The Geologic Investigation of the Taurus-Littrow Valley: Apollo 17 Landing Site

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THE GEOLOGIC INVESTIGATION OF THE TAURUS-LITTROW VALLEY: APOLLO 17 LANDING SITE

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ABSTRACT

Astronauts Cernan and Schmitt, of Apollo 17, landed in the Taurus-Littrow valley of the Moon on December 11,1972. Their major objectives were (1) to sample very ancient lunar material such as might be found in pre-Imbrian highlands as distant as possible from the Imbrium basin and (2) to sample pyroclastic materials that had been interpreted as significantly younger than the mare basalts returned from previous Apollo landing sites. The crew worked approximately 22 hours on the lunar surface; they traversed about 30 km, collected nearly 120 kg of samples, took more than 2,200 photographs, and recorded many direct geologic observations. The lunar surface data, sample results, and geologic interpretation from orbital photographs are the bases for this geologic synthesis.

The Taurus-Littrow massifs are interpreted as the upper part of the thick, faulted ejecta deposited on the rim of the transient cavity of the large southern Serenitatis basin, which was formed about 3.9 to 4.0 b.y. ago by the impact of a planetesimal. The target rocks, predominantly of the dunite-anorthosite-norite-troctolite suite or its metamorphosed equivalents, were fractured, sheared, crushed, and melted by the impact. The resulting mixture of crushed rock and melt was transported up and out of the transient cavity and deposited on and beyond its rim. Hot fragmental to partly molten ejecta and relatively cool cataclasite and relict target rocks were intermixed in a melange of lenses, pods, and veins. Crystallization of melts and thermal metamorphism of fine-,grained fragmental debris produced breccia composed of rock and mineral fragments in a fine-grained, coherent, crystalline matrix. Such breccia dominates the massif samples.

High-angle faults that bound the massifs were activated during formation of the basin, so that structural relief of several kilometers was imposed on the ejecta almost as soon as it was deposited. Massive slumping that produced thick wedges of colluvium on the lower massif slopes probably occurred nearly contemporaneously with the faulting. Material of the Sculptured Hills, perhaps largely cataclasite excavated from the southern Serenitatis basin by the same impact, was then deposited on and around the massifs.

Basalt, estimated to be about 1,400 m thick in the landing site, flooded the Taurus-Littrow graben before approximately 3.7 b.y. ago. The basalt (subfloor basalt) is part of a more extensive unit that was broadly warped and cut by extensional faults before the accumulation in Mare Serenitatis of younger, less deformed basalts that overlap it. A thin volcanic ash unit, probably about 3.5 b.y. old, mantled the subfloor basalt and the nearby highlands. It, too, was subsequently overlapped by the younger basalt of Mare Serenitatis.

In the time since deposition of the volcanic ash, continued bombardment by primary and secondary projectiles has produced regolith, which is a mechanical mixture of debris derived mainly from the subfloor basalt, the volcanic ash, and the rocks of the nearby massifs and Sculptured Hills. The regolith and the underlying volcanic ash form an unconsolidated surficial deposit with an average thickness of about 14 m, sufficiently thick to permit abnormally rapid degradation of the smaller craters, especially those less than 200 m in diameter, so as to create a surface that appears less cratered than other mare surfaces. Admixed volcanic ash gives the surface a distinctive dark color, which, in combination with the less cratered appearance, led to its interpretation before the mission as a young dark mantling unit.

The uppermost part of the regolith over much of the landing area is basalt-rich ejecta from the clustered craters of the valley floor. Most of the valley-floor craters are interpreted as part of a secondary cluster formed by projectiles of ejecta from Tycho. When they struck the face of the South Massif, the projectiles mobilized fine-grained regolith material that was deposited on the valley floor as the light mantle. Exposure ages suggest that the swarm of secondary projectiles struck the Taurus-Littrow area about 100 m.y. ago.

The Lee-Lincoln fault scarp is part of an extensive system of wrinkle ridges and scarps that transect both mare and highlands rocks. The scarp cuts the crater Lara, but the major part of the displacement occurred before deposition of the light mantle. Small extensional faults cut the surface of the light mantle west of the LeeLincoln scarp.

INTRODUCTION

Apollo 17, the sixth and last manned lunar landing of the Apollo program, touched down in a mountain valley near the edge of Mare Serenitatis (fig. 1) on December 11, 1972. The landing site, south of the Taurus Mountains and the crater Littrow, was named TaurusLittrow to distinguish it from an earlier proposed landing site nearby. During their 72-hour stay at TaurusLittrow, astronauts Eugene A. Cernan and Harrison H. Schmitt spent more than 22 hours on the lunar surface, traversed about 30 km, collected nearly 120 kg of rocks and soil, and took more than 2,200 photographs. Their traverses, sampling, direct observations, and photographs spanned the full width of the spectacular Taurus-Littrow valley (fig. 2) to become the superlative finale to the first chapter of manned planetary exploration.

A chronological approach seems the most direct way to recount the geologic investigation of the TaurusLittrow area. Hence this report consists of three major parts: (1) premission geologic interpretation based mainly on photogeology; (2) field and sample data (including results published through 1976), and (3) postmission geologic synthesis.

Examination of the high-resolution photographs taken from lunar orbit by Apollo 15 indicated that a landing between Mare Serenitatis and Mare Crisium would be attractive. In February 1972, the National Aeronautics and Space Administration (NASA) selected the Taurus-Littrow site for exploration by Apollo 17 (Hinners, 1973). Before that time, published geologic maps of the Taurus-Littrow area consisted of a map of the Mare Serenitatis region (Carr, 1966), which was prepared from telescopic photographs and observations that included part of the Taurus-Littrow highlands west of the landing site, and the 1:5,000,000scale map of the near side of the Moon (Wilhelms and McCauley, 1971) . In addition, geologic sketch maps

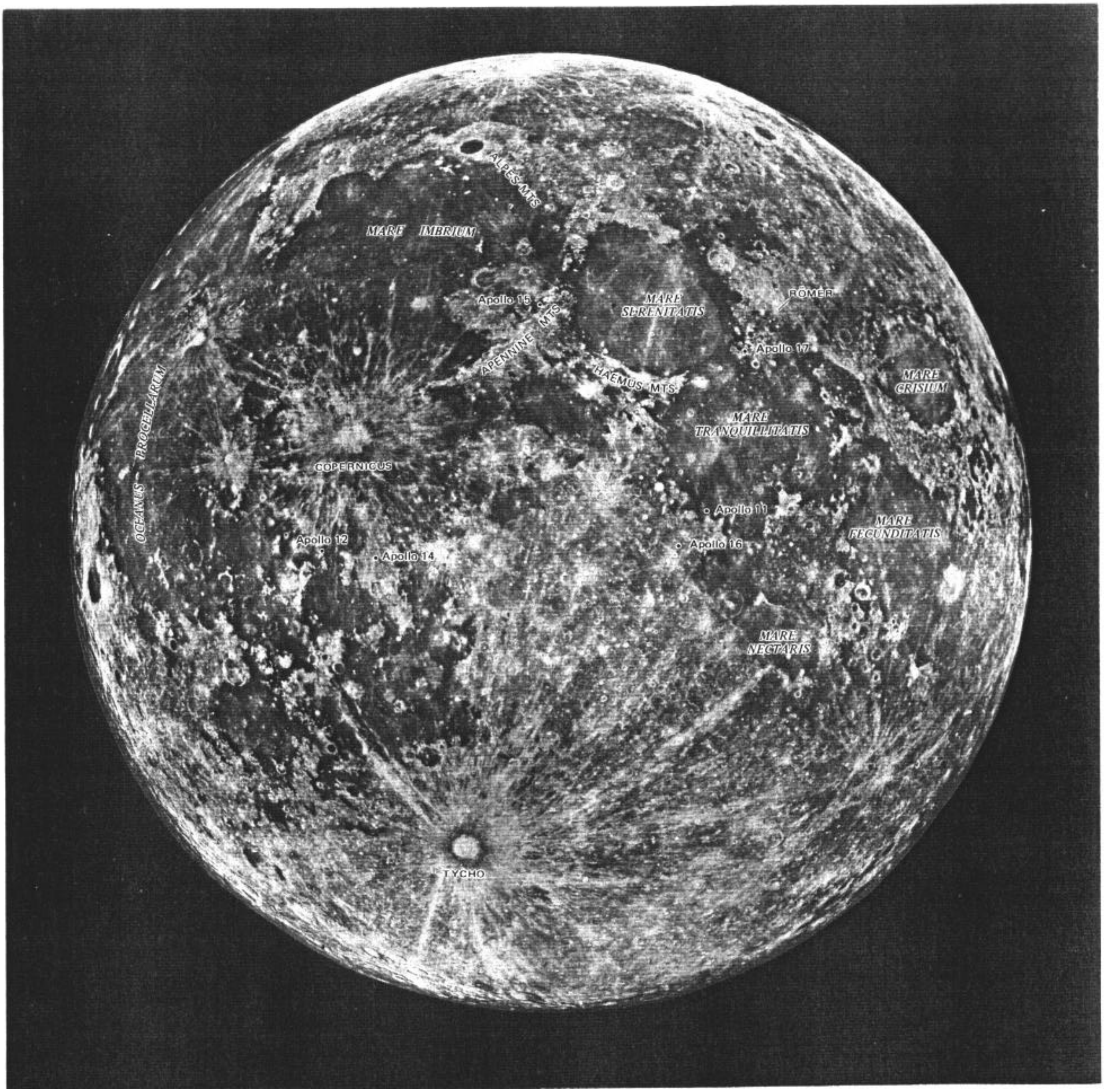


FIGURE I.-Full-moon photograph showing locations of Apollo landing sites and major features of lunar nearside. (Telescopic photograph L 18, taken January 17, 1946, from Lick Observatory, Mount Hamilton, Calif.)

prepared from Apollo 15 orbital photographs (Carr, 1972; El-Baz, 1972) were included in the Apollo 15 Preliminary Science Report.

Early in 1972, geologic study of the Taurus-Littrow area was greatly accelerated as preparations for Apollo 17 began Utilizing Apollo 15 photographs, Scott and Carr (1972) prepared a 1:250,000-scale geologic map of the Taurus-Littrow region, Lucchitta (1972) prepared a 1:50,000-scale map of the Taurus-Littrow valley and its bordering highlands, and Wolfe and Freeman (1972) prepared a 1:25,000-scale geologic map as the basis for detailed traverse planning. During this period, Scott and Pohn (1972) completed the 1:1,000,000-scale map of the Macrobius quadrangle, which includes the Apollo 17 landing site and spans almost the entire highland region between Mare Serenitatis and Mare Crisium. Related investigations also underway before the mission included a theoretical study of lunar cinder cones and the mechanics of their eruption (McGetchin and Head, 1973), a model for distribution of basin ejecta

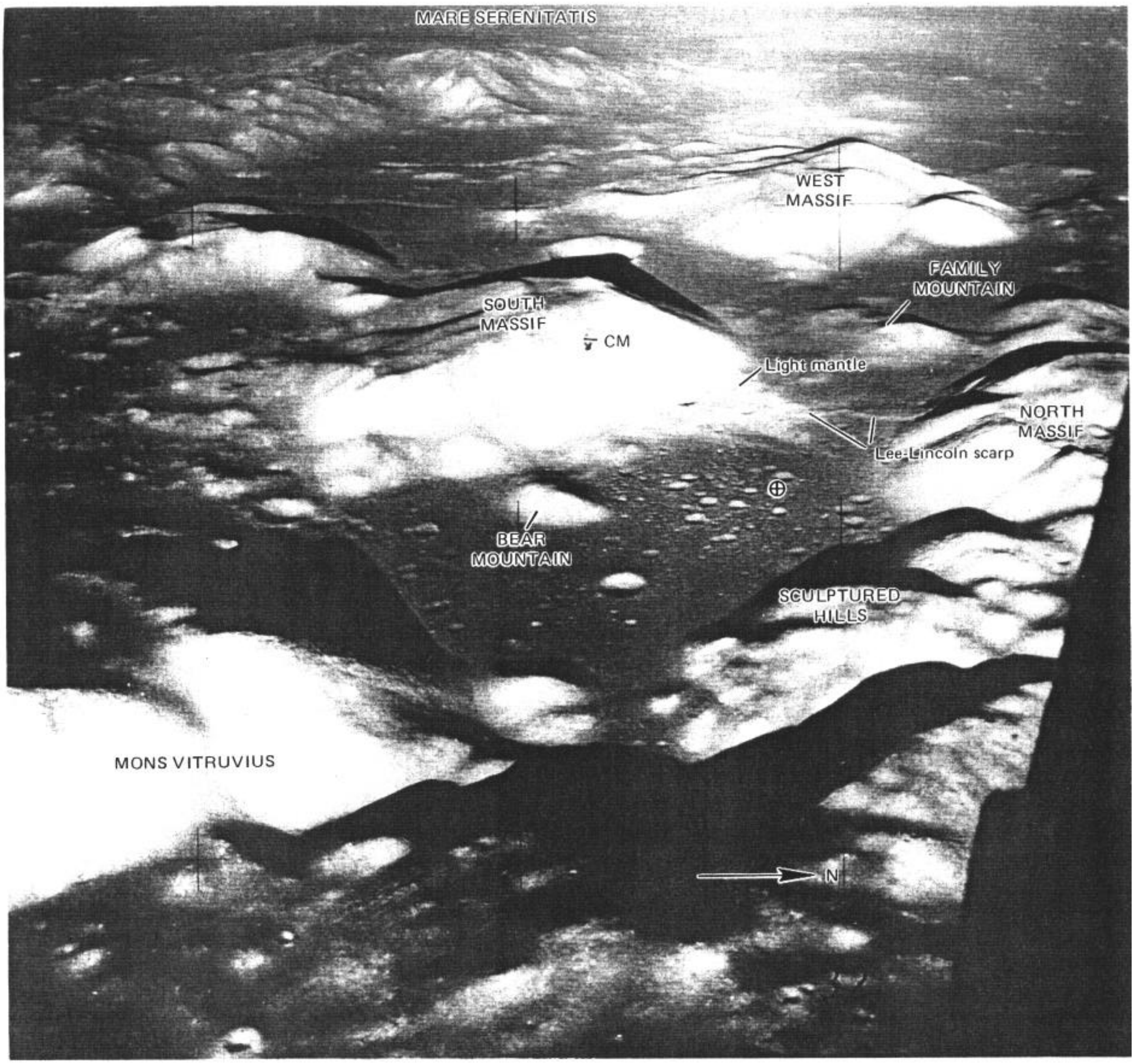


FIGURE 2.-View to west of Taurus-Littrow valley from orbiting Lunar Module. South Massif, seen beyond orbiting Command Module (CM), is more than 2 km high; the light mantle projects northeast across valley floor from its base. Crossing the 7-km-wide valley floor and intersecting North Massif near right edge of photograph is east-facing Lee-Lincoln scarp. Circled cross shows landing point. (NASA photograph AS 17-147-22466.)

and the resulting stratigraphy of the massifs (McGetchin and others, 1973), a structural analysis of the Taurus-Littrow region (Head, 1974a) , an evaluation of' the light mantle and its depositional mechanism (Howard, 1973), and an analysis of the composition and physical properties of the dark mantle (Dieters and others, 1973). The results of these studies were used by the Apollo 17 planners in the effort to maximize the scientific return from the mission.

Detailed plans for geologic exploration of the Apollo 17 site were prepared largely by a consortium that included V. L. Freeman, J. W. Head, W. R. Muehlberger. H. H. Schmitt, and E. W. Wolfe. The plans were subject to critical review and modification by NASA scientific and engineering panels. Special credit for the scientific success of the Apollo 17 mission is due J. R. Sevier, Chairman of the Traverse Planning Subcommittee of the Science Working Panel, and R. A. Parker, Apollo 17 Mission Scientist, both of the Manned Spacecraft Center (now the Lyndon B. Johnson Space Center). With patience and diplomacy, they integrated the lunar surface experiments and investigations and acted as liaison between the lunar surface science and operations communities.

Overall responsibility for planning the geologic exploration, preparing the crew for the scientific task, providing geologic guidance during the mission on the lunar surface, and interpreting the results of the field observations rested with the Apollo Field Geology Investigation Team. The team members, acting under the leadership of W. R. Muehlberger, principal investigator, were N. G. Bailey, R. M. Batson, V. L. Freeman, M. H. Hait, J. W. Head, H. E. Holt, K. A. Howard, E. D. Jackson, K. B. Larson, B. K. Lucchitta, T. R. McGetchin, Harold Masursky, L. R. Page, D. L. Peck, V. S. Reed, J. J. Rennilson, D. H. Scott, L. T. Silver, R. L. Sutton, D. E. Stuart-Alexander, G. A. Swann, S. R. Titley, N. J. Trask, R. L. Tyner, G. E. U1rich, H. G. Wilshire, and E. W. Wolfe. Published postmission reports of this group (Apollo Field Geology Investigation Team, 1973; Muehlberger and others, 1973) and unpublished reports (in particular, Apollo Field Geology Investigation Team, 1975) have been used extensively in this report in the sections dealing with traverse geology and postmission geologic interpretations.

The premission geologic maps are not reproduced here. The Apollo 17 orbital photographs of the TaurusLittrow area are superior to the Apollo 15 photographs used for premission mapping, and a new 1:250,000scale map (pl. 1) has been prepared. This map is similar to the premission map of Scott and Carr (1972) , but it portrays more structural detail and embodies stratigraphic concepts developed as a consequence of the mission results. A new 1:25,000-scale geologic map (pl. 2) was also prepared. It incorporates the premission mapping of Wolfe and Freeman (1972) with additional geologic details from Apollo 17 panoramic camera photographs. No revised version of the 1:50,000-scale map was prepared, because the premission map (Lucchitta, 1972) adequately portrays the distribution of units.

Planimetric station maps (for example, fig. 8) , traverse maps (figs. 6 and 7) , and panoramas (pls3-9) were prepared largely by R. M. Batson, K. B. Larson, and R. L. Tyner. Their methods are described in the section entitled, "Apollo 17 Lunar Surface Photography."

We thank G. H. Heiken (Los Alamos Scientific Laboratory) and H. J. Moore for their helpful critical reviews of the manuscript.

PREMISSION GEOLOGIC INTERPRETATIONS

The Taurus-Littrow area is predominantly a highlands region near the intersection of Mare Serenitatis and Mare Tranquillitatis (fig. 3). Stuart-Alexander and Howard (1970) and Hartmann and Wood (1971) interpreted the Serenitatis basin as one of the Moon's old circular impact basins but considered it younger than basin structures associated with Mare Tranquillitatis.

Wilhelms and McCauley (1971) mapped the Serenitatis basin as a structure of four rings concentric to a single basin center (fig. 3). The diameter of their outermost ring is about 1,400 km. The outer two rings of their inferred basin structure are difficult to recog

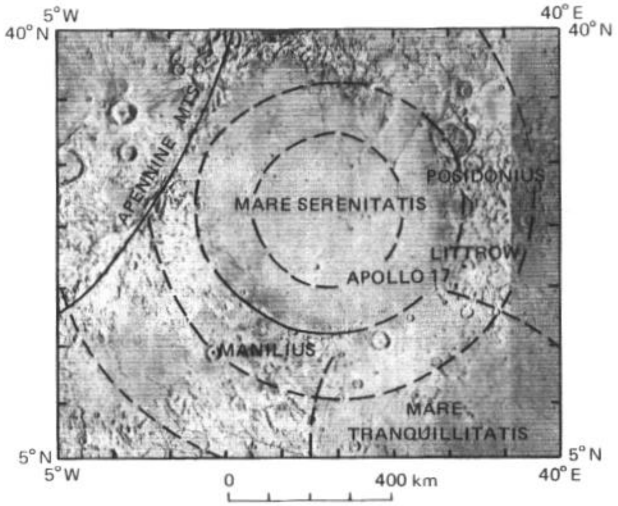


FIGURE 3.-Ring structure of Serenitatis basin as shown by Wilhelms and McCauley (1971).

nize; only the first ring, defined by wrinkle ridges within Mare Serenitatis, and segments of the second ring, defined by the discontinuous mountainous border of Mare Serenitatis, are distinct. Hence, StuartAlexander and Howard (1970) and Hartmann and Wood (1971) suggested that the second ring, less than 700 km in diameter, is the basin rim. As shown by Wilhelms and McCauley (1971), the crest of the second ring is slightly west of the Apollo 17 landing site.

The dominance of feldspathic impact breccia collected from other highlands localities by Apollos 14, 15, and 16 led Lucchitta (1972), Scott and Carr (1972), and Wolfe and others (1972 a,b) to suggest that the Taurus-Littrow massifs would be largely impact breccia. However, a cautious alternate hypothesis-that the massifs might be of volcanic origin-was based on their domelike shapes.

There were various opinions about the origin of the massif breccias to be sampled. Wilhelms and McCauley (1971) interpreted the massifs to be primarily prebasin rocks uplifted during basin formation. This interpretation was adopted by Carr, Howard, and El-Baz (1971) for the massifs of the Apennine Mountains, which bound the Imbrium basin. In contrast, Scott and Carr (1972) wrote that the highlands in the Taurus-Littrow area are probably mostly breccia formed by the Serenitatis impact and preexisting breccia excavated by the impact. Lucchitta (1972) and McGetchin, Settle, and Head (1973) suggested that, while Serenitatis ejecta would be dominant in the massifs, it might be thin enough so that layers of ejecta from older basins would be exposed beneath it in the lower parts of the massifs. The general consensus was that postSerenitatis crater and basin ejecta, particularly from the Imbrium and Crisium basins, might mantle or cap the massifs.

Detailed mapping (Lucchitta, 1972; Wolfe and Freeman, 1972) showed that rock ledges are exposed high on the massifs and that boulders had rolled from ledges to the valley floor. It was expected that the lower slopes of the massifs as well as the bounding faults were covered by talus from the upper parts of the massifs (Wolfe and others, 1972b).

The Sculptured Hills unit (hilly terra material of Scott and Carr, 1972; hilly material of Lucchitta, 1972) is characterized by closely spaced domical hills and is widespread in the highlands between the Serenitatis and Crisium basins. In comparison with the massifs, boulders and rocky ledges are relatively scarce in the Sculptured Hills, which suggested that they might be underlain by less coherent material that is lithologically distinct from the massif material (Wolfe and others, 1972b). However, the premission geologic mappers (Lucchitta, 1972; Scott and Carr, 1972; Wolfe and Freeman, 1972) agreed that the unit most probably consists mainly of basin ejecta. Lucchitta (1972) and Head (1974a) noted the similarity in distribution and morphology of the Sculptured Hills unit of the Serenitatis basin and the Alpes Formation of the lmbrium basin, a relation from which Head interpreted the Sculptured Hills materials to be related to the Serenitatis impact.

A unit of low hills material was mapped locally within the Taurus-Littrow valley along the margins of the more prominent highland masses (Lucchitta, 1972; Wolfe and Freeman, 1972). It was interpreted as down-faulted highlands material or deposits formed by mass wasting of material from the massifs or the Sculptured Hills.

The premission geologic mappers interpreted the smooth surface of the Taurus-Littrow valley floor as indicating partial filling of the valley by material that behaved as a fluid during emplacement. Prior to Apollo 16, there probably would have been little reluctance to interpret the filling as basaltic lava flows, but caution was inspired by the discovery at the Apollo 16 site that the plains-forming Cayley Formation in that area consists of feldspathic impact breccia (Muehlberger and others, 1972). Hence, the valley filling was variously called mare or plains material (Scott and Carr, 1972), plains material (Lucchitta, 1972), and subfloor material (Wolfe and Freeman, 19 72), and it was interpreted as either lava or impact products of Imbrian age. Abundant blocks up to several meters across were mapped on the walls and rims of many of the larger craters of the Taurus-Littrow valley floor (Wolfe and Freeman, 1972). These were interpreted as fragments of subfloor material excavated by crater impacts.

The valley floor, its westward extension between the Taurus-Littrow highlands and Mare Serenitatis, and discontinuous patches in the nearby highlands are covered by smooth dark material that looks less intensely cratered than the basalt filling of Mare Serenitatis. No blocks could be seen in orbital photographs with approximately 2-m resolution. This dark mantle was believed to overlie craters of early Copernican age and to be pocked by later Copernican craters. Although Scott and Carr (1972) noted that dark mantle material appeared to be overlapped by mare basalt of Imbrian age in the northwestern part of their map area, and that similar-looking material seemed to predate mare basalt along the southwestern edge of Mare Serenitatis, the unit was interpreted in the landing area as a young pyroclastic deposit up to tens of meters thick. Numerous dark craters, pits, and fissures in the TaurusLittrow region were considered to be possible vents. Shorty crater, near the northeastern margin of the light mantle (called bright mantle in some premission reports), has a dark rim and halo; El-Baz (1972) and Scott and Carr (1972) suggested that it, specifically, might have been either a vent for dark volcanic ash or an impact crater that excavated dark material from beneath the light mantle.

Particular interest in finding volcanic vents of Copernican age at the Apollo 17 site was generated by visual observations of the Apollo 15 Command Module pilot, (El-Baz and Worden, 1972). In subsequent interpretation of those observations and of Apollo 15 orbital photographs, El-Baz (1972) interpreted darkhaloed craters (fig. 4) as probable cinder cones from which the dark mantling pyroclastic material was extruded. In a related model study, McGetchin and Head (1973) applied well-documented parameters from the eruption of Northeast Crater at Mount Etna to theoretical lunar conditions of vacuum and reduced gravity. They found that the lunar equivalent of the small cinder cone on Mount Etna would be less than a tenth as high and about four times as broad as its terrestrial counterpart. Maximum slope angles would be less than 2° instead of the 30° typical of terrestrial cinder cones, and ballistic ejecta would have been thrown more than six times as far. The Mount Etna cone, in the lunar environment, would be 3 m high and 1,200 m across, with a ballistic range of nearly 2 km. The obvious implication was that vents so low and broad as to be unrecognizable in the orbital photographs could easily have produced overlapping pyroclastic deposits that cover the entire valley floor.

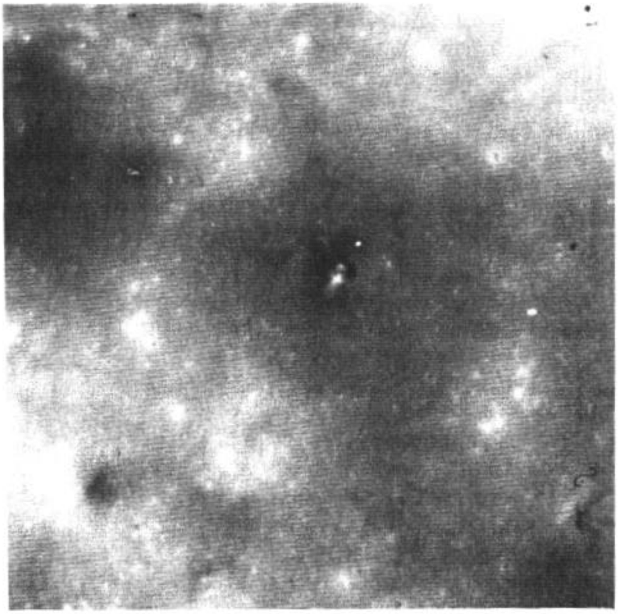


FIGURE 4.-Dark-haloed crater about 15 km west of Apollo 17 landing site. Crater was interpreted and illustrated as a probable volcanic cone (El-Baz and Worden, 1972; El-Baz, 1972) and mapped as a possible volcanic vent by Scott and Carr (1972) and Lucchitta (1972). Crater diameter is approximately 100 m. North at top. (Portion of Apollo 15 panoramic camera photograph AS15-9554.)

The raylike light mantle extends 6.5 km northeast across the Taurus-Littrow valley from the base of the South Massif. The premission mappers unanimously regarded it as the deposit of a relatively recent avalanche of debris from the face of the South Massif. No blocks could be detected in orbital photographs with 2-m resolution. The light mantle was estimated to thin from about 20 m near the South Massif to a feather edge at its distal end (Wolfe and others, 1972a). Underlying older craters and the fresh Lee-Lincoln fault scarp, both interpreted as older than the light mantle (Lucchitta, 1972; Wolfe and others, 1972b; Howard, 1973), are distinct even though mantled.

The avalanche was thought to have been initiated perhaps by a violent seismic event (Lucchitta, 1972) or by the impact of ejecta from a large, distant impact crater, possibly Tycho (Scott and Carr, 1972; Lucchitta, 1972). At the crest of the South Massif, Lucchitta as well as Scott and Carr mapped a cluster of secondary craters of Copernican age and indicated that they could have been formed by ejecta from Tycho. Scott and Carr suggested the additional hypothesis that the light mantle might consist of secondary crater ejecta intermixed with South Massif material. I-Ioward (1973) described similar but less extensive lunar avalanches that were apparently triggered when secondary projectiles impinged on steep slopes that face away from the primary craters.

The light mantle was considered young because only late Copernican craters are superimposed on its surface. Generally, it appeared to overlie the dark mantle. However, Lucchitta (1972) and Scott and Carr (1972) recognized ambiguous age relations in places where the boundary was diffuse. Hence, Scott and Carr (1972) suggested that the slide and the dark mantle interfinger and that, at least in part, they were deposited concurrently.

Chains and clusters of craters of Copernican age are abundant on the valley floor and in nearby highlands. The large central cluster in the landing area contains distinct 500- to 700-m craters (for example, craters Sherlock, Steno, and Emory, pl. 2) and abundant closely spaced or overlapping 100- to 300-m craters. Blocky light-colored patches in the walls and rims of the larger craters in particular were interpreted as crater materials exposed in windows through the overlying dark mantle. Scott and Carr (1972) and Lucchitta (1972) suggested that the Copernican clusters were formed by secondary projectiles from Tycho. More subdued large craters near 700 m in diameter (craters Camelot, Henry, Shakespeare, and Cochise, pl. 2) were interpreted as possible secondary craters produced by ejecta from Romer (Lucchitta, 1972).

The deformational history of the Taurus-Littrow region was outlined by Scott and Carr (1972) and discussed in detail by Head (1974a). They concluded that systems of northwest- and northeast-trending fractures, the lunar grid (Strom, 1964), predated the Serenitatis impact and acted as loci along which faulting was more pronounced during later deformation. Major grabens, including the Taurus-Littrow valley, were formed radial and concentric to the Serenitatis basin by the Serenitatis impact. The steep-sided massif blocks now stand where these trends parallel the older lunar grid. Head (1974a) summarized evidence that, in other large impact basins, massifs also occur in regions where basin radials parallel the lunar grid. Imbrium-basin radials are parallel to the northwest-trending faults that bound the massifs. Possibly these faults were rejuvenated by the Imbrium impact. At a later time smaller grabens such as the Rimae Littrow, largely concentric to Serenitatis, were formed on the plains adjacent to the mare. These grabens, which are truncated or flooded by younger mare basalts, may have resulted from stresses due to isostatic readjustment of the Serenitatis basin or adjustments related to the accumulation of the mare fill. Scott and Carr (1972) mapped a few still younger grabens that are superimposed on the younger basalts of Mare Serenitatis.

The youngest deformational feature recognized prior to the mission was the east-facing Lee-Lincoln scarp. Locally as high as 80 m, it crosses the valley floor and continues onto the North Massif. The scarp consists of north- and northwest-striking segments, each on the order of 5 km long. Some segments are single, continuous, approximately straight scarps; others are zones of discontinuous en echelon scarps (Wolfe and others, 1972b). Head (1974a) suggested that it was either a high-angle reverse fault with frequent changes of strike where pre-existing structures were reactivated or a normal fault dipping gently but variably eastward. The scarp was generally interpreted as older than the dark and light mantles; but segments of it in the light mantle are so sharp as to suggest that some movement is younger than the light mantle (Lucchitta, 1972; Wolfe and others, 1972b).

EXPLORATION OBJECTIVES AND PLAN

Two major geologic objectives of the Apollo 17 mission were identified by the NASA Ad Hoc Site Evaluation Committee before selection of the Taurus-Littrow site (Hinners, 1973). They were (1) sampling of very old lunar material such as might be found in pre Imbrian highlands as distant as possible from the Imbrium basin and (2) sampling of volcanic materials significantly younger than the mare basalts returned from the Apollos 11, 12, and 15 sites (that is, younger than about 3 b.y. old). Photogeologic interpretation had suggested that such young volcanic materials on the moon were pyroclastic, which would make them attractive not only for extending our knowledge of the Moon's thermal history, but also because they might provide a record of volatile materials from the Moon's interior; furthermore, they might. contain xenoliths of deep-seated lunar rocks.

The Taurus-Littrow valley seemed ideally suited for these mission objectives. Accordingly, the major objectives for observation and sampling during the mission, ranked in order of decreasing priority, were (1) highlands (massifs and Sculptured Hills), (2) dark mantle, and (3) subfloor material.

Lunar Roving Vehicle (LRV) traverses were designed to achieve these objectives during the three extravehicular activity (EVA) periods (fig. 5). Extensive sampling and observations of both the South Massif and the North Massif as well as of the Sculptured Hills were planned to provide data on areal variation in the highlands materials. It was hoped that vertical variation in the South Massif might be reflected by lateral variation in the light mantle. Therefore, three sample stations on the light mantle were planned, with intermediate stops in which surficial materials would be sampled by scoop from the LRV.

Dark mantle material was to be examined and collected at several stations and LRV stops on the valley floor. Planned stops included the rims of the large craters Emory, Sherlock, and Camelot, where it was hoped that contact relations could be examined between the young dark mantle and the older crater rim, wall, and floor materials. Blocks larger than 2 m on the rims of these craters had been interpreted as ejecta from the subfloor unit; they were the prime targets for observation and sampling of subfloor material. Stops at Shorty and Van Serg craters were planned for study and collection of dark mantle material supposedly excavated by impacts or erupted from volcanic vents. The area around the lunar module (LM) and several LRV sample stops would provide opportunities for observation and sampling of the typical smooth dark mantle surface of the valley floor. Sampling of the dark mantle at different locations would provide information about lateral variation.

TRAVERSE GEOLOGY AND SAMPLES

The actual traverse (fig. 6) closely approximated the planned one. Unfortunately, shortage of time prevented visits to Emory and Sherlock craters. The major part of EVA-1 was devoted to deployment of the Apollo Lunar Surface Experiments Package (ALSEP) near the landing point. Numerous samples and a deep drill core were collected in the LM/ALSEP/SEP area (SEP denotes the transmitter for the Surface Electrical Properties experiment). EVA's 2 and 3 were devoted primarily to exploration and sampling of the South and North Massifs, light mantle, Sculptured Hills, subfloor basalt, and the dark surficial materials of the valley floor. Gravity-meter readings were recorded during these EVA's as part of the Traverse Gravimeter experiment.

Detailed maps of the traverses are shown in figure 7. In addition to showing stations and LRV stops, the maps show the location of the transmitter for the Surface Electrical Properties (SEP) experiment and the localities where explosive packages (EP's) for the Lunar Seismic Profiling experiment (LSPE) were deployed. Also shown are the positions from which the astronauts took 360° photographic panoramas, which

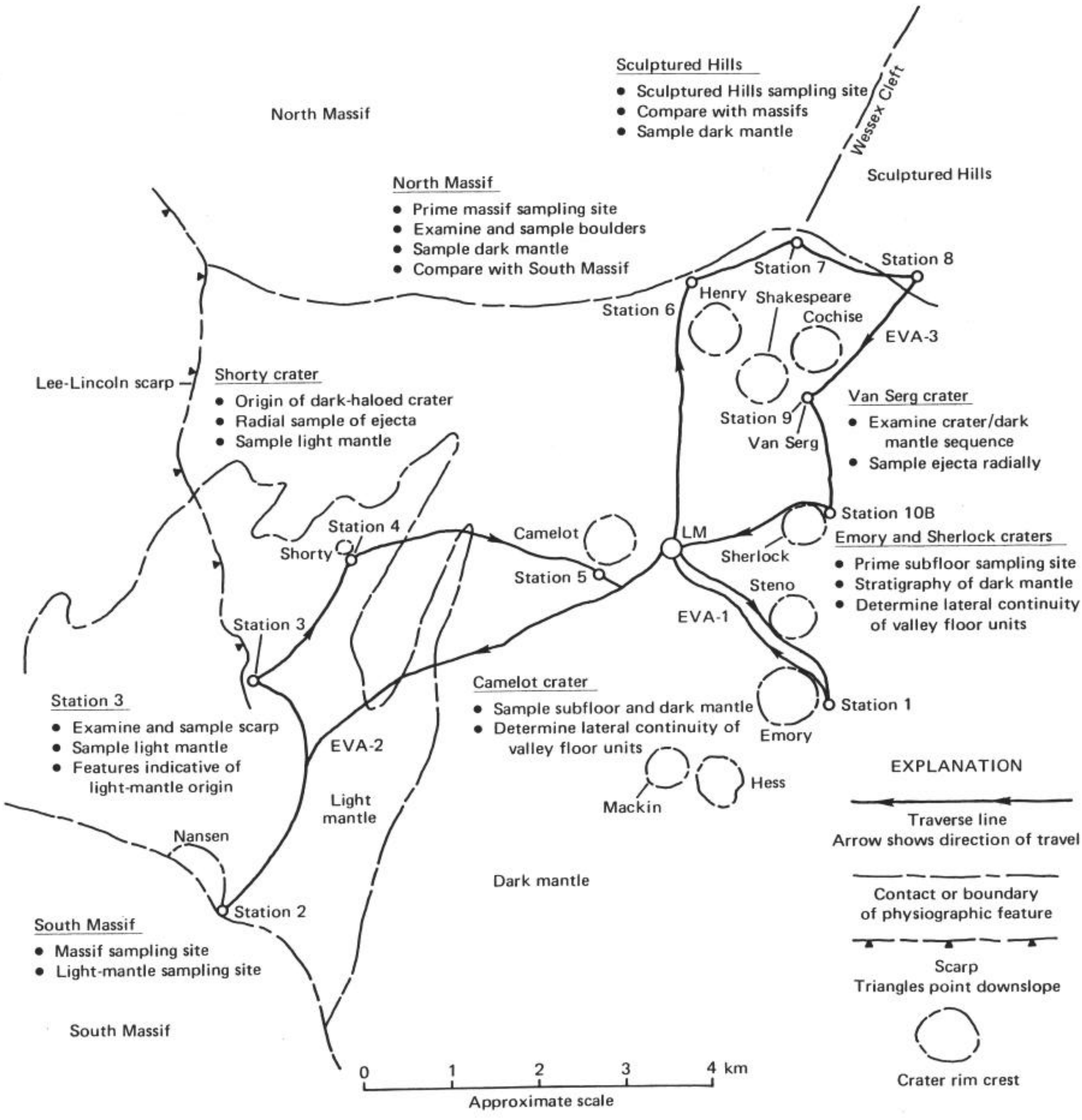


FIGURE 5-Preplanned traverses and geologic objectives (after Muehlberger and others, 1973).

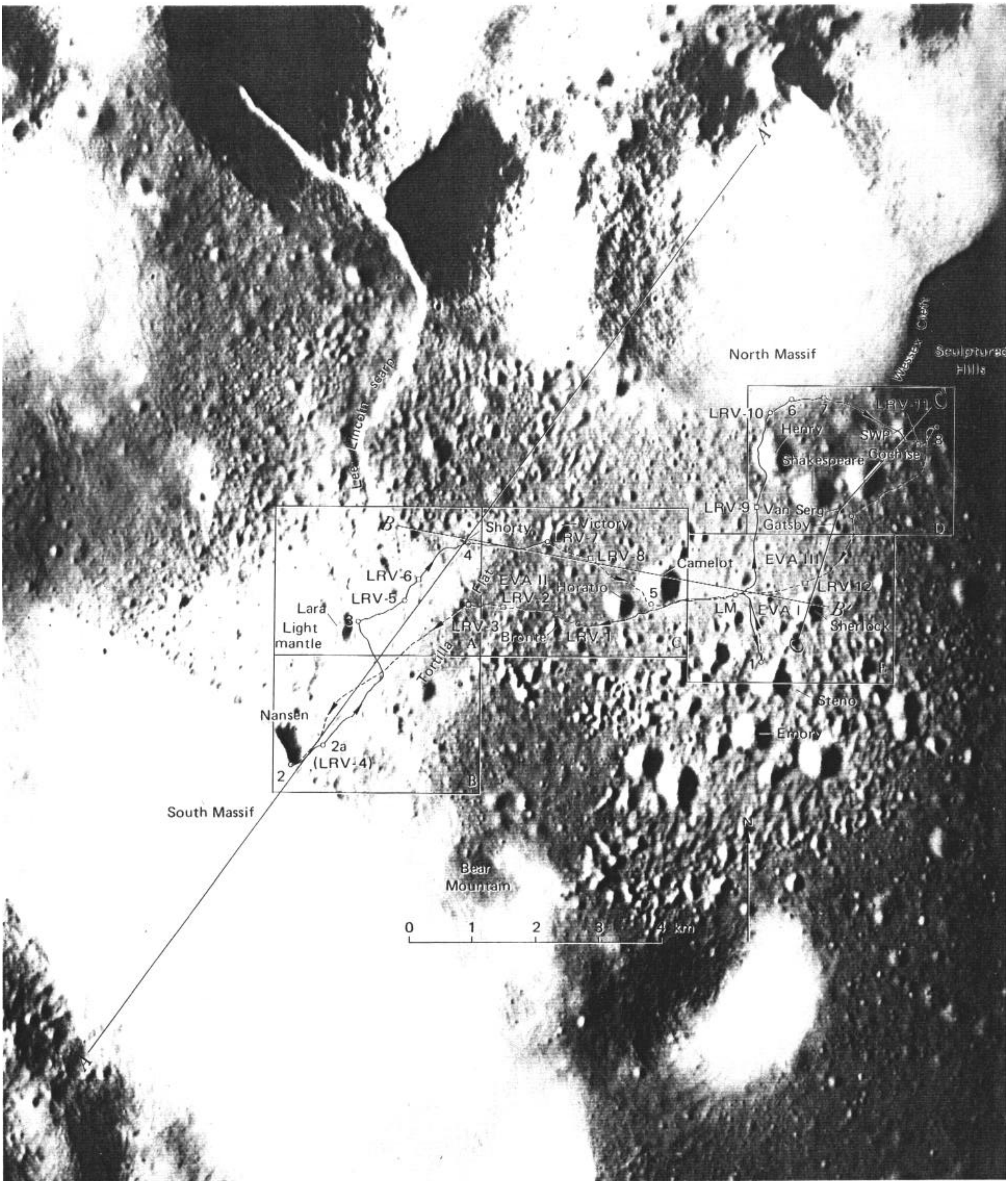
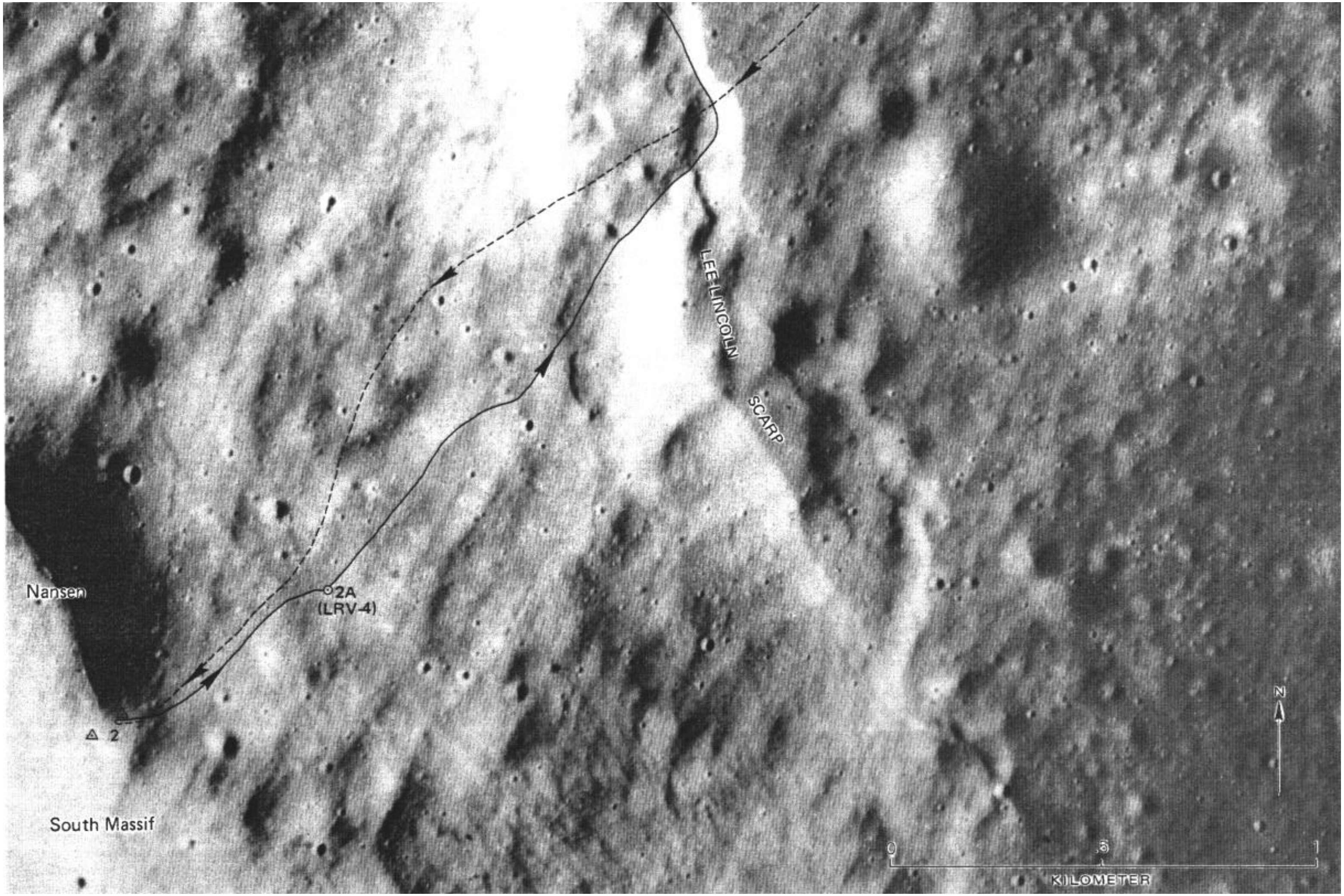


FIGURE 6. - Apollo 17 traverse path, stations (LM and 1 through 9), and Lunar Rover sample stops (LRV-1 through LRV-12). Circles, locations whose positions are known within 10 m; squares, approximate locations; solid line, traverse path, derived in part from very long base interferometry by 1. M. Salzberg. Goddard Space Flight Center; dashed line, approximate traverse path; arrows. direction of travel. Lettered boxes (A through F), outlines of detailed traverse maps (fig. 7). Cross section of figure 242 is along line A-A'; cross sections of figure 248 are along lines *B-B'* and C-C'. (NASA panoramic camera photograph AS17-2309.) (Modified from Muehlberger and others, 1973; Apollo Field Geology Investigation Team, 1973.)

FIGURE 7. - Detailed maps showing traverse path and stations. Locations of detailed maps are shown on figure 6. Triangle, site of panorama, location accurate within 10 m, not shown in LM area; EP-1 through EP-8, lunar seismic profiling experiment (LSPE) explosive packages; SEP, transmitter for Surface Electrical Properties experiment; ALSEP, location of the central station for the Apollo Lunar Surface Experiments Package; other symbols as in figure 6. (NASA panoramic camera photograph AS 17-2309.) (Modified from Muehlberger and others, 1973.)



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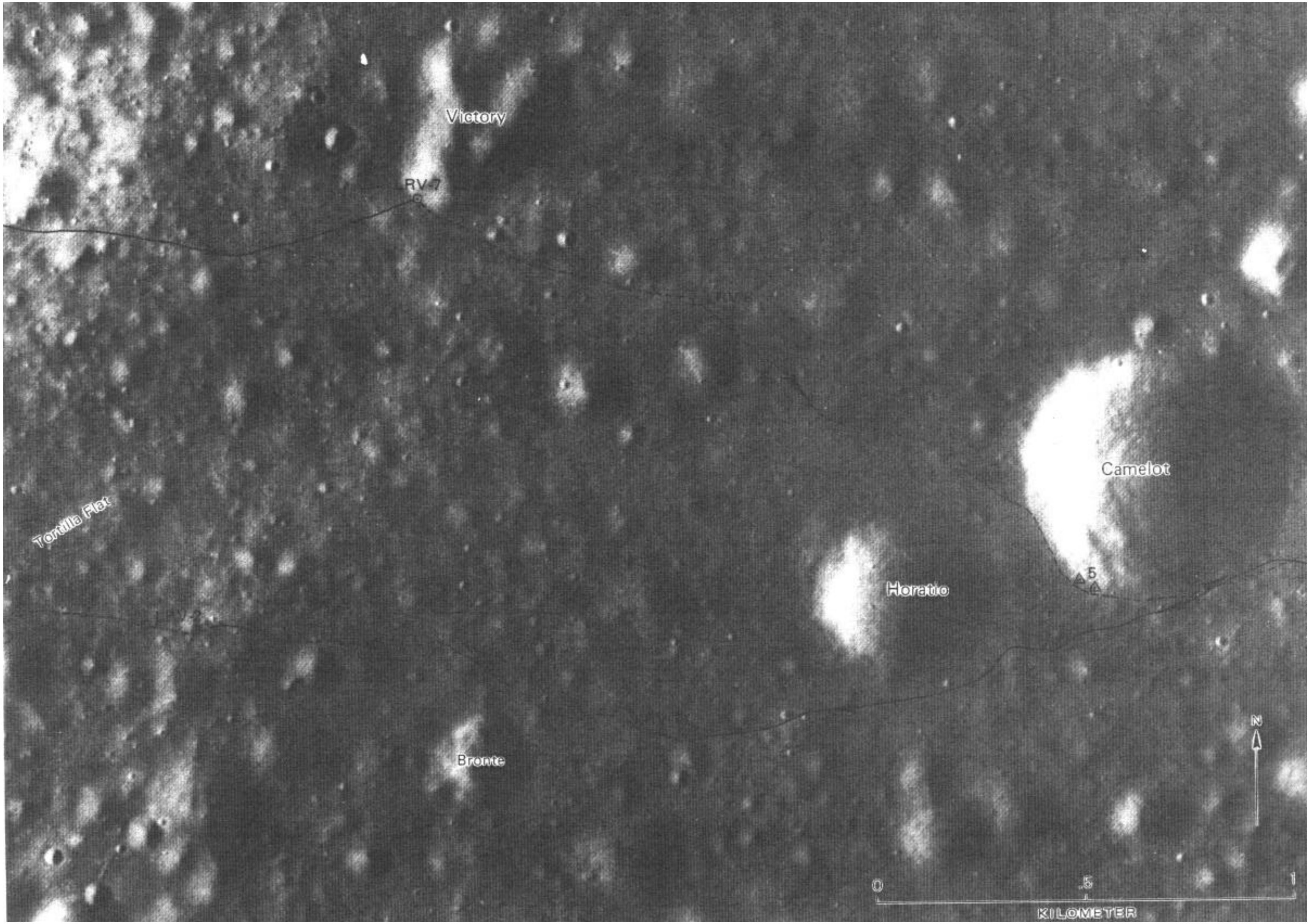

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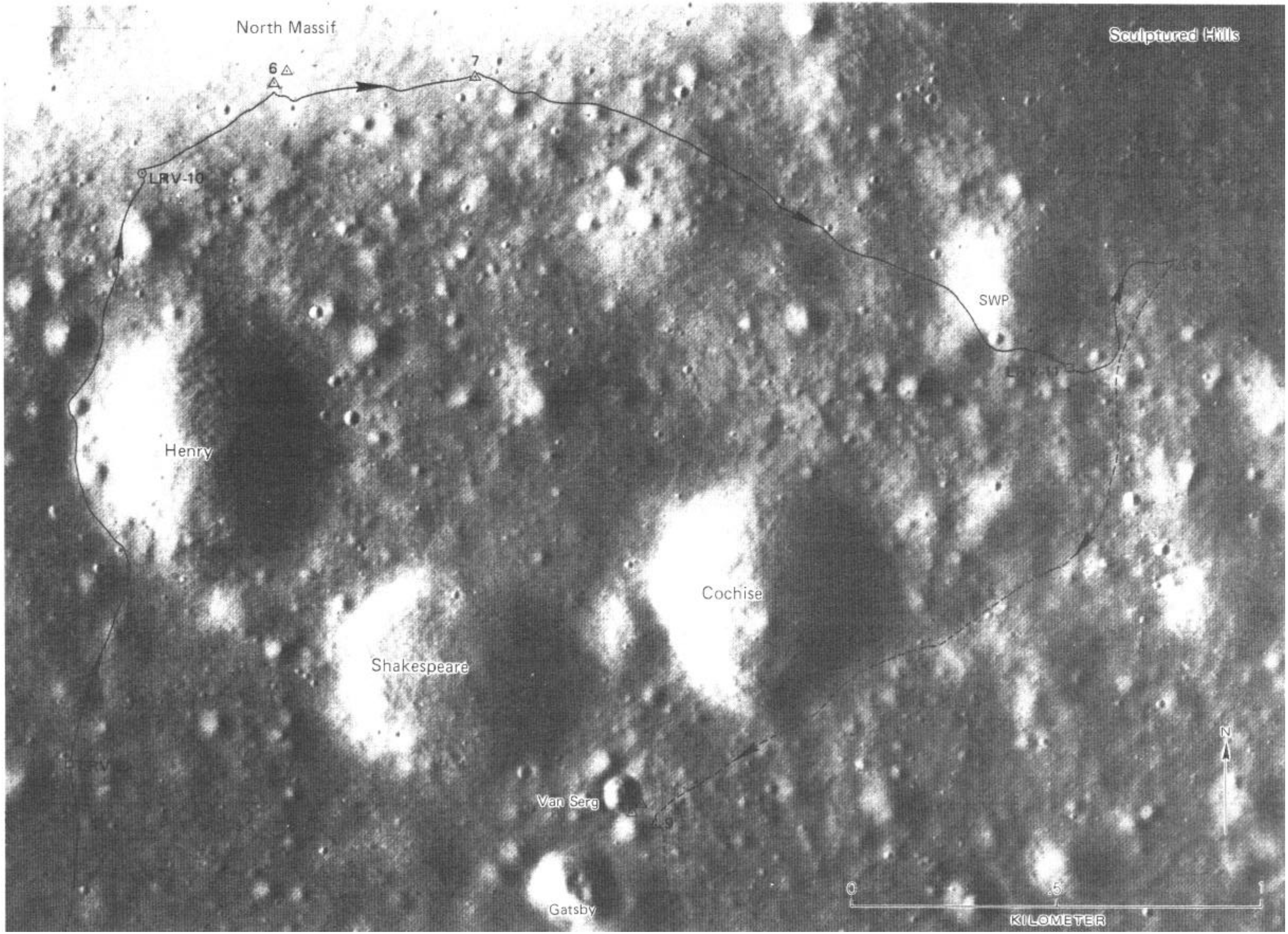

FIGURE - 7. - Continued,

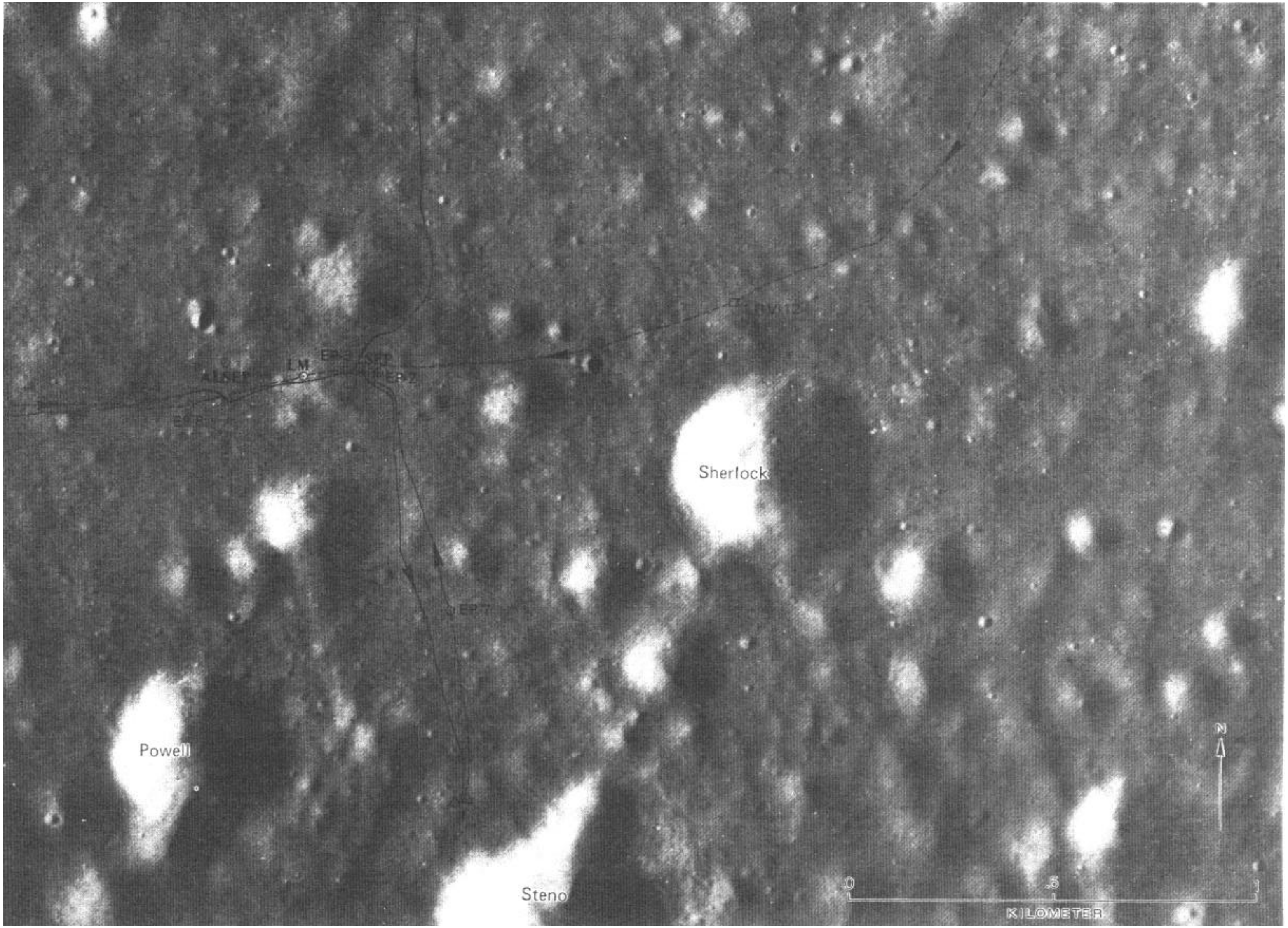

FIGURE 7. -Continued,

provide the primary data for determining precise station locations and for constructing maps showing sample locations at each station. Photographic and cartographic procedures as well as an annotated catalog of the Apollo 17 lunar surface photographs are described at the end of this report.

Samples were numbered in the Lunar Receiving Laboratory (LRL) according to a systematic scheme. The first digit (7) refers to an Apollo 17 sample, the second to the station number (0 represents the LM/ALSEP/SEP area). During EVA-2 and EVA-3, samples were collected from the surface between traverse station stops by the use of along-handled sample bag holder without the need for the crew to dismount from the LRV. These LRV-stops are labeled LRV-1 through LRV-12 in figures 6 and 7. The second digit of samples from LRV-stops, and also from station 2a, is the number of the next station; hence, samples from LRV-7 and LRV-8, between stations 4 and 5, are, respectively, 75110-15 and 75120-24. LRL numbers for sediment samples end with digits 0 through 4; numbers for rock fragments larger than 1 cm end with digits 5 through 9.

CLASSIFICATION OF SAMPLES

Description and classification of the Apollo 17 samples larger than 5 g is based on direct observation of hand specimens in the Lunar Receiving Laboratory, on examination of one or more thin sections of some rocks, and on published descriptions.

Table 1 shows a general classification scheme for lunar samples. The classification represents an attempt to group the samples under the orthodox terrestrial headings of igneous, sedimentary, and metamorphic subdivisions to reflect the dominant process in their formation. Unlike the varied terrestrial processes of rock formation and modification, impact has been the principal process for modifying and redistributing the lunar igneous rocks. The products of this single process of rock modification are thus dominated by a spectrum of fragmented racks showing varying degrees of thermal effects, and, while the names given them may be familiar, the relative abundances of the different rock types are unlike the relative abundances of similar rocks on the earth. As might be expected from a process that provides so little time for thermal and compositional equilibration, many of its products are mixtures of incompletely fragmented and melted materials. The temperature distribution in the ejects deposits must, therefore, have been complex, with steep local gradients and variable development of postdepositional thermal effects. The returned samples fully illustrate these complexities.

The igneous rocks that originally formed the major part of the Moon's crust have been so disrupted and

TABLE 1.-General classification scheme for lunar samples

I. Igneous.
   A. Platonic.
   B. Volcanic.
II. Sedimentary.
   A. Unconsolidated (surface ejects).
   B. Impact consolidated.
   C. Weakly lithified (welded or sintered).
III. Metamorphic.
   A. With recognizable igneous or metamorphic source rocks.
      1. Dynamically metamorphosed (cataclastic).
      2. Thermally metamorphosed (matrix recrystallized).
      3. Impact-fused (matrix substantially fused).
      4. Thermally metamorphosed or impact-fused, undifferentiated (aphanitic, poikilitic).
   B. With indistinguishable or mixed source rocks.
      1. Dynamically metamorphosed (cataclastic): Aphanitic and coarser grained crystalline rock fragments and mineral debris mixed by cataclastic flow.
      2. Thermally metamorphosed: Recrystallized (granoblastic).
      3. Impact fused: Melt texture (glassy, feathery, intersertal, ophitic).
      4. Thermally metamorphosed or impact fused, undifferentiated (aphanitic, poikilitic).

modified by large basin-forming impacts that very few remnants of the original rock have survived intact. The classification has been applied as strictly as the sampling allows to show the dominant petrographic character of the rock rather than what we or others may infer its parent to have been. Thus, names of lunar platonic igneous rocks must satisfy the characteristics of terrestrial platonic igneous rocks (see for example Holmes, 1928). Where platonic or volcanic igneous rocks have been significantly modified by mechanical and thermal effects, their classifications are changed to reflect those modifications. When the source rock is identifiable, its platonic or volcanic rock name is used as a modifier to convey the maximum amount of information in the name (for example, norite cataclasite). The vast majority of impact-modified igneous rocks, however, have been so severely altered and mixed that the source rocks cannot be directly specified.

Products of impact cratering (Shoemaker, 1960; Moore, 1969, 1971; Shoemaker and others, 1973; Wilshire and Moore, 1974), whether ejected or remaining beneath the cavity, range from broken rock and mineral debris insufficiently heated to become consolidated after deposition (the sedimentary division) to impact melts that solidify to rocks with igneous textures (impact-fused rocks). Between these extremes are crushed but incompletely disaggregated rocks (cataclasites), heated rock debris that recrystallized after deposition (thermally metamorphosed rocks), and complex mixtures of impact melt and solid debris that have small-scale transitions from melt to thermal metamorphic textures. Materials classified as sedimentary have been transported and mixed by the impact process. Unconsolidated elastic material may be reworked by later impact events to yield regolith breccia, which is poorly consolidated, weakly welded or sintered rock (Phinney and others, 1976) or sheared impactindurated rock.

Rocks that have been severely modified by mechanical or thermal effects of impact are classified as metamorphic. They are subdivided first on the basis of whether their source rocks are identifiable and second on the basis of degree of thermal effect. Mechanically disrupted but weakly metamorphosed rocks are classed as cataclasites (dynamically metamorphosed). Such rocks are intensely shattered, but their sources are still identifiable. There is no sharp separation of these rocks from the sedimentary rocks because mobilization of disrupted rock (that is, cataclastic flow) during crater formation ultimately yields disaggregated ejecta (Wilshire and Moore, 1974).

Rocks that were sufficiently heated to have recrystallized are classed as thermally metamorphosed rocks. The majority of these are breccia, which is subdivided on the basis of dominant matrix texture. Where recognizable igneous or metamorphic relics indicative of the parent igneous rock are scarce or absent, the rocks are simply labeled "metaclastic" rocks. The thermally metamorphosed matrices have fine-grained granoblastic texture. Gradations between textures and inhomogeneous distribution of them in the same rock are commonplace.

Impact-fused rocks have textures ranging from glassy to intersertal to ophitic. There is evidence that some such rocks form by direct impact melting of platonic igneous rocks (for example, Dowty and others, 1974), but many are complex mixtures of more than one parent rock type (Dymek and others, 1976b; James and Blanchard, 1976). There are rapid transitions among different textural types in the same sample, leading to difficulties in classification and contradictions among different workers, each of whom studied only a small part of the sample.

There is no sharp boundary between impactmetamorphosed rocks whose matrices have recrystallized in the solid state and those whose matrices were largely melted (impact-fused rocks); indeed, some rocks have both textures in the matrix. Moreover, rapid transitions within single breccia samples from cataclastic to melt to thermal-metamorphic texture in the matrix are a result of multiple impacts and of complex mixing of heated and unheated rock debris during excavation and transportation of ejecta. Classification thus becomes a matter of judgment, often swayed by individual thin sections that may not be truly representative. To avoid too rigid a classification scheme, the uncertainties are accommodated by a class of undifferentiated thermally metamorphosed or impact-fused rocks.

Similarities between the coarser grained poikilitic and ophitic rocks have led to some controversy over the origin of the poikilitic rocks. Some authors consider all poikilitic rocks to be impact melts with various amounts of solid debris (Simonds, 1975; Simonds and others, 1973; Irving, 1975); others (Wilshire and others, 1981; Bence and others, 1973) consider them to be largely metamorphic in origin with various but subordinate degrees of impact melt in addition to the relict rock and mineral debris. Still others (for example, Chao, 1973; Chao and others, 1975b) consider some poikilitic rocks to be metamorphic and some to be dominantly igneous. It is our view that these rocks probably represent a spectrum of degrees of fusion: those containing abundant newly crystallized plagioclase laths and interstitial material with intersertal texture were largely fused, whereas those without such textures may have formed by recrystallization of largely solid rock and mineral debris. Both of these types contain evidence of having been fluidized, but the presence of gas cavities does not necessarily indicate fusion, as is commonly assumed. For example, Reynolds (1954) emphasized the presence of drusy cavities in a conglomerate dike as evidence of emplacement of the dike as a solid-gas mixture. Because of their transitional or uncertain genesis, rocks with poikilitic texture have been classed here as undifferentiated thermal metamorphic or impact fused.

Similar problems occur with the large group of polymict breccias with aphanitic matrices. Some authors (for example, Phinney and others, 1976) consider all of these to represent mixtures of melt and solid debris, while others (for example, Wilshire and Jackson, 1972) consider identical rocks from the Apollo 14 site to be thermally metamorphosed. Still others (for example, James, 1977) consider that some aphanites with granoblastic texture recrystallized from glass, a sequence also suggested by Chao (1973) for certain poikilitic rocks with metamorphic textures. In view of the enormous quantities of unmelted pulverized rock and mineral debris excavated from impact caters, it seems unreasonable to suppose that all aphanitic rocks must represent quenched impact melt. It is our view that these rocks, like the poikilitic rocks, represent a spectrum of degrees of fusion and cataclasis, and those with granoblastic texture may have formed by essentially solid-state recrystallization of powdered rock debris. These rocks are identified as breccia with aphanitic matrix without specifying the dominance of thermal metamorphism or impact fusion.

The Apollo 17 samples are classified in table 2. The rare surviving plutonic igneous rocks, clasts of such rocks in the impact breccia, and other impact-modified materials with known source rocks indicate that the dominant nonmare source rocks of the Apollo 17 suite are troctolite, olivine norite, norite, and noritic anorthosite with some dunite.

Mare rocks are classified according to their modal compositions as olivine basalt or basalt to allow classification of the many as yet unanalyzed rocks. This scheme will, of course, be supplanted in time by chemical classification. The orange glass, sample 74220, is considered to be pyroclastic (Heiken and others, 1974) and is classed as ash because of the particle size range.

The "soil" samples are classified as sedimentary materials. Their dominant components, usually mare basalt, highlands material, or glass that may have been derived from either mare or highlands, are indicated. In general, the dominant component of the samples reflects the nature of the local bedrock, but core samples are stratified and have various proportions of highlands and mare fragments; the variations are reflected in the bulk composition of the samples. "Soil" and core sample descriptions were obtained largely from Butler (1973) and Heiken (1974).

Reworking of surficial materials has led to weak consolidation of some of the heterogeneous sediments by welding of glass shards and sintering (Simonds, 1973; Phinney and others, 1976) to form weakly lithified polymict breccia (commonly called "regolith" or "soil" breccia). In practice, such breccia is distinguished from severely disrupted but relatively unrecrystallized cataclasite on the basis of abundance of glass shards and extreme diversity of lithic clasts in the regolith breccia, but there is a point beyond which the two types cannot be distinguished. Surficial material thought to have been merely compacted by impact (impact- indurated polymict breccia) has the same diverse components as the welded or sintered breccia but is generally more compact and has distinctive fracture patterns (for example, 79135).

Dynamically metamorphosed rocks with recognizable source rocks are mostly shattered plutonic rocks such as norite, troctolite, and dunite, but there are two cataclasites derived from mare basalt. Many of the plutonic rocks had undergone deep-seated partial thermal metamorphism before impact excavation (Wilshire, 1974; Stewart, 1975), yielding coarse granoblastic-polygonal textures that tend to survive cataclasis better than their unrecrystallized counterparts. Where such recrystallization is thought to have been substantial, the plutonic rock name is modified by "meta-". The majority, probably all, of the members of this group derived from plutonic source rocks are clasts from more complex breccia.

The samples listed as cataclastic rocks with mixed source rocks are thought to he the products either of mixing of aphanite and crushed debris formed contemporaneously in a single impact or of cataclastic flow of breccia whose original components were plutonic rock clasts in a fine-grained thermally metamorphosed matrix. Slight para- and post-consolidation deformation of such rocks commonly inverts the original clast-matrix relations (Wilshire and others, 1973; Wilshire and Moore, 1974) so that broken pieces of the original matrix become isolated in material derived by disaggregation and cataclastic flow of the original clasts. Where this material has not been subsequently metamorphosed, it may be classed, as we have done, as cataclastic.

Breccias whose matrices have been unequivocally and substantially fused include gabbro, basalt, and polymict breccias, all with glassy matrices.

Thermally metamorphosed or undifferentiated thermally metamorphosed or impact-fused rocks with recognizable source rocks were largely derived from impact crushing and perhaps partial melting of single rock types (all plutonic sources) or from partly recrystallized plutonic rock (76535) that was thermally metamorphosed before excavation.

Thermally metamorphosed rocks or undifferentiated thermally metamorphosed or impact-fused rocks with indistinguishable or mixed sources are mainly polymict breccia, but some (metaclastic rocks) have few or no lithic clasts. It is likely that the great lithologic diversity of clasts in the polymict breccia actually represents only a small variety of plutonic source rocks, with the lithologic diversity representing various degrees of mechanical breakdown and mixing and various thermal effects resulting directly from the impact process. The matrix of this breccia shows a similar range of impactrelated mechanical and thermal effects ranging from aphanitic to fine-grained granoblastic to coarsegrained poikilitic texture.

The dominant rock type returned from the TaurusLittrow highlands is polymict breccia with an aphanitic matrix; polymict breccia with a poikilitic matrix is also common. Both are classified as undifferentiated thermally metamorphosed or impact-fused rocks with the understanding that either type of thermal effect could he dominant in any particular sample.

LM/ALSEP/SEP AREA

LOCATION

The Lunar Module (LM) landed in a relatively smooth area about 800 m east of Camelot crater and near the northwest boundary of a large cluster of craters on the valley floor (fig. 6; pl. 2). Sampling was concentrated