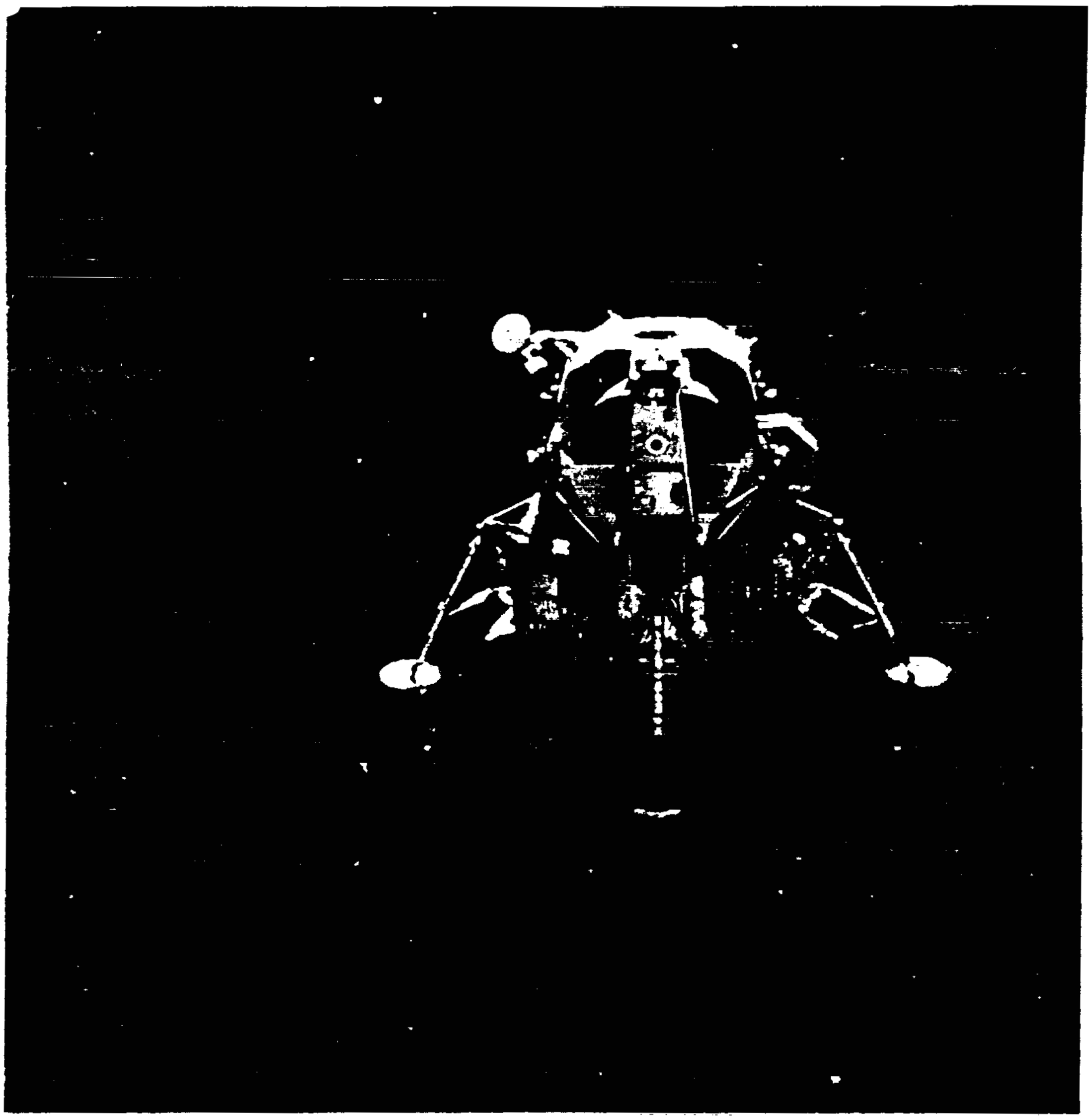

Figure 2-20.- Apollo 16 lunar module after undocking.

route. The third extravehicular activity lasted approximately 5 hours 40 minutes, and the distance traveled totaled 11.4 kilometers. The total weight of the lunar samples collected was 94 kilograms. The areas explored are described in greater detail in section 3.2.1.

While the lunar module crew was on the surface, the Command Module Pilot obtained photographs, measured physical properties of the moon, and made visual observations. Also the Command Module Pilot made comprehensive deep-space measurements, providing scientific data that could be used to validate findings from the Apollo 15 mission.

Lunar ascent, initiated after the crew had spent more than 71 hours on the lunar surface, was followed by normal rendezvous and docking. Attitude control of the lunar module ascent stage was lost at jettison; consequently, a deorbit maneuver was not possible. Analysis indicated that the ascent stage impacted the lunar surface before the Apollo 17 mission commenced; however, no data were available for substantiation.

A particles and fields subsatellite like that launched from Apollo 15 was launched into lunar orbit, and systems operation was normal. A planned spacecraft orbit shaping maneuver was not performed before ejection of the subsatellite; therefore, the subsatellite was placed in a nonoptimum orbit that resulted in a much shorter lifetime than planned. Loss of all subsatellite tracking and telemetry data on the 425th revolution (May 29, 1972) indicated that the subsatellite had impacted the lunar surface.

The mass spectrometer deployment boom stalled during a retract cycle and was, therefore, jettisoned before transearth injection. The second plane-change maneuver and some orbital science photography were deleted so that transearth injection could be performed approximately 24 hours earlier than originally planned.

Activities during the transearth coast phase of the mission included photography for a Skylab program study of the behavior and effects of particles emanating from the spacecraft, and the second light-flash observation session. During an extravehicular operation, the Command Module Pilot retrieved film cassettes from the scientific instrument module cameras, visually inspected the equipment, and exposed an experiment to provide data on microbial response to the space environment. Two midcourse corrections were made on the return flight to achieve the desired entry interface conditions.

Entry and landing sequences were normal. While on the drogue parachutes, the command module was viewed on television, and continuous coverage was provided through crew recovery. The spacecraft landed in the mid-Pacific near the planned target. Although the vehicle came to rest in the stable II attitude, it was uprighted in approximately 5 minutes. The crew was delivered on board the primary recovery ship, the U.S.S. *Ticonderoga*, 37 minutes after landing.

All of the primary mission objectives and most of the detailed objectives were met, even though the mission was terminated one day earlier than planned. Especially significant scientific data obtained were images and spectra of the earth's atmosphere and geocorona in the wavelength range below 1600 angstroms. Additional information about the Apollo 16 mission is contained in references 2-30 and 2-31.

2.4.12 Apollo 17 Mission

Apollo 17, the final Apollo mission, was the third in the series of lunar landing missions designed for maximum scientific return. As such, the spacecraft and launch vehicle were similar to those for Apollo 15 and 16. Some experiments included in the payload, however, were unique to this mission. The selected landing site was the Taurus-Littrow area.

The space vehicle was launched from Kennedy Space Center Launch Complex 39A at 12:33:00 a.m. e.s.t. (05:33:00 G.m.t.) on December 7, 1972, the only nighttime launch of an Apollo spacecraft (fig. 2-21). The crewmen for the flight were Eugene A. Cernan, Commander; Ronald E. Evans, Command Module Pilot; and Harrison H. Schmitt, Lunar Module Pilot.

The launch countdown had proceeded smoothly until 30 seconds before the scheduled ignition when a failure in the automatic countdown sequencer occurred and delayed the launch 2 hours 40

Figure 2-21.- Lift-off of Apollo 17 space vehicle.

minutes. A successful launch placed the S-IVB/spacecraft combination in a circular earth orbit in preparation for translunar injection. After ejection of the docked spacecraft, the S-IVB stage was maneuvered for lunar impact, which occurred approximately 84 miles from the planned point. The impact was recorded by the Apollo 12, 14, 15, and 16 passive seismometers.

Translunar coast time was shortened to compensate for the launch delay. Activities during translunar coast included a heat flow and convection demonstration, a continuation of the series of light-flash investigations conducted by previous crews, and a midcourse correction to achieve the desired altitude of closest approach to the lunar surface. The scientific instrument module door was jettisoned as planned approximately 4-1/2 hours before lunar orbit insertion. The insertion maneuver resulted in a 170- by 53-mile orbit. Approximately 5 hours later, the first of two descent orbit insertion maneuvers was performed lowering the orbit to 59 by 15 miles. The command and service module/lunar module combination were retained in this orbit approximately 17 hours before the spacecraft were undocked and separated. After undocking, the command and service module orbit was circularized; and the second lunar module descent orbit insertion maneuver was performed, lowering the pericynthion to approximately 6 miles. Powered descent was initiated from this orbit, and the lunar module landed within 200 meters of the preferred landing point. The landing site location is latitude 20°9'55" N. and longitude 30°45'57" E. based on the coordinates of reference 2-32. Approximately 117 seconds of hover time remained at engine shutdown.

The first extravehicular activity began 4 hours after landing. The lunar roving vehicle was off-loaded, equipment was unstowed, and the lunar surface experiments package was deployed approximately 185 meters west-northwest of the lunar module. At the experiments package deployment site, the Commander drilled two holes for heat-flow experiment probes and one deep-core hole. The crew sampled two geologic units, deployed two explosive packages, and took seven traverse gravimeter measurements during the extravehicular activity. The crew also collected samples weighing approximately 14 kilograms during the 7 hours 12 minutes of extravehicular activity.

The second extravehicular activity began at approximately 138 hours mission elapsed time. During the traverse, the extravehicular plan was modified to allow more time at points of geological interest. Three explosive packages were deployed in support of the lunar seismic profiling experiment and seven traverse gravimeter measurements were taken. Approximately 34 kilograms of samples were gathered during the 7 hours 37 minutes of extravehicular activity.

The crew commenced the third extravehicular activity after a 15-1/2-hour period in the lunar module. Specific sampling objectives were accomplished, and nine traverse gravimeter measurements were made. The surface electrical properties experiment was terminated because the receiver temperature was increasing to a level which could have affected the data tape. Consequently, the tape recorder was removed on the way back to the lunar module. Samples weighing approximately 62 kilograms were obtained during the 7-hour 15-minute extravehicular period for a total of approximately 110 kilograms for the mission. The lunar roving vehicle was driven about 34 kilometers during the three extravehicular activities. The total extravehicular time was 22 hours 4 minutes.

Numerous science activities were conducted in lunar orbit while the surface was being explored. In addition to the panoramic camera, the mapping camera, and the laser altimeter (which were used on previous missions), three new experiments were included in the service module. An ultraviolet spectrometer measured lunar atmospheric density and composition, an infrared radiometer mapped the thermal characteristics of the moon, and a lunar sounder acquired data on subsurface structure. The command and service module orbit did not decay as predicted while the lunar module was on the lunar surface. Consequently, a small orbital trim maneuver was performed to lower the orbit. In addition, a planned plane-change maneuver was made in preparation for rendezvous.

Lunar ascent was initiated after a surface stay time of almost 75 hours. Rendezvous and docking were normal; and, after transfer of samples and equipment from the ascent stage to the command module, the ascent stage was jettisoned and deorbited. The impact point was about 10 kilometers southwest of the Apollo 17 landing site. After spending an additional day in lunar orbit performing scientific experiments, the crew performed the transearth injection maneuver at the planned time.

During transearth coast, the Command Module Pilot conducted a 1-hour 6-minute extravehicular operation in which he retrieved film cassettes from the scientific instrument module bay. The crew later performed another light-flash experiment, operated the infrared radiometer and ultraviolet spectrometer, and made a transearth midcourse correction.

Entry and landing sequences were normal with the command module landing in the Pacific Ocean west of Hawaii, approximately 1 mile from the planned location. Apollo 17 was the longest mission of the program (301 hours 51 minutes 59 seconds) and brought to a close one of the most ambitious and successful endeavors of man. The Apollo 17 mission, the most productive and trouble-free lunar landing mission, represented the culmination of continual advancements in hardware, procedures, and operations. Reference 2-33 contains detailed information on the mission operations and hardware performance, and reference 2-34 has preliminary science results.

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2-18. Surveyor III Site Map 1:2 000. First ed., prepared for NASA by Army Map Service, Corps of Engineers, January 1968.

2-19. Apollo 12 Mission Report. NASA Johnson Space Center Report MSC-01855, March 1970.

2-20. Apollo 12 Preliminary Science Report. NASA SP-235, 1970.

2-21. Apollo 13 Anomaly Report No. 1 - Cryogenic Tank 2 Anomaly. NASA Johnson Space Center Report MSC-02545, July 1970.

2-22. Apollo 13 Mission Report. NASA Johnson Space Center Report MSC-02680, September 1970.

2-23. Lunar Topographic Photomap of Fra Mauro 1:25 000. Third ed., prepared by Mapping Sciences Laboratory, NASA Johnson Space Center, November 1970.

2-24. Apollo 14 Mission Report. NASA Johnson Space Center Report MSC-04112, May 1971.

2-25. Apollo 14 Preliminary Science Report. NASA SP-272, 1971.

2-26. Rima Hadley Lunar Photomap, Orbiter V Site 26.1 1:250 000. First ed., prepared by U.S. Army Topographic Command, April 1970.

2-27. Apollo 15 Mission Report. NASA Johnson Space Center Report MSC-05161, December 1971.

2-28. Apollo 15 Preliminary Science Report. NASA SP-289, 1972.

2-29. Lunar Topographic Photomap of Descartes 1:25 000. First ed., prepared by U.S. Army Topographic Command, January 1972.

2-30. Apollo 16 Mission Report. NASA Johnson Space Center Report MSC-07230, August 1972.

2-31. Apollo 16 Preliminary Science Report. NASA SP-315, 1972.

2-32. Lunar Topographic Photomap of Taurus-Littrow 1:25 000. First ed., prepared by U.S. Army Topographic Command, September 1972.

2-33. Apollo 17 Mission Report. NASA Johnson Space Center Report JSC-07904, March 1973.

2-34. Apollo 17 Preliminary Science Report. NASA SP-330, 1973.

3.0 SCIENCE SUMMARY

3.1 INTRODUCTION

The reality of, and enthusiasm for, lunar science greatly increased with the safe return of the Apollo 11 astronauts from man's landing on the moon. Although serious effort in planning, designing, developing, testing, and training for the scientific aspects of the Apollo program had been started much earlier by NASA, the greater emphasis had been correctly concentrated on the accomplishment of the safe lunar landing and return of the crews. Early accomplishment of the spacecraft operational objectives opened the way for more attention to be focused on the scientific potential of Apollo missions. The operational and scientific success of each successive mission stimulated a more vigorous interest in the solar system and established the study of the moon as a modern interdisciplinary science.

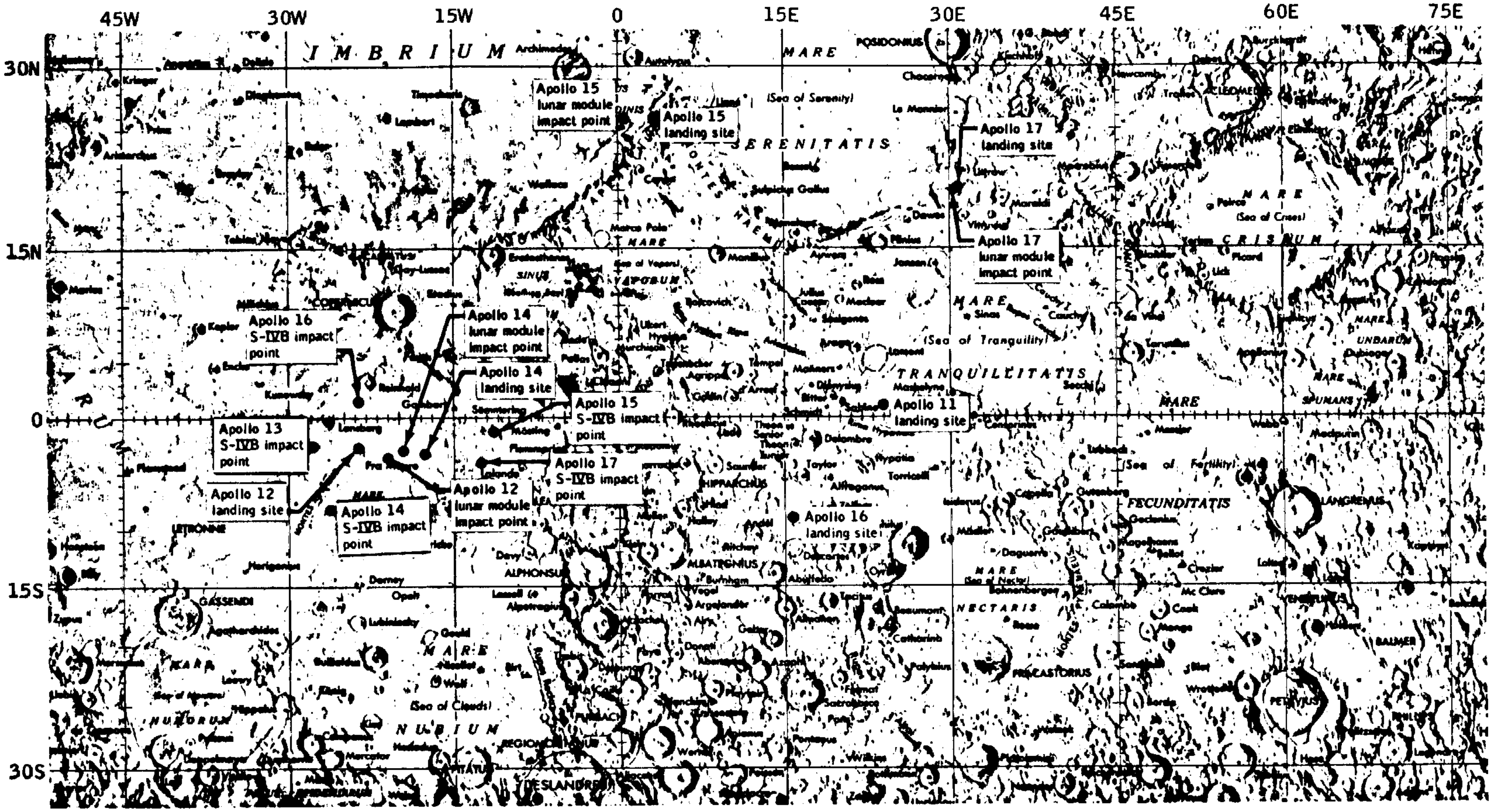
Although a considerable amount of scientific data was obtained during the early Apollo missions (Apollo 7 through 14), a significantly greater amount of data was obtained as the result of the Apollo 15, 16, and 17 missions. For each of the latter missions, a diverse set of experiments was installed in the service module and collected data during lunar orbit. These experiments increased the scientific scope of the missions, and the data obtained complemented the data from the experiments being operated on the lunar surface. In addition, more extensive first-hand exploration of the lunar surface was accomplished by the crews on these missions because longer stay times were allowed, and because the addition of the lunar roving vehicle increased the range of travel on the lunar surface as well as the load of instruments, equipment, and lunar sample material transported on crew traverses. Also, more science data were provided by the lunar surface complement of experiments operated by the crews during the extravehicular activities and by the continuing postmission telemetry from the science stations established at each site.

The large amount of data and material collected as the result of the lunar missions will continue to provide study sources for many years. The crews took thousands of science-quality photographs on the lunar surface and from lunar orbit. Approximately 380 kilograms of lunar soil and rocks were brought back to earth in the returning spacecraft. Five long-term science stations were established on the lunar surface with 22 operating experiments continuing to transmit science data to the earth. The Apollo 12 crew retrieved selected components of a previously landed Surveyor spacecraft. Many materials were transported to the moon, exposed in the lunar environment, and returned for analysis and study.

Findings resulting from the Apollo lunar science program are discussed in the following sections. Science hardware performance is also discussed in conjunction with each experiment. Much of the information in these sections was extracted from the Apollo Preliminary Science Report series. In some cases, publication of results was scheduled by NASA before sufficient data were available to the principal investigators for comprehensive analyses. Thus, results published in the early reports were not as complete as in later reports. In these cases, an attempt has been made to include the latest information. References 3-1, 3-2 and 3-3 provide reviews of the present understanding of the moon's composition and history.

3.2 LUNAR SURFACE SCIENCE

During each Apollo lunar landing mission, the crewmen emplaced and activated a lunar geophysical observatory to be controlled and monitored from earth, collected samples of lunar soil and rock, photographically documented the geologic features of the landing area, and performed other exploration activities. The locations of the Apollo landing sites are shown in figure 3-1 and the lunar surface science activities (formal experiments and science detailed objectives) are identified in table 3-I. The Apollo missions during which the activities were accomplished are also indicated in the table.



LUNAR CHART (LPC-1)
SCALE 1:10,000,000
1ST EDITION MARCH 1970

Figure 3-1.- Apollo landing sites and impact locations on the lunar surface.

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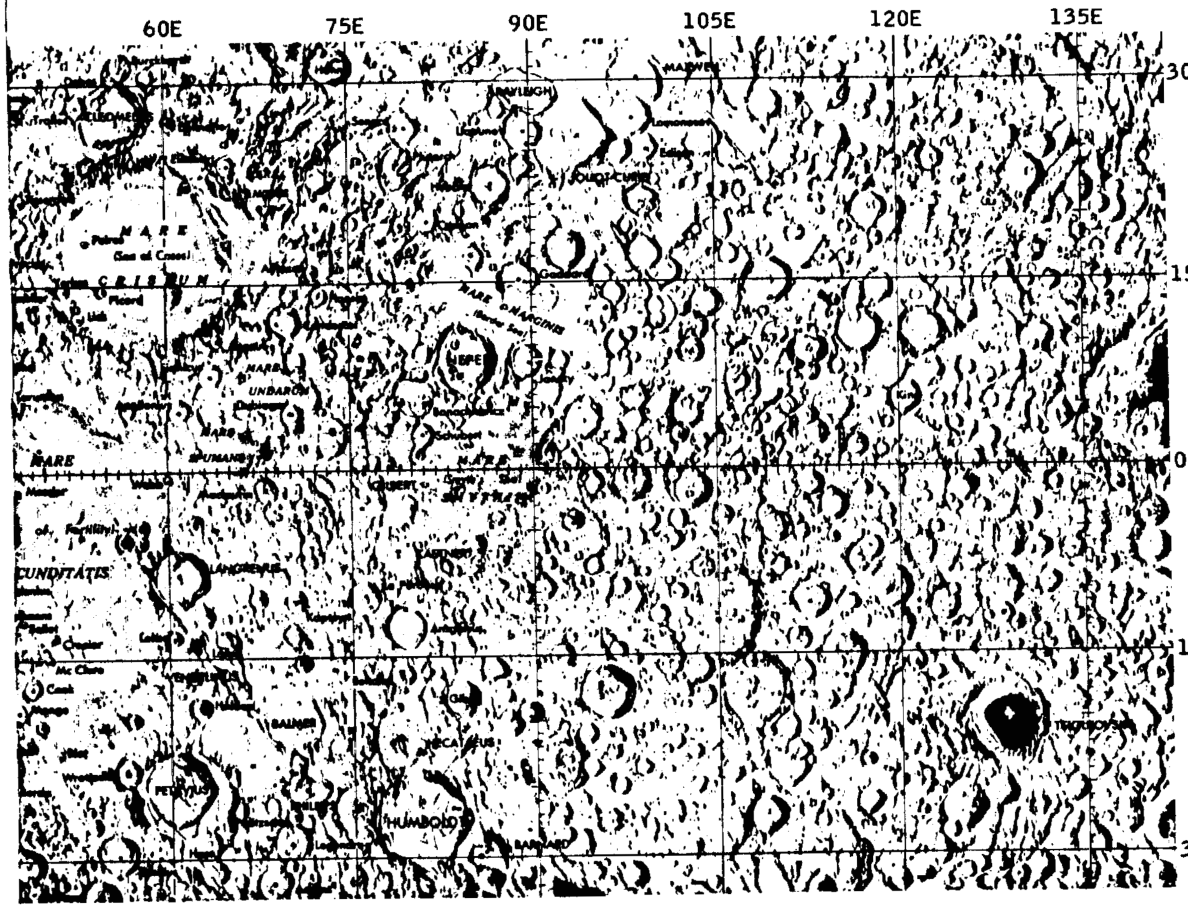

MERCATOR PROJECTION (45°N to 45°S)
Scale 1:10,000,000 at 34°N and S Latitudes.

PREPARED BY THE AERONAUTICAL CHART AND INFORMATION CENTER, UNITED STATES AIR FORCE, UNDER THE DIRECTION OF THE DEPARTMENT OF DEFENSE

Lithographed by ACIC 3-70 [illegible]

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TABLE 3-I.- APOLLO LUNAR SURFACE SCIENCE SUMMARY

Experiment/objective	Experiment number	Mission 11	12	14	15	16	17
[a]Lunar geology investigation	S-059	X	X	X	X	X	X
Soil mechanics experiment	S-200	X	X	X	X	X	X
Lunar sample analysis	--	X	X	X	X	X	X
[b]Passive seismic experiment	S-031	X	X	X	X	X	
[b]Active seismic experiment	S-033			X		X	
[b]Sesimic profiling experiment	S-203						X
[b]Lunar surface magnetometer experiment	S-034		X		X	X	
Portable magnetometer experiment	S-198			X		X	
[b]Heat flow experiment	S-037				X	X	X
[b]Lunar surface gravimeter experiment	S-207						X
Traverse gravimeter experiment	S-199						X
Surface electrical properties experiment	S-204						X
Lunar neutron probe experiment	S-299						X
[b]Laser ranging retro-reflector	S-078	X		X	X		
[b]Charged-particle lunar environment experiment	S-038			X			
[b]Solar wind spectrometer experiment	S-035		X		X		
Solar wind composition experiment	S-080	X	X	X	X	X	
[b]Suprathermal ion detector experiment	S-036		X	X	X		
[b]Cold cathode gage experiment	S-058		X	X	X		
Cosmic ray detector (sheets) experiment	S-152					X	X
[b]Lunar dust detector experiment	M-515	X	X	X	X		
[b]Lunar ejecta and meteorites experiment	S-202						X
[b]Lunar atmospheric composition experiment	S-205						X
Surveyor III analysis	--		X				
Long-term lunar surface exposure	--						X
Far ultraviolet camera/spectrograph	S-201					X	

[a] Field geology activities included documentary photography, collection of lunar material samples, and crew observations.

[b] Part of an Apollo lunar surface experiments package.

As noted in table 3-I, some experiments are part of the geophysical observatories called Apollo lunar surface experiments packages. Using a long-life self-contained power source (radioisotope thermoelectric generator) and communications equipment, each Apollo lunar surface experiments package operates as a remote science station to collect and transmit to earth scientific and engineering data obtained over extended periods of time. The system was flown on Apollo 12 and all subsequent Apollo missions. The aborted lunar landing of Apollo 13 resulted in the loss of the package of experiments; however, the overall program objectives were met by rearranging the experiment assignments of the subsequent flights. A variation of the Apollo lunar surface experiments package, known as the early Apollo scientific experiments package, was flown on the Apollo 11 mission. This package was selected to minimize deployment time and to simplify crew tasks during the first extravehicular activity on the lunar surface.

Rock and soil samples have been collected from most of the major physiographic or photogeologic units identified on the lunar surface prior to the Apollo missions. This collection has and will continue to provide a steady flow of data on the history of the moon. The staggering amount of published material presenting the results of experiments and the analyses of lunar samples cannot be covered in this document. However, the major findings are briefly summarized.

The moon may have accreted to its present mass 4.6 billion years ago. Early activity may have included large-scale magmatic differentiation to produce an anorthositic crust. Throughout early lunar history until about 3.9 billion years ago, the lunar surface was subjected to intense bombardment which produced most of the large ring basins and the deposits of the lunar highlands. Samples from the highlands indicate a very complex history of shock melting and fracturing of the anorthositic crust. Fragments interpreted as plutonic rocks from the crust have been found in some breccia samples collected at highland sites.

Millions of years after the period of intense bombardment, volcanism along the margins of the large ring basins, such as Mare Imbrium, began to fill the basins with lava flows. In a period from about 3.8 to 3.1 billion years ago, these basins were filled with iron- and titanium-rich basaltic lavas; these are now the flat, dark colored mare plains.

Meteoritic bombardment of the lunar surface has continued to the present, although less vigorously than in the past, forming craters and covering the surface with loose debris or regolith. Studies of soil samples from the regolith sections (cores) reveal an incredibly complex history of bombardment by meteorites and galactic and solar radiation through time.

The moon is now inactive, having cooled to a state of inactivity more than 3 billion years ago, the time of formation of the youngest lavas. In contrast with the earth, there is no water and there are no life forms. The surface is, however, constantly changing due to bombardment by cosmic debris.

3.2.1 Geology of the Apollo 11 Landing Site

Tranquillity Base, the Apollo 11 landing site, is approximately 20 kilometers south-southwest of the crater Sabine D in the southwestern part of Mare Tranquillitatis (Sea of Tranquillity) and 41.5 kilometers north-northeast of the western promontory of the Kant Plateau, which is the nearest highland region. The Surveyor V spacecraft is approximately 25 kilometers north-northwest of the Apollo 11 landing site, and the impact crater formed by Ranger VIII is 68 kilometers northeast of the landing site (ref. 3-4). Figure 3-2 shows the Apollo 11 landing site relative to the Surveyor V and Ranger VIII locations. Figure 3-3 is a diagram of the lunar surface activity areas.

The following observations suggest that the mare material is relatively thin.

a. An unusual ridge ring named Lamont, which occurs in the southwestern part of the mare, may be localized over the shallowly buried rim of a premare crater.

b. No large positive gravity anomaly, such as those occurring over the deep mare-filled circular basins, is associated with the Sea of Tranquillity (ref. 3-5).

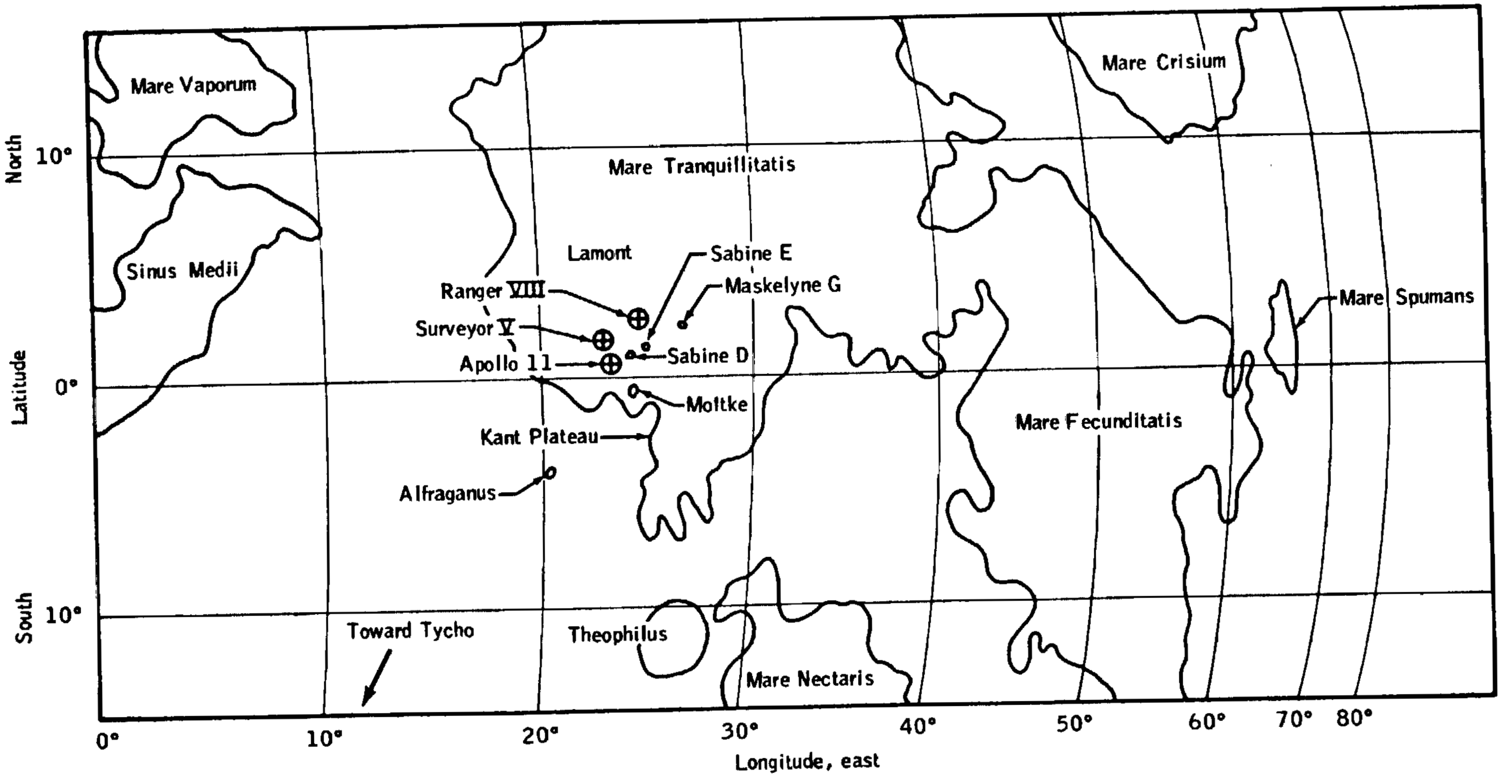

Figure 3-2.- Apollo 11 landing location relative to Surveyor V and Ranger VIII.

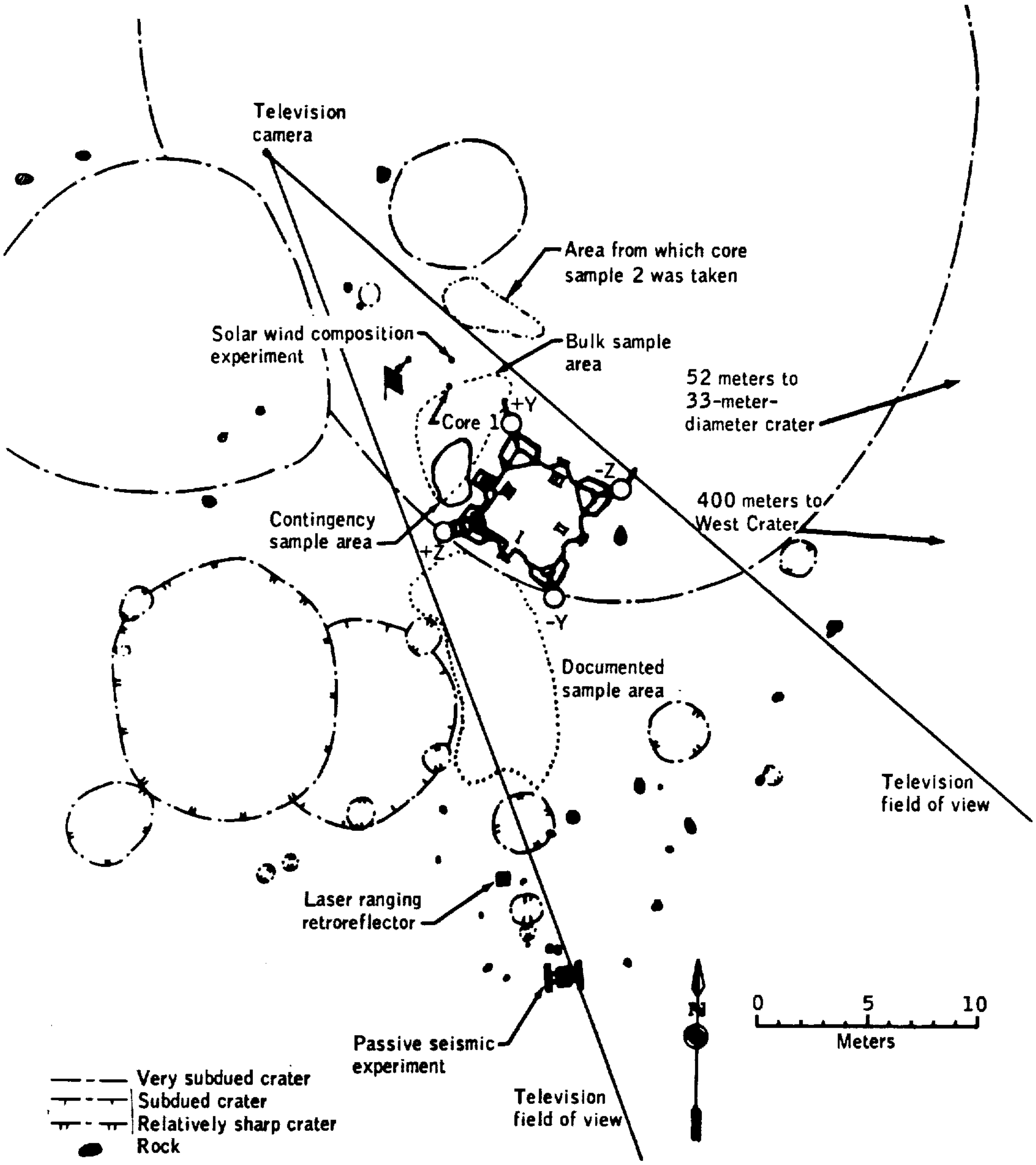

Figure 3-3.- Diagram of Apollo 11 lunar surface activity area.

The southern part of the Sea of Tranquillity is crossed by relatively faint but distinct rays trending north-northwest and by prominent secondary craters associated with the crater Theophilus, which is located 320 kilometers southeast of the landing site. Approximately 15 kilometers west of the landing site is a fairly prominent ray that trends north-northeast. The crater with which this ray is associated is not definitely known; the ray may be related to the crater Alfraganus, 160 kilometers southwest of the landing site, or to Tycho, approximately 1500 kilometers southwest of the landing site. Neither the ray that trends north-northeast nor any of the rays that trend north-northwest cross the landing site; these rays are sufficiently close, however, so that material from Theophilus, Alfraganus, or Tycho is possibly found near the landing site. Craters such as Sabine D and Sabine E (fig. 3-2), with a diameter greater than 1 kilometer, may have been excavated partly in premare rocks; and premare rock fragments that have been ejected from these craters may also occur near the lunar module landing site (ref. 3-6).

Based on albedo and crater density, three geologic units can be distinguished in the mare material near the landing site. The lunar module landed on the most densely cratered unit of these three geologic units. These units may correspond to lava flows of different ages; if so, the unit at the landing site is probably the oldest.

The approximately 21 kilograms of lunar material returned by the Apollo 11 crew were characterized by the lunar sample analysis planning team as follows (ref. 3-7): The samples from Tranquillity Base consist of basaltic igneous rocks; microbreccias, which are a mixture of rock, glass and mineral fragments; and lunar soil. The soil is a diverse mixture of crystalline and glassy fragments with various shapes; the soil also includes fragments of iron, some of which may be of meteoric origin. Most rock fragments are similar to and apparently derived from the larger igneous rocks; the rocks in turn were probably once part of the underlying bedrock. A few of the crystalline fragments are totally different from any of the igneous rocks of the Tranquillity site. A strong possibility exists that these fragments represent samples from the nearby highlands.

Many rock surfaces and individual fragments in the soil show evidence of surface erosion by hypervelocity impacts. Examination of the surfaces of the glassy fragments, which are themselves formed by impact processes, shows that these objects contain beautifully preserved microscopic pits as small as 10 microns in diameter. These pits are the result of high velocity impacts by tiny particles. There is also evidence that the impact process is accompanied by local melting, splashing, evaporation, and condensation.

The crystalline rocks, which have typical igneous textures, range from very-fine-grained vesicular rocks to medium-grained equigranular rocks. The most common minerals are pyroxene (often highly zoned with iron-rich rims), plagioclase, ilmenite, olivine, and cristobalite. Free metallic iron and troilite, both of which are extremely rare on earth, are common accessory minerals in the igneous rocks. All the silicate minerals are unusually transparent and clear because of the complete absence of hydrothermal alteration. Laboratory experiments with silicate liquids similar in composition to the lunar liquids show that, at the time of crystallization, the observed phases can have coexisted only in a very dry, highly reducing system; the partial pressure of oxygen in this system is estimated to be 10^{-13} atmosphere. This pressure is more than five orders of magnitude lower than that for typical terrestrial basaltic magmas. The very low abundance of ferric ions in pyroxenes, determined by Mossbauer spectroscopy and electron spin resonance, is further evidence of the low oxidation level of the magmas. The melting experiments also indicate that 98 percent of the primary igneous liquid crystallized in the temperature range 1480° to 1330° K, with minor interstitial liquids continuing to crystallize down to temperatures around 1220° K. Microscopic and microprobe examination provides clear-cut evidence for the existence of an interstitial liquid rich in potassium and aluminum that probably was immiscible with the main liquid. Further, calculations indicate that the viscosity of the lunar magmas was approximately an order of magnitude lower than that of terrestrial basaltic magmas. This characteristic may play a significant role in the explanation of the textural features, the differentiation mechanisms that produced the observed chemical composition, and the morphological features of the lunar seas themselves.

The regolith consists chiefly of particles less than 1 millimeter in diameter. The regolith is weak and easily trenched to depths of several centimeters. Surface material was easily dislodged when kicked. The flagpole for the United States flag and the core tubes, when pressed into the surface, penetrated with ease to a depth of 10 to 12 centimeters. At that depth, the regolith was not sufficiently strong, however, to hold the core tubes upright; a hammer was needed to drive the core tubes to depths of 15 to 20 centimeters. The tubes, rods, and scoop that were pressed into the subsurface at several sample sites encountered rocks in the subsurface.

The crewman's boots left prints approximately 3 millimeters to 3 centimeters deep in the fine-grained regolith material. Smooth molds of the boot treads were preserved in the bootprints, and angles of 70° were maintained in the walls of the bootprints. The fine-grained surficial material tended to break into slabs, cracking as far as 12 to 15 centimeters from the edges of the footprints.

The finest fraction of the regolith adhered weakly to boots, gloves, space suits, handtools, and rocks on the lunar surface. On repeated contact, the coating on the boots thickened until boot color was completely obscured. When the fine particles of the regolith were brushed off, a stain remained on the space suits.

In places where fine-grained material was kicked by the crewmen, the freshly exposed material was conspicuously darker than the undisturbed surface. The subsurface material probably lies at depths no greater than a millimeter from the surface. The existence of a thin surface layer of lighter colored material at widely scattered localities indicates that some widespread process of surface material alteration is occurring on the moon.

Fillets (fine-grained material which is banked against the sides of some of the larger rock fragments) were observed at least as far as 70 meters from the lunar module, and most fillets are almost certainly natural features of the surface. On sloping surfaces, the crew observed that the fillets were larger on the uphill sides of rocks than on the downhill sides. The sides of rocks are ballistic traps, and the fillets have probably been formed by the trapping of low-velocity secondary particles. Asymmetric development of fillets around rocks on slopes may be caused partly by preferential downhill transport of material by ballistic processes and partly by downhill creep or flow of the fine-grained material (ref. 3-6).

3.2.2 Geology of the Apollo 12 Landing Site

The Apollo 12 landing site is on the northwestern rim of the 200-meter-diameter crater in which the Surveyor III spacecraft (fig. 3-4) touched down on April 20, 1967, in the eastern part of Oceanus Procellarum (Ocean of Storms), approximately 120 kilometers southeast of the crater Lansberg and due north of the center of Mare Cognitum (Known Sea). The landing site is on a broad ray associated with the crater Copernicus, 370 kilometers to the north. The landing site is characterized by a distinctive cluster of craters ranging in diameter from 50 to 400 meters. Two geologic traverses (fig. 3-5) were made on or near the rims of these craters and on deposits of ejecta from the craters. During the traverses, the crew collected approximately 34 kilograms of lunar material.

The lunar regolith at the Apollo 12 landing site is composed of fragmental material which ranges in size from particles too fine to be seen with the naked eye to blocks several meters in diameter. Along several parts of the traverse made during the second extravehicular activity period, the crew found fine-grained material of relatively high albedo that in some places was in the shallow subsurface and in other places lay on the surface. Some of this light-gray material may constitute a discontinuous deposit that is observed through telescopes as a ray of Copernicus.

Darker regolith material that generally overlies the light-gray material is only a few centimeters thick in some places but probably thickens greatly on the rims of some craters. The darker material varies from place to place in the size, shape, and abundance of its constituent particles and in the presence or absence of patterned ground. Most local differences are probably the result of local cratering events.

Many crew comments concerned the large amount of glass contained in the regolith. Irregularly shaped, small fragments of glass and glass beads are abundant both on and within the regolith; glass is also splattered on some blocks of rock at the surface and is found within many shallow craters.

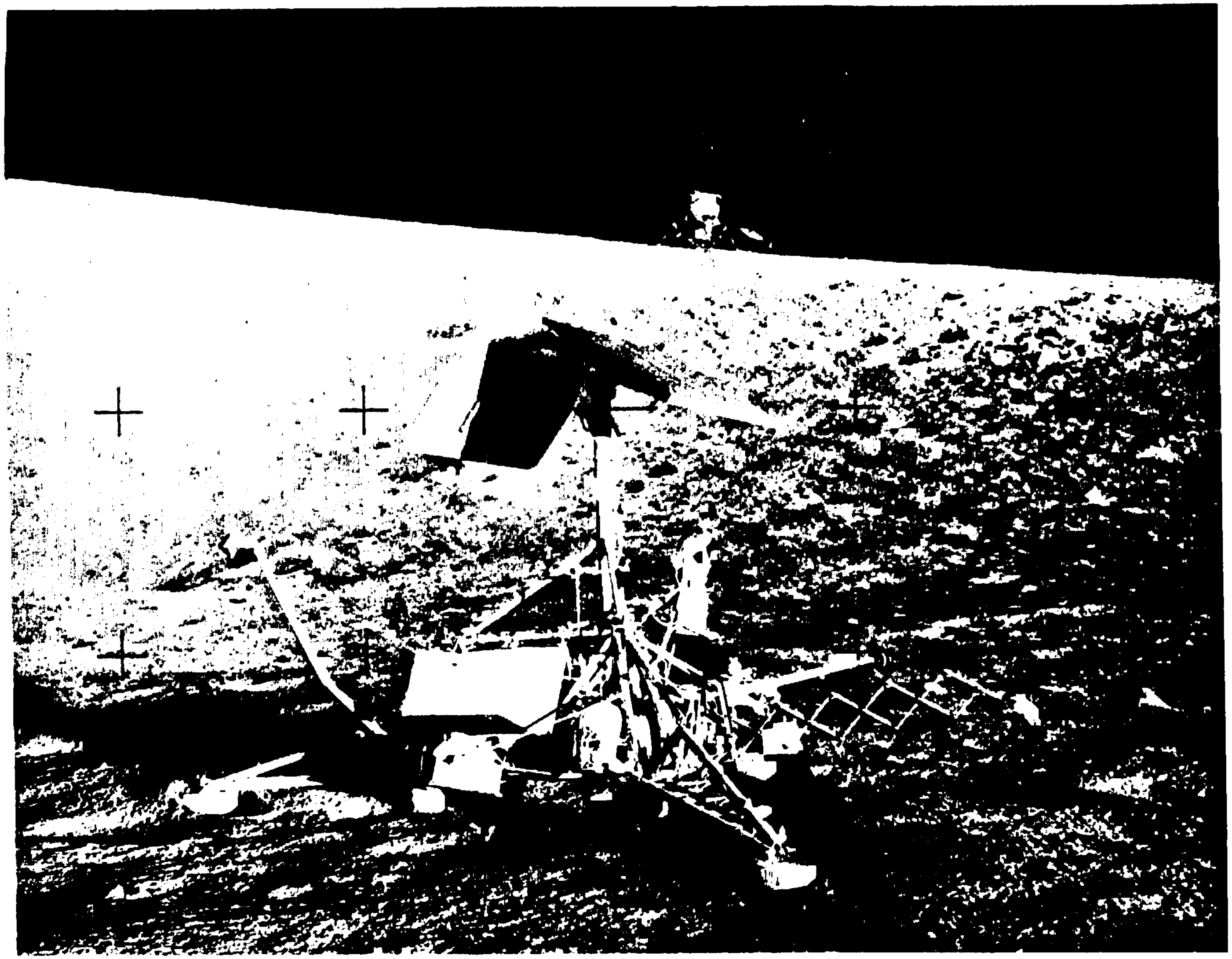

Figure 3-4.- Surveyor III with Apollo 12 lunar module in background.

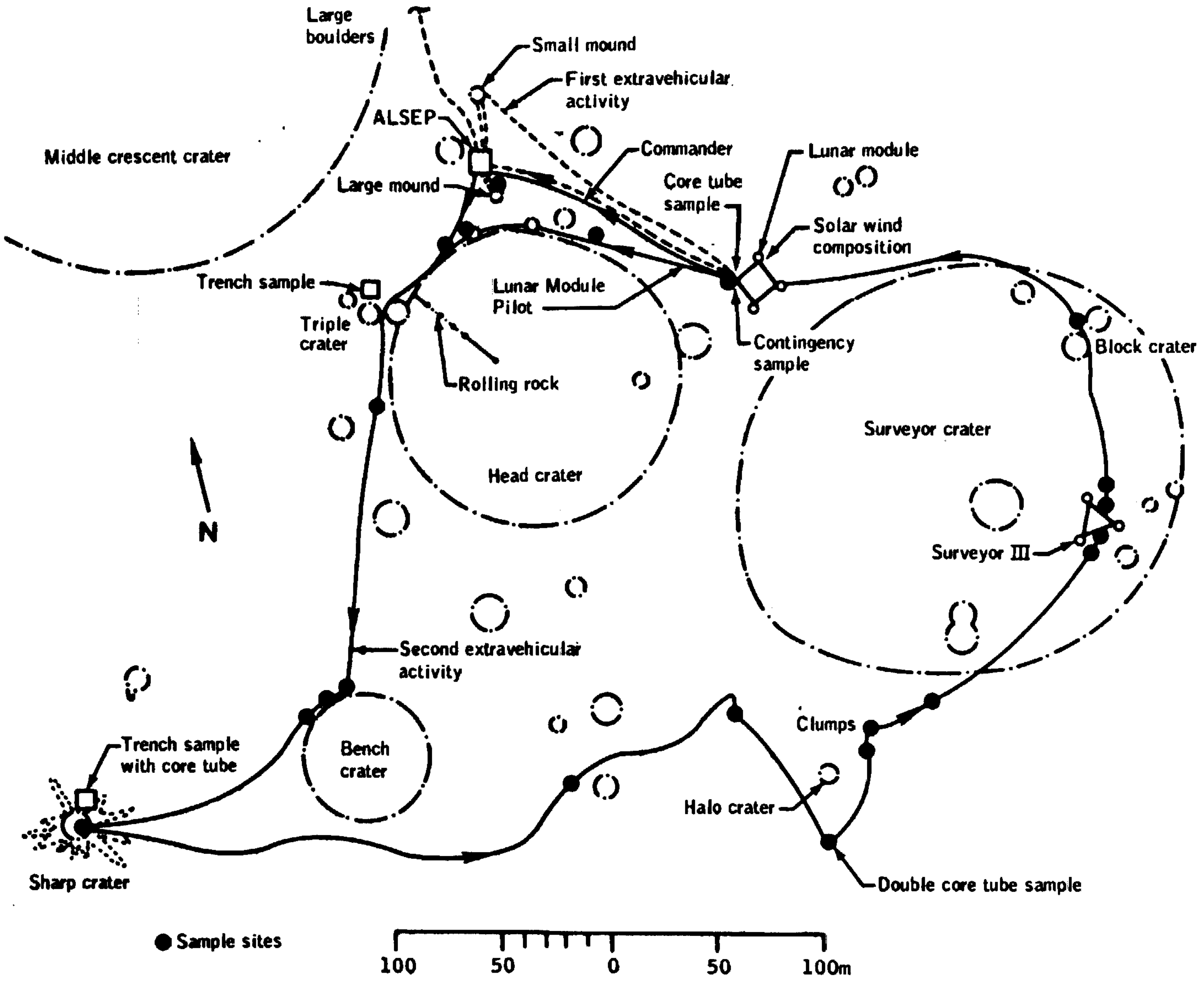

Figure 3-5. - Apollo 12 traverse diagram.

Much of the surface in the area of the geologic traverse made during the second extravehicular activity period is patterned by small, linear grooves. These grooves are visible on the returned photographs and were reported from several localities by the crew. The grooves are similar in appearance to those which are visible in some of the photographs from the Apollo 11 mission. The linear features have been interpreted as being caused by drainage of fine-grained material into fractures in the underlying bedrock. This interpretation would imply northeast- and northwest-trending joint sets in the bedrock of the Apollo 11 site and north- and east-trending joint sets in the Apollo 12 site bedrock.

One notable difference between the collection of rocks obtained at the Apollo 12 landing site and the collection obtained at Tranquillity Base is the ratio of crystalline rocks to microbreccia. At the Apollo 12 site, the rocks collected were predominantly crystalline, whereas, at Tranquillity Base, approximately half the rocks collected were crystalline and half were microbreccia. This difference is probably attributable to the fact that the rocks collected at the Apollo 12 landing site were primarily on or near crater rims. On the crater rims, the regolith is thin or only weakly developed, and many rocks observed are probably derived from craters that have been excavated in bedrock that is well below the regolith. By contrast, Tranquillity Base is on a thick, mature regolith, where many observed rock fragments were produced by shock lithification of regolith material and were ejected from craters too shallow to excavate bedrock (ref. 3-8).

Analysis of the returned Apollo 12 lunar samples showed the following:

a. Although still old by terrestrial standards, the Apollo 12 rocks are approximately 600 to 700 million years younger than the rocks from the Apollo 11 site.

b. Whereas the Apollo 11 collection contained approximately half vitric breccias, the Apollo 12 collection contained only two breccias in the 45 rocks collected.

c. The regolith at the Apollo 12 site is approximately half as thick as the regolith at the Apollo 11 site. Complex stratification within the regolith is evident.

d. A bright-colored layer of material referred to as KREEP was sampled at varying depths. It consists of fragments rich in potassium, rare earth elements, and phosphorous. It may have originated as ejecta from a distant, large crater, perhaps Copernicus.

e. The amount of solar wind material in the Apollo 12 fines is considerably lower than that in the Apollo 11 fines.

f. The lavas, in contrast to those from Apollo 11, display a wide range in both modal mineralogy and primary texture, indicating a variety of cooling histories.

g. Chemically, the "nonearthly" character of the Apollo 11 samples (high refractory element concentration and low volatile element concentration) is also noted in the Apollo 12 samples but to a lesser degree.

The soil at the Apollo 12 site is similar in appearance and behavior to the soils encountered at the Apollo 11 and the Surveyor equatorial landing sites. However, local variations in soil texture, color, grain size, compactness, and consistency are evident. No direct correlation between crater slope angle and consistency of soil cover is apparent. The consistency of the soil cover depends mainly on the geologic history of lunar terrain features and local environmental conditions.

3.2.3 Geology of the Apollo 14 Landing Site

The Apollo 14 landing site is in a broad, shallow valley between radial ridges of the Fra Mauro Formation, approximately 500 kilometers from the edge of Mare Imbrium (Sea of Rains, and also referred to geologically as the Imbrium Basin), which is the largest circular mare on the moon. The crater Copernicus lies 360 kilometers to the north, and the bright ray material that emanates from Copernicus covers much of the landing site region. The Fra Mauro region is an area of prime scientific interest because this region contains some of the most clearly exposed geological formations that are characteristic of the Fra Mauro Formation.

The Fra Mauro Formation is an extensive geological unit that is distributed in an approximately radially symmetric fashion around the Sea of Rains over much of the near side of the moon. Stratigraphic data indicate that the Fra Mauro Formation is older than the mare at the Apollo 11 and 12 sites. The Formation is thought to be part of the ejecta blanket that resulted from the excavation of the Imbrium Basin. The Apollo 14 landing site thus offered an opportunity to sample material that had been shocked during one of the major cataclysmic events in the geological history of the moon and, thereby, to determine the date of the event. Furthermore, because of the size of the Imbrium Basin, the belief was that some material had come from deep (tens of kilometers) within the original lunar crust. Thus, a landing at the Fra Mauro Formation, in principle, was expected to offer an opportunity to sample the most extensive vertical section available of the primordial moon (ref. 3-9).

The lunar module landed approximately 1100 meters west of Cone Crater,* which is located on the ridge of the Fra Mauro Formation. Cone Crater is a sharp-rimmed, relatively young crater approximately 340 meters in diameter that ejected blocks of material as much as 15 meters across, which were derived from beneath the regolith. Sampling and photographing of these blocks were the primary objectives of the mission. Rays of blocky ejecta from Cone Crater extend westward beyond the landing site. The landing took place on a smooth terrain unit recognized in photographs previously taken during earlier Lunar Orbiter and Apollo missions. Sampling and describing this geological unit was another important objective of this mission.

During the first period of extravehicular activity, the crew traversed westward over the smooth terrain for a round-trip distance of approximately 550 meters and deployed the Apollo lunar surface experiments package (fig. 3-6). The crew covered a round-trip distance of approximately 2900 meters eastward from the lunar module during the second extravehicular activity (fig. 3-6). During the traverse, the crew crossed the smooth terrain, the Fra Mauro ridge unit, and a section through the continuous ejecta blanket of Cone Crater to within 20 meters of the crater rim crest. Forty-eight rock samples, the locations of which have been determined, were collected at points along the traverse. The modular equipment transporter (sec. 4.8) was used to transport the samples and the collection tools. Approximately 43 kilograms of lunar material, including 69 rock samples, were collected during the two periods of extravehicular activity.

Although the soil surface texture and appearance at the Apollo 14 landing site are similar to those at the Apollo 11 and 12 landing sites, a greater variation exists in the characteristics of the soil at shallow depths (a few centimeters) in both lateral and vertical directions than had previously been supposed. The stratigraphy at the trench site showed a dark, fine-grained material (to a depth of 3 to 5 centimeters) underlain by a very thin glassy layer that, in turn, is underlain by a material of medium to coarse sand gradation. As had been the case in previous missions, dust was easily kicked up and tended to adhere to any surface contacted; however, overall dust was less of a problem than on previous missions. No difficulty was encountered in digging a trench into the lunar surface. Because of unexpectedly low cohesion of the soil at the trench site, the trench sidewalls caved in at somewhat shallower trench depths than had been predicted.

The Apollo 14 site is densely covered with craters in all stages of destruction. Some craters as much as 400 meters across have undergone nearly complete destruction, and the overlapping of relatively large, very gentle depressions gives the topography at the site a strongly undulating aspect. In contrast, the largest craters that have undergone nearly complete destruction at the Apollo 11 and 12 landing sites are approximately 50 to 100 meters in diameter.

The lunar regolith at Fra Mauro is thicker than at the mare sites. The surface material is finer grained in the western portion of the site away from the Cone Crater ejecta blanket than in the continuous ejecta blanket itself. Rock fragments larger than a few centimeters in diameter are rare in the western part of the site and become progressively more abundant toward Cone Crater. The regolith appears to be looser and less cohesive than that developed on the mare material; downslope movement of this loose debris has caused the eradication of small craters on slopes and extensive slumping of crater walls.

Boulders as large as 15 meters in diameter are present on the rim of Cone Crater; photographs of these boulders provided the first dramatic glimpse of relatively large segments derived from lunar bedrock and of detailed rock structures (fig. 3-7). Smaller boulders occur throughout the Cone Crater ejecta blanket and as isolated occurrences on raylike extensions of the ejecta blanket.

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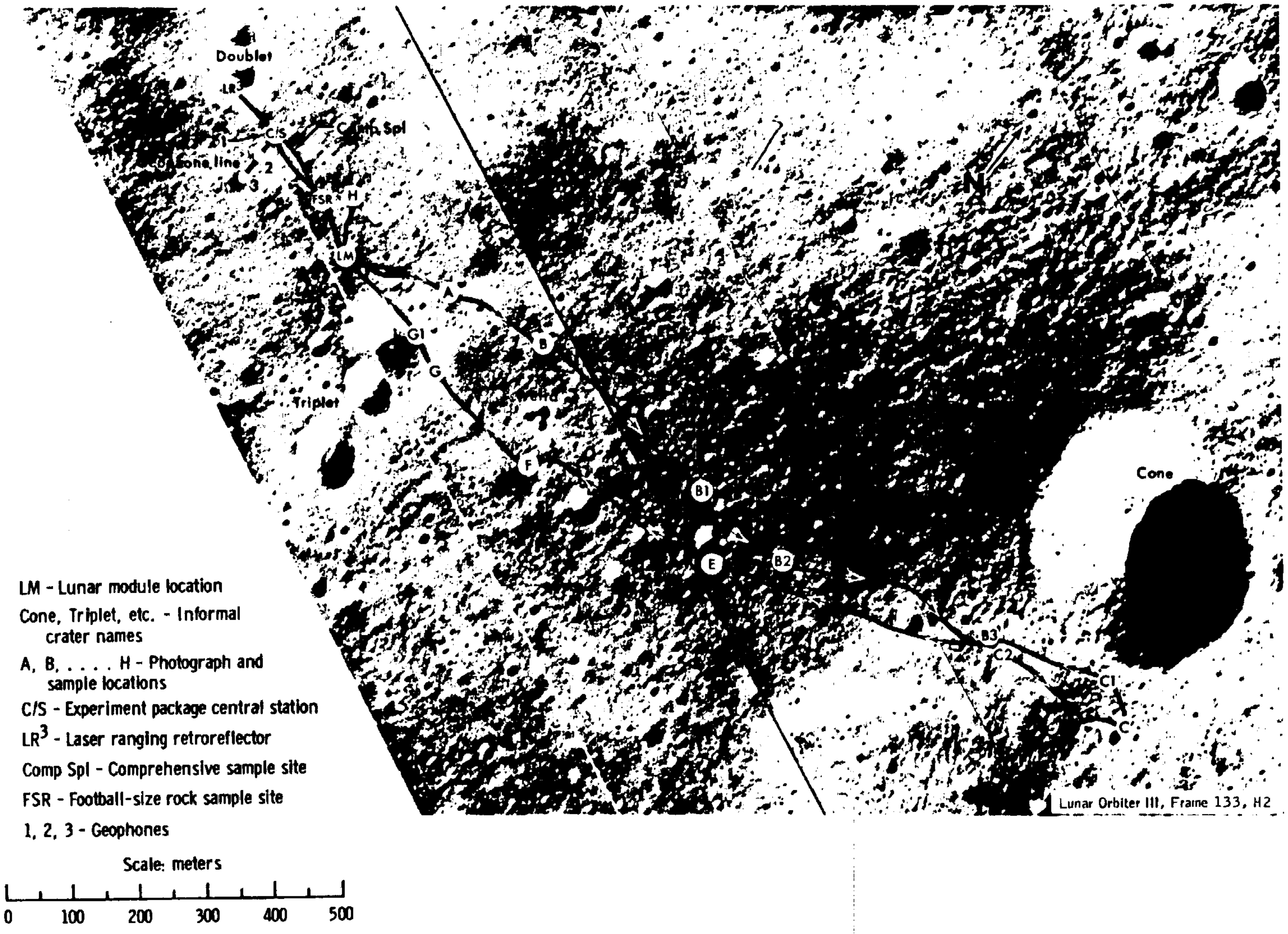
*Informal designation.



Lunar Orbiter III, Frame 133, H2

Figure 3-6. - Apollo 14 traverse routes.

Figure 3-7.- Boulders sampled near rim of Cone Crater.

All the boulders for which stereophotographs are available appear to be coherent breccias, some with discrete clasts as much as 150 centimeters in diameter, larger than any returned samples. Both light and dark clasts are recognizable. Resistance of the breccias to the weathering effects of the lunar environment varies considerably; some breccias have weathered to smooth, resistant surfaces and others to hackly, rough surfaces that may be rubbly. Significant and striking features within the boulders are sets of parallel fractures spaced at several millimeters to approximately 1 centimeter. Several intersecting sets of differently spaced fractures are present in some boulders.

Portions of some boulders close to the rim of Cone Crater are crudely layered with very light material that forms irregular bands from 25 to 40 centimeters thick. The light bands contain both lighter and darker clasts up to 10 centimeters across, and the host rock of the bands contains light clasts up to 10 centimeters across. Irregular parts of other boulders are also very light, but a layered relationship is not evident. Boulders containing light layers occur only near the rim of Cone Crater and, hence, may come from deeper levels in the crater.

Most large blocks have fillets of lunar fines and fragments embanked against the basal edges. The size of a fillet is commonly proportional to the size, degree of rounding, and apparent friability of the host rock. Fillets are preferentially developed against outward-sloping rock surfaces and contain coarse fragments spalled off the host rock. Burial of rocks is a combined product of (1) ejecta blanketing by adjacent impact events of all sizes, particularly on well-rounded rocks the tops of which are close to the surface, and (2) self-burial by micrometeorite and thermal erosion of the exposed rock surfaces.

Two well-developed sets of surface lineaments have the northwest and northeast trends observed at the Apollo 11 and 12 sites. A secondary set trends north. The large number of very long, straight lineaments is unique to the Apollo 14 site. These lineaments may be the result of very small, recent, vertical displacements along fractures or of the sifting of fine-grained material down into fractures that were propagated to the surface from a more coherent, joint substrate.

The samples consist almost entirely of complex breccias, displaying shock and thermal effects that are consistent with their postulated origin as debris from a large cratering event. The breccias are noritic in bulk composition. Some of the samples are vitric breccias which may have been formed by welding within the ejecta blanket of a smaller or local cratering event. Many of the breccia samples contain veins or pods of impact melt. On a larger scale, a plagioclase-rich basalt sample collected at the site may have been a lava, but was more likely crystallized in a pool of impact melt.

Radiometric ages for the Apollo 14 site cluster around a value of 3.9 billion years; if the Fra Mauro site is truly ejecta from Imbrium, then the Imbrium event occurred at that time (ref. 3-10).

Apollo 14 soil and breccia are enriched in the siderophile elements (iridium, rhenium, gold, nickel), relative to soils from mare surfaces. They may be derived from the Imbrium projectile itself or bodies which impacted the lunar surface to form pre-Imbrium craters.

In summary, the compositions of the Apollo 14 rocks are compatible with their derivation as an ejecta deposit from the Imbrium Basin. These rock samples are largely fragmental and show pronounced shock effects, and the composition of most samples is distinctly different from that of basaltic rocks from lunar maria. The crystallinity observed in many fragmental rocks is compatible with a single very large impact event in which annealing took place within a thick, hot ejecta blanket.

3.2.4 Geology of the Apollo 15 Landing Site

The landing site of Apollo 15 is on a dark mare plain (part of Palus Putredinis, or the Marsh of Decay) near the sinuous Rima Hadley (Hadley Rille) and the frontal scarp of the Montes Apenninus (Apennine Mountains) (fig. 3-8). This scarp is the main boundary of the Imbrium Basin, which is centered approximately 650 kilometers to the northwest. The largest mountains of the Apennines are a chain of discontinuous rectilinear massifs 2 to 5 kilometers high that are interpreted as fault blocks uplifted and segmented at the time of the Imbrium impact. Between the massifs and beyond them outside the basin are hilly areas that merge southeastward with a terrain

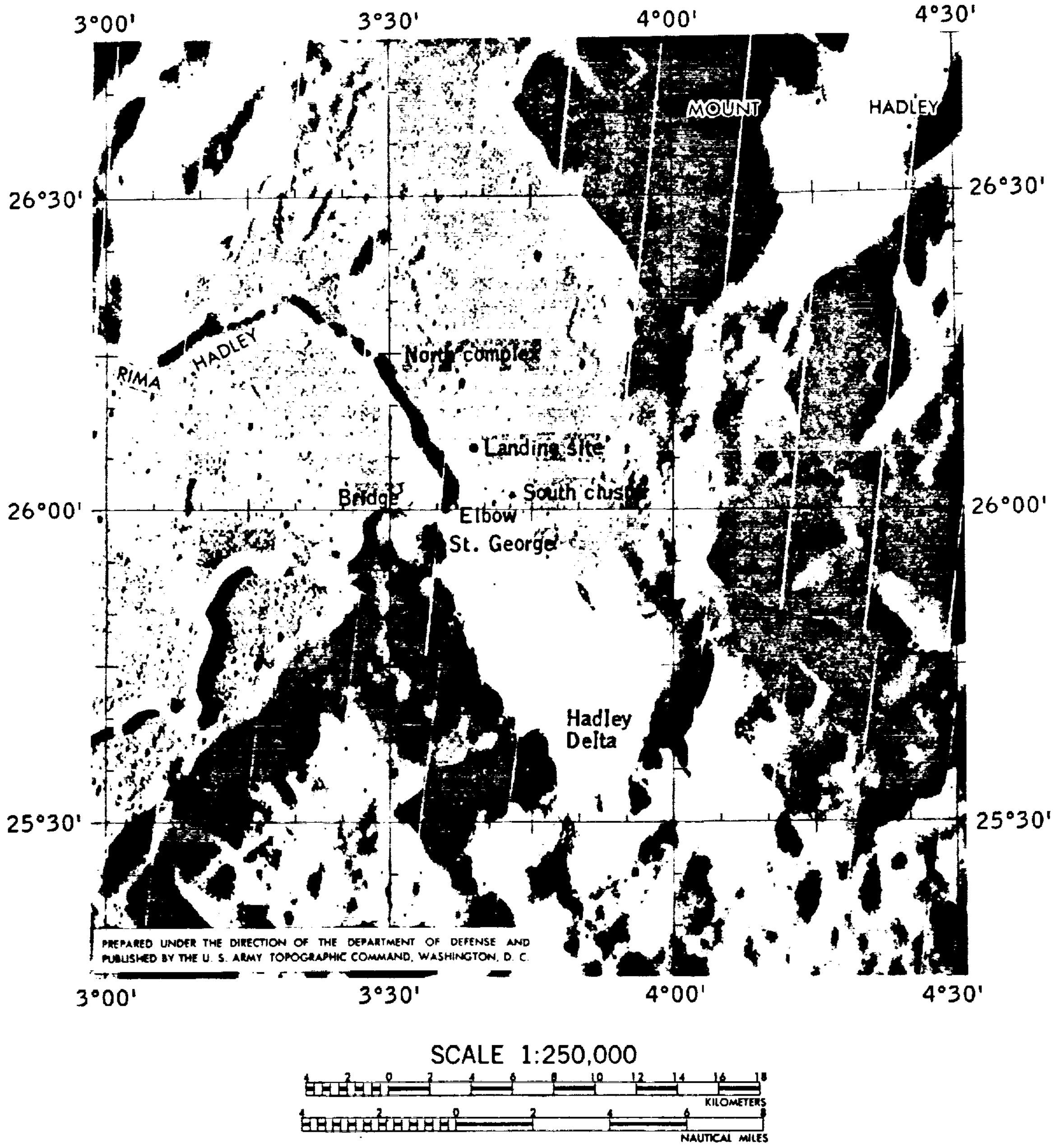


Figure 3-8.- Lunar module landing site on photomap of Hadley Plain.

interpreted as a blanket of ejecta from the Imbrium Basin, known as the Fra Mauro Formation. The hills appear to be jostled blocks mantled and subdued by the Imbrium ejecta. The large massifs, however, are not similarly subdued and so may be composed mainly of pre-Imbrium ejecta. The area is near the old Mare Serenitatis (Sea of Serenity) basin, which suggests that at least part of the pre-Imbrium material in the massifs is ejecta from the Sea of Serenity.

The mare material of the Marsh of Decay fills the lowlands at the base of the Apennines and creates a dark plain. The regional relations to the west show that several events occurred between the formation of the Imbrium Basin and the emplacement of the mare material. These events included the deposition of the premare plains-forming material and the cratering event that formed the crater Archimedes. The morphologies of the craters on the mare surface at the landing site indicate that the age of the surface is late Imbrian or early Eratosthenian.

Some hills and mountains in the area are dark like the mare and may be coated by a thin mantle of dark material. The region contains numerous diffuse light-colored rays and satellitic clusters of secondary impact craters from the large Copernican craters Autolycus and Aristillus to the north.

Hadley Rille (fig. 3-8) follows a winding course through the mare and locally abuts premare massifs. Hadley Rille appears to be one of the freshest sinuous rilles, and rock outcrops are common along the upper walls. The rille is more than 100 kilometers long, 1500 meters wide, and 400 meters deep.

The regional relations indicate that the mare rocks may rest on faulted pre-Imbrium rocks, breccia from the Imbrium impact, and light plains-forming units such as the Apennine Bench Formation. Whether or not the rille penetrates the premare material is unknown. The mare surface is covered with regolith approximately 5 meters thick.

Two major Apennine massifs, Mons Hadley (Mount Hadley) to the northeast and Hadley Delta just south of the landing site (fig. 3-8), tower over the Hadley plain to heights of 4.5 to 3.5 kilometers, respectively. The face of Mount Hadley is steep and high in albedo. The northern face of Hadley Delta, called the Front during the Apollo 15 mission, rises abruptly above the younger mare surface, except near Elbow Crater* where the contact is gradational, apparently because of the accumulation of debris from the slopes. As elsewhere on the moon, the steep slopes of the massifs are sparsely cratered because the craters are destroyed by the downslope movement of debris. A prominent exception is St. George,* a subdued crater 2.5 kilometers in diameter that predates the mare. The scarcity of blocks on both massifs indicates a thick regolith. The lower slopes of Hadley Delta were visited, and rock samples collected there indicate that the bedrock beneath the regolith consists of breccias.

The areas traversed by the Apollo 15 crew are shown in figure 3-9. The surface of the mare in the area visited is generally a plain that slopes slightly downward to the northwest. To the crew, the surface appeared hummocky or rolling, with subtle ridges and gentle valleys. The surface texture appeared smooth with scattered rocks occupying less than 5 percent of the total area. Widely separated, locally rough areas occur where recent impacts have left sharp crater rims and small boulder fields. The visible ridges and valleys are largely the forms of greatly subdued large craters, and the smoothness is caused by the destruction of blocks by erosion from small impacts. A large but indistinct ray shown on premission maps as crossing the mare surface was not visible to the crew as either a topographic or compositional feature, but the crew did note patches of lighter-colored material that may represent remnants of rays that have been largely mixed with the mare regolith.

The contact between the mare and the front of Hadley Delta is marked by a change of slope and a band of soft material with fewer large craters than are typical of the mare. The soft material of the band is probably a thickened regolith that includes debris derived from the slope by both cratering processes and downslope creep. Samples from talus at the base of highlands terrain (Hadley Delta) consist of breccias rich in fragments of plagioclase-rich basalt and anorthosite. They may have been deposited as ejecta by pre-Imbrium events or the Imbrium event. One of the anorthosite samples had a radiometric age of 4.1 billion years, a lower limit, since this rock has experienced a complex history of brecciation. There is a variety of mare basalt samples and a clastic rock composed of green glass spheres which may be of volcanic origin. The basalt (lava) samples are rich in iron and poor in sodium, as are other mare lavas. They have an age of 3.3 billion years.

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*Informal designations.

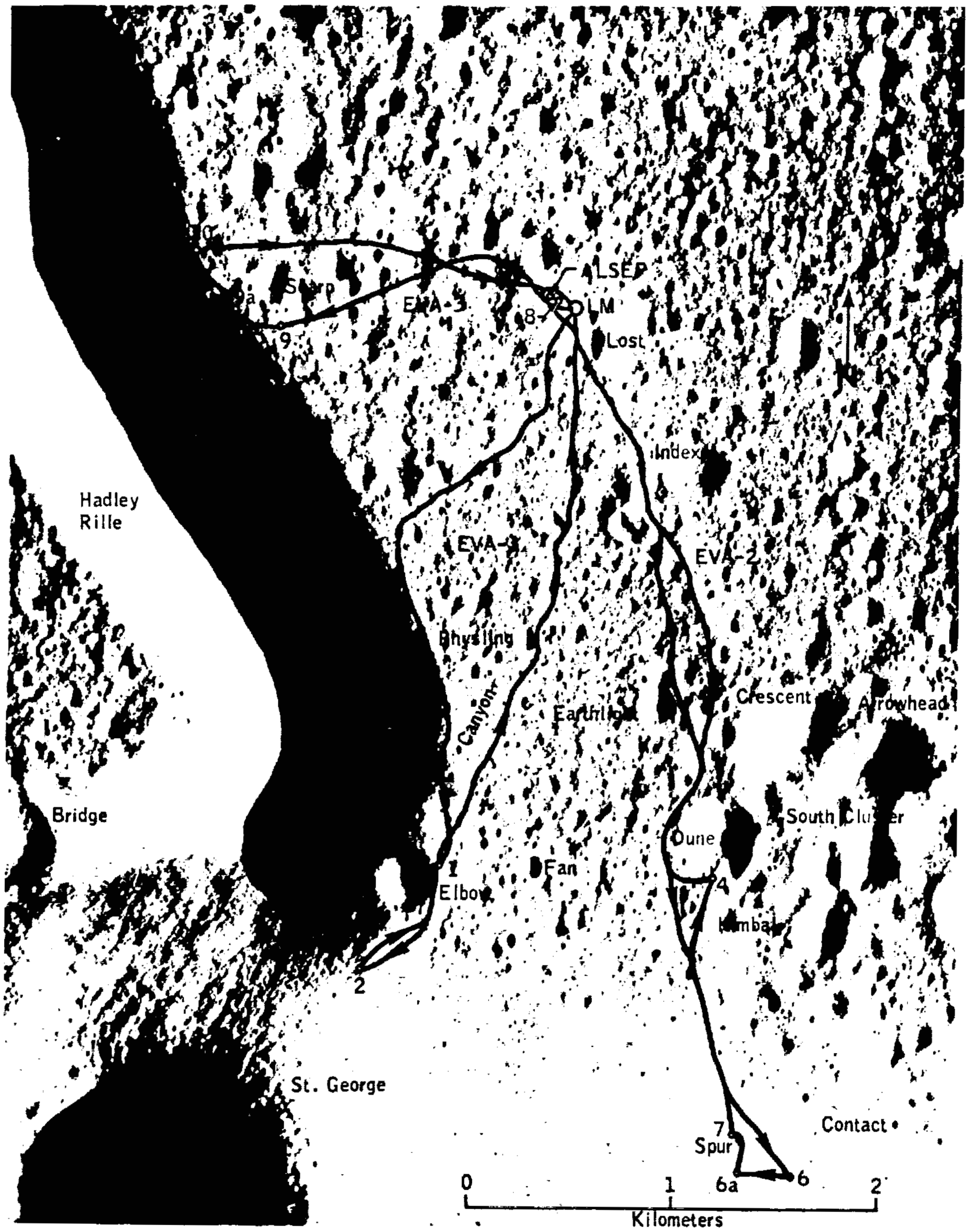

Figure 3-9.- Apollo 15 lunar surface traverse routes.

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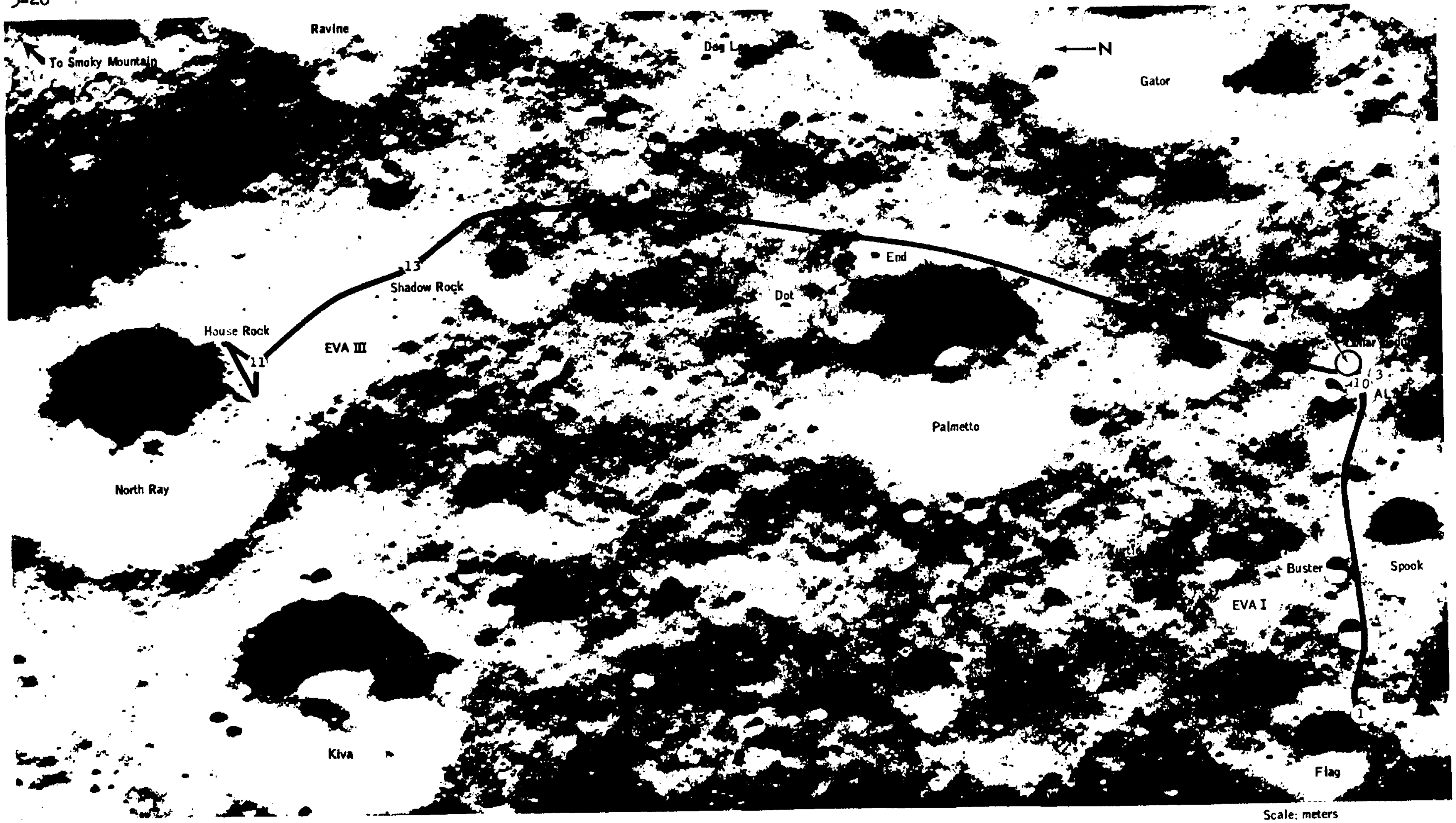

Figure 3-10.- Apollo 16 landing area and traverse routes.

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A 2.4-meter-deep core of the regolith revealed that it is composed of many soil layers ranging in thickness from a few millimeters to several tens of centimeters. The regolith is composed of layers of ejecta from impact craters, which are, in turn, reworked and mixed by micrometeorite bombardment. The 2.4-meter section at this site has undergone reworking and mixing for about 500 million years.

Soil mechanics analyses (from penetrometer tests, core sampling, and trenching performed by the astronauts; from photographs; and from other data) for the Apollo 15 site indicate the following:

a. Soil densities range from 1.36 to 2.15 grams per cubic centimeter.

b. No evidence of deep-seated slope failures is apparent, although surficial downslope movement of soil has occurred and the soil on steep slopes along the Apennine Front is in a near-failure condition.

3.2.5 Geology of the Apollo 16 Landing Site

The Apollo 16 lunar module landed at the western edge of the Descartes Mountains approximately 50 kilometers west of the Kant Plateau, part of the highest topographic surface on the near side of the moon. The Apollo 16 mission accomplished the first landing in the central lunar highlands, and the crew successfully explored and sampled a kind of terrain not previously visited. The landing site was selected as an area characteristic of both terra plains and rugged hilly and furrowed terra. The consensus of premission photogeologic interpretation was that both units were of probable volcanic origin. However, surface observations indicated that few or no volcanic rocks or landforms existed at the landing site but rather that the area is underlain by a wide variety of impact-generated breccias (ref. 3-11).

Ray materials derived from North Ray and South Ray Craters (fig. 3-10)* are the two most apparent sources of surface debris on the Cayley Plains. Ejecta from South Ray Crater also appear to mantle much of the surface of Stone Mountain near sampling stations 4 and 5 (fig. 3-10), so that uncertainty still exists as to whether Descartes materials were, in fact, sampled. Size distribution studies of fragments on the lunar surface suggest that the ejecta units of these two craters differ in character. Rock fragments are much less abundant in the North Ray ejecta blanket, which suggests that the North Ray impact may have excavated more friable material, that the length of time since the cratering event has been sufficient for subsequent impacts to destroy the smaller blocks, or both. South Ray ejecta, as mapped, include bright and dark areas, but the only surface differences observed are that the brightest areas have larger block sizes and a greater abundance of blocks. The mapped interray areas have no lunar surface characteristics that distinguish them from adjacent South Ray ejecta; they are, more or less, free of coarser rock fragments. Both ray and interray areas show a progressive northward decrease in total rock abundance and in relative abundance of the coarser sizes.

The regolith present on the ejecta blanket of North Ray Crater is only a few centimeters thick. Where ejecta blankets or ray deposits are not identifiable, the regolith is 10 to 15 meters thick. The surface of the regolith is medium gray, but high-albedo soils are present at depths of 1 to 2 centimeters in most of the traverse area.

The net weight of returned samples was approximately 94 kilograms. Of the total sample weight, almost 75 percent consists of rock fragments larger than 1 centimeter in diameter, nearly 20 percent consists of soil or residue fines, and the remainder consists of core and drive tube samples. The Apollo 16 rocks may be divided into three broad groups: fine- to coarse-grained, mostly homogeneous crystalline rocks; rocks composed substantially of glass; and fragmental rocks (breccias). The proportion of fragmental rocks in the returned samples exceeds 75 percent. Of 25 rocks classified as crystalline, 7 appear to be igneous. Although all the igneous rocks have been shattered and deformed to some extent, the predeformation textures are substantially intact. The two largest samples returned are coarse-grained nonvesicular rocks composed largely of plagioclase. These rocks resemble an Apollo 15 anorthosite sample but are probably more severely shock-deformed. Three are fine-grained, highly feldspathic rocks with crystal-lined vugs. Eighteen crystalline rocks appear to be metaclastic rocks with generally small proportions of lithic debris; these are hard, angular rocks characterized by fine-grained sugary textures. Five samples largely composed of glass were returned. Two of these are spheres, one hollow and one solid.

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*Designations of lunar features shown in figure 3-10 are informal.

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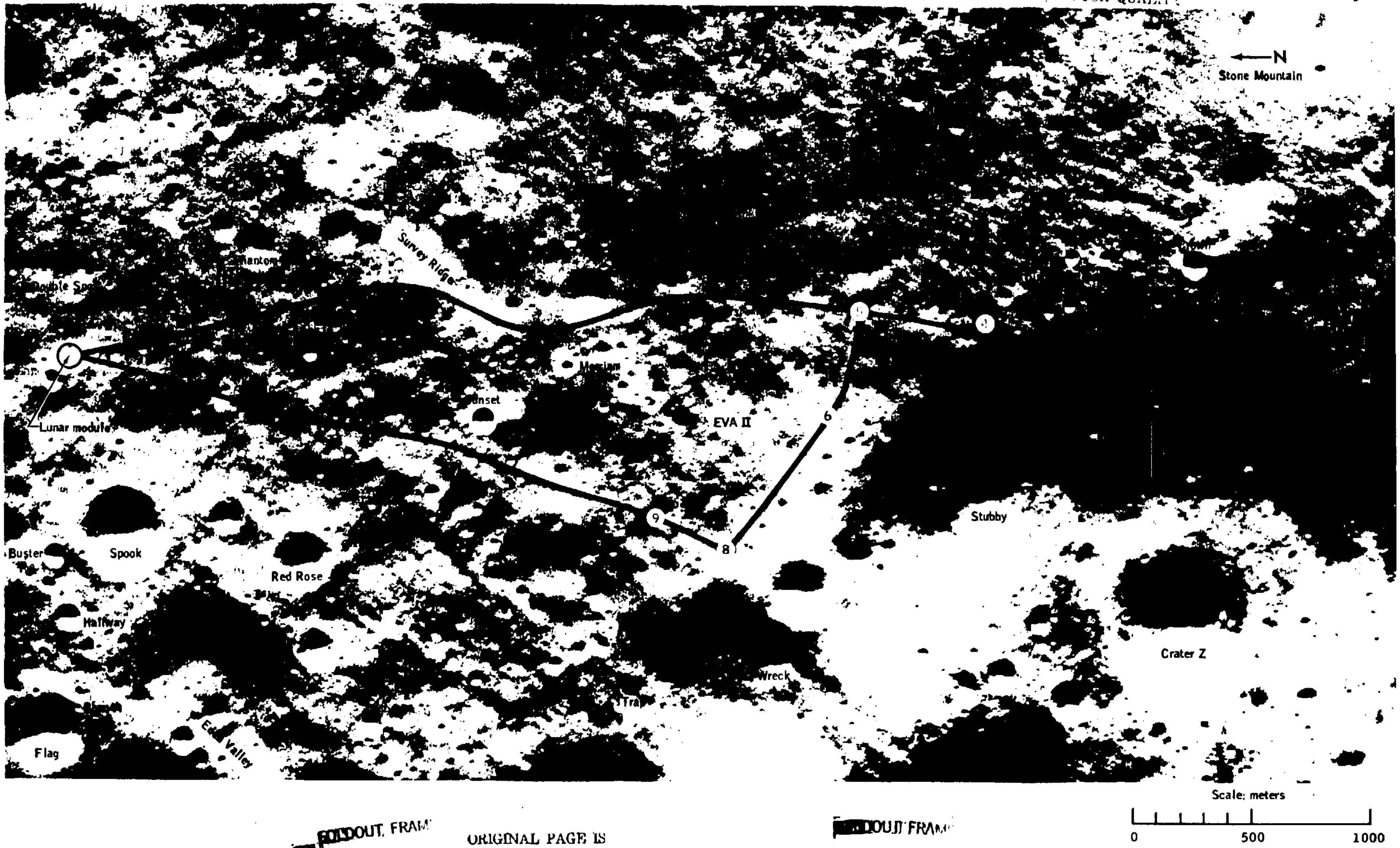

Figure 3-10.- Apollo 16 landing area and traverse routes (concluded).

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