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INTERAGENCY REPORT: ASTROGEOLOGY 14

FIVE-DAY MISSION PLAN TO INVESTIGATE THE GEOLOGY OF THE MARIUS HILLS REGION OF THE MOON

by

Donald P. Elston and Charles R. Willingham

April 1969

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CONTENTS

ILLUSTRATIONS

In pocket

TABLES

ABBREVIATIONS

ELM Extended Lunar Module

LRV Lunar Roving Vehicle

ABBREVIATIONS--Continued

LSS	Lunar Surveying System
ALSEP	Apollo Lunar Surface Experiments Package
LFU	Lunar Flying Unit
EVA	Extra-Vehicular Activity

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SYNOPSIS

High-resolution Orbiter photographs of the Marius Hills region of the Moon reveal a complex of apparent constructional features that are interpreted to be volcanic in origin. In common with features and materials elsewhere on the Moon, the inferred volcanic features appear to have been modified in fine and locally in moderate detail by impact cratering, and the freshest exposures appear to occur principally in the wall and rim materials of youthful impact craters.

Field investigations and sampling of the inferred endogenetic materials in the Marius Hills probably would furnish information important to understanding lunar igneous, volcanic, and differentiation processes. Moreover, sampling of endogenetic materials which are associated with--and which locally have been modified by--impact cratering would also provide information on the cratering history of the surface and on the character of exogenetically emplaced materials. The recognition and discrimination of both endogenetic and exogenetic materials during the course of the mission would be important to the conduct of the field investigations and to sampling, as well as to post-mission analysis and interpretation of the data.

Exploration traverses are proposed which cross features that are thought to be important to understanding the geologic evolution of the Marius Hills. The traverses also cross features which, from analogies with terrestrial and meteoritic materials, may contain deposits of water. Such features include possible maar craters and the rim materials of some dark-halo craters of possible impact origin.

Plans for a 5-day post-early Apollo roving- and flying-vehicle mission have been prepared that provide for 1) the concurrent study of lunar volcanism and impact phenomena, and 2) exploration for possible sources of hydrated minerals and interstitial ices. The field investigations are designed to obtain information on 1) the evolution of a probable volcanic terrain, 2) the impact and shock metamorphic history of the lunar materials, and 3) the origin, character, and distribution of potential deposits of endogenetically and exogenetically emplaced volatiles. The proposed fieldwork involves reconnaissance geological investigations of stratigraphy and structure, sampling diverse geologic features at various localities to acquire a fairly representative suite of materials, and acquisition of supporting field geophysical data (seismic, gravity, magnetics, and heat flow).

The Marius Hills region is particularly well suited for study because it contains diverse features of inferred volcanic and impact origin that are both small enough and close enough together to be studied during comparatively short traverses (about 10 km long). Nearly all the types of features recognized in the Marius Hills could be studied within 5 km of the proposed landing site, using a roving vehicle (LRV) and a flying unit (LFU). During the proposed 5-day mission the roving vehicle is employed in eight 3-hour traverses, during which nearly 100 stations are briefly occupied to provide a station density slightly greater than one station per kilometer of surface traverse. In addition, three flying-vehicle sorties are scheduled to six stations not readily accessible to the roving vehicle. Two flying vehicle sorties are held in reserve for supplemental investigations of sites found to be important during LRV exploration, or to visit LRV stations not occupied by the roving vehicle because of operational difficulties.

The astronauts are aided by a proposed scientific support system that includes: 1) a lunar surveying system containing television and film cameras, and a magnetics staff, with both systems mounted on and used principally from the LRV and LFU; 2) navigation systems on the LRV and LFU; 3) sample examination, analysis, and handling equipment to be used in the lunar environment at the base station; and, 4) an Earth-based scientific advisory support group. A small microscope is provisionally included in the Extended Lunar Module (ELM) so that selected samples could be examined between periods of extra-vehicular activity. Information that would aid near-real-time traverse evaluation and planning, and the selection of samples for return to Earth, thus could be obtained.

Materials that could be sampled during the proposed mission include nine inferred kinds of volcanic or possibly intrusive rocks, and eight inferred kinds of impact-modified materials. Thirteen sites that may contain hydrous minerals, and possibly interstitial ground ice (permafrost), could be investigated and sampled.

Sampling, sample handling and analysis, and the selection of samples for return to Earth, require much of the time allotted to scientific exploration. Roving vehicle driving times use about 1 to 1-1/2 hours of each of the 3-hour exploration traverses, assuming a nominal 7 km/hr average traverse speed. A 5-km operational radius appears to be satisfactory for the examination of the diverse, relatively small geologic features in the Marius Hills, but investigation of features much farther than 5 km from the ELM by manned LRV traverses would markedly reduce the time available for field investigations and for sampling to obtain representative materials. Field investigations around stations more than 5 km from the ELM might be most efficiently carried out by use of the flying unit.

INTRODUCTION

The 5-day exploration plan presented here is modified and expanded from a 3-day plan for the Marius Hills region (Karlstrom and others, 1968). The 3-day plan outlines steps for exploration of the inferred volcanic complex. During preparation of the

3-day mission plan, it was realized that the launch and delivery system concept, that was being relied on for logistics support, had a payload that could support a 5-day mission--a discovery that led to the preparation of this mission plan. Exploration in the Marius Hills presumably would take place following Apollo foot-traverse exploration missions to point localities on the Moon. Manned exploration around an Extended Lunar Module (ELM) for periods of 3 days or more may occur as single missions. They conceivably might also constitute the beginning- or end-point of an unmanned lunar roving vehicle mission extending hundreds of kilometers across the lunar surface.

The 5-day exploration plan outlines steps in a fairly comprehensive reconnaissance field investigation of geologic features of the Marius Hills. Geologic mapping of Lunar Orbiter photographs suggests that the surface features are the product of both endogenetic and exogenetic processes, and that many of the freshest exposures are associated with inferred impact craters. Because of this, features and materials related to the inferred volcanic complex, and features and materials modified by inferred impact processes, could be examined at the same time for information relevant to the evolution of endogenetic materials, to lunar impact-cratering history, and to the character of impacting materials.

The proposed transportation systems, the exploration and scientific support systems, and the inferred mobility and extra-vehicular activity constraints are basically the same as those that were assumed for the 3-day mission. The weights of some individual payload items, and operating constraints for the roving vehicle (LRV), have been somewhat modified on the basis of discussions held by the NASA Working Group on the Lunar Roving Vehicle (August 27-28, 1968).

EXPLORATION OBJECTIVES

The general purpose of the field exploration is to obtain information on 1) the origin and history of lunar materials and structures, 2) processes responsible for those materials and structures, and 3) processes that have modified them.

Problems Related to Endogenetic Processes

The Marius Hills region (pls. 1-3) displays certain physiographic features (cones, domes, and ridges) that have been attributed to volcanism by McCauley (1967a, b; 1968) and Karlstrom and others (1968). As discussed in their reports, elongate fissure (punctured) cones, the axes of which lie on and parallel to north-trending regional structures, are considered analogous to elongate terrestrial volcanic cones, such as those in northern Arizona's San Francisco volcanic field and in the Hawaiian volcanic complex. Moreover, the Marius Hills are on a regional north-trending welt that bears some resemblance to terrestrial mid-oceanic ridges. The inferred volcanic features display a wide variety of forms, suggesting that the rocks may differ in composition and may be petrologically differentiated. The oldest rocks thus might be mafic, and the younger ones intermediate to felsic in composition, as in many terrestrial volcanic centers. If the inferred volcanic materials in the Marius Hills are younger than the adjacent mare plains, and if geophysical data indicate that they are in areas of anomalous heat flow and density, then inferences might be drawn regarding the existence and the age of subsurface convection currents.

The number of small craters on the plateau-plain materials in the Marius Hills appears to be greater than that on mare material that borders the Marius Hills on the northwest (pl. 1). If the plateau-plain material is younger than the surrounding mare, as the map explanation (pl. 3) shows, then many of its small craters may well be volcanic rather than impact in origin. Alternatively, if the plateau-plain material is older than adjacent mare material, the small craters on both could be mainly of impact origin.

The dating of materials that are little modified or unmodified by impact, and the gas-retention ages of highly shocked materials derived from impact craters, would provide information on the time of formation of the various plains materials and constructional features, and on the flux of impacting materials over discrete spans of time. The age data might enable correlation of the materials here with those of regions studied during other missions, and aid in correlation and interpretation from photogeologic data.

Fissure or punctured cones have been mapped as relatively young features that postdate plateau-plain material (pls. 1-3). This concept may be overly simplified because plateau-plain material, similar in appearance and crater density throughout the region, locally embays (and thus apparently postdates) fissure cone material in the southeast part of the area of plate 2. Moreover, the several fissure cones (pl. 2) differ in degree of physiographic freshness and thus, perhaps, in age. Some may have formed before or during emplacement of plateau-plain materials that are now exposed at the lunar surface. Investigation of several fissure cones therefore is planned to provide information on the origin and age of the cones, and on the evolution of the inferred Marius Hills volcanic complex.

By analogy with terrestrial features and materials, lunar materials emplaced by explosive volcanic activity (vent materials and ejecta aprons of maar craters) could be sources of water held in chemical bond; they might also contain water in the form of interstitial ices (permafrost) derived from volcanic exhalations. The mineral serpentine, common in diatremic pipes underlying maar craters and in volatile-rich kimberlite pipes, consists of about 13 percent water. Explosive volcanic activity that produces some terrestrial maar craters may be due to evolution of volatiles from a deep-seated magma, accompanying a drop in pressure as the volcanic materials approach the surface. The mechanics of maar-forming eruptions have been described by Shoemaker (1962, p. 298-301).

The floors of most maar craters are lower than the surrounding terrain, and the craters are enclosed by low, smooth aprons of ejecta. Kimberlite tuff from northeastern Arizona and average "basaltic" kimberlite contain about 7 to 13 percent H_2O+ (Watson, 1967, table 8.4). Pipe(?), floor, and rim materials of possible lunar maar craters should be examined to establish their origin, and should be sampled as part of a general search for water-rich tuffs, and for interstitial ice derived from the H_2O component of volcanic gases. One comparatively large (about 1 km diameter) maar-type crater lies 1.5 km north of the landing site (pl. 2). Several small rimless (maar?) craters are also within the exploration area.

Terrestrial volcanic complexes commonly display local alteration halos and phenomena in and near their vent areas. Altered rocks in a sulfur-acid alteration sequence may include hydrous minerals (such as kaolinite, alunite, and opal), and contain about 8 to 12 weight percent total water, of which about 4 to 6 weight percent could be H_2O+ (J. Green, personal commun., 1968). The proposed exploration traverses in the Marius Hills cross features which, by analogy with terrestrial volcanic features, could include water-rich deposits that are the result of post-emplacement volcanic alterations.

Problems Related to Exogenetic Processes

Sampling of endogenetic materials associated with impact craters should provide the basis for: 1) an understanding of primary and secondary impact cratering in the area, and the recognition of exogenetic materials; 2) the development of an impact-cratering chronology for regional and Moon-wide correlations; and 3) testing an hypothesis that volatiles may have been emplaced in certain impact breccias as the result of cratering by cometary materials.

Scattered bright-halo craters in the Marius Hills are inferred to be youthful impact craters, in and around which fresh fragments and blocks of materials, ranging from lightly brecciated to locally severely shocked, are presumably exposed. In addition, there are some scattered small low-rimmed craters that exhibit apparently smooth and comparatively dark rim materials. Although some of the dark-halo craters may be volcanic cinder cones, others may be of impact origin and may be analogous to certain relatively young, dark-rimmed probable impact craters in the eastern part of the Moon (Elston, 1967, 1968a). If the dark rim materials of some of the craters are impact-darkened breccias, they may, by analogy with certain polymict meteorite breccias, contain water, carbon, and rare gases held in layer-structure silicates of probable carbonaceous meteorite (cometary?) origin. Layer-structure silicates in such polymict meteorite breccias contain on the order of 1 to 2 weight percent H_2O+. If some dark-halo craters are the result of cometary impact, volatiles in the form of ice (permafrost) also might be present in their rim materials. If interstitial ice does occur, water contents could be very high.

Whereas low-density, carbon- and water-bearing meteorite materials (cometary?) may have been responsible for the excavation of dark, smooth-rimmed impact(?) craters in the Marius Hills, craters that are enclosed by bright, rubbly ejecta may have formed from the impact of relatively dense stony and metallic materials (asteroidal?). The ejecta and the breccia of such craters may contain traces, and locally discrete inclusions, of the impacting materials. Dense, metalliferous impactite locally may be present. The identification of impact-produced breccias on the lunar surface should enable correlations with certain types of meteorite polymict breccias that may be of lunar origin (Elston, 1968b).

Lastly, several inferred satellitic or secondary crater swarms exist in the Marius Hills region. The swarms appear to have been derived principally from three large rayed impact craters of Copernican age: Cavalerius to the southwest, Aristarchus to the north, and Kepler to the east. From experience with terrestrial secondary craters (Roberts and Carlson, 1963; reconnaissance examination and sampling of satellitic craters around the nuclear crater Sedan by E. M. Shoemaker and D. P. Elston, 1963; and Elston and Milton, 1963), the ejecta and wall materials of lunar satellitic craters could very likely provide samples of material derived from primary craters. Such nonlocal lunar materials could, in turn, also contain traces of the impacting materials that produced the primary craters. Thus, investigation of satellitic crater swarms in the Marius Hills could provide data on the composition and age of materials derived from a fairly large area of the Moon, and furnish information important to understanding lunar geologic history.

Field Geophysical Exploration

Field geophysical exploration in the Marius Hills would include the establishment of a network of gravity stations, a survey of the total magnetic field, a survey of remanent magnetism, establishment of heat-flow stations, and deployment of geophone arrays and explosive charges for an Active Seismic Experiment (ASE). From terrestrial experience, a gravity station network with a density of about one station per 1.5 km^2 probably would provide information on the mass distribution within a few kilometers of the lunar surface. Gravity, magnetic, and heat-flow data would support or refute the hypothesis that the Marius Hills region is analogous to a terrestrial mid-oceanic ridge. If the north-trending welt is an active "ridge," it might be marked by gravity, magnetic, and heat-flow anomalies spatially related to the trend of the welt.

The heat-flow stations in the 5-day mission plan are arranged in a cross that is oriented with one arm parallel and one arm perpendicular to the axis of the north-trending welt. A heat-flow gradient perpendicular to the welt might suggest convective activity in the lunar subsurface. Additionally, localized thermal anomalies might correlate with youthful features of inferred volcanic origin.

The Active Seismic Experiment in the 5-day mission plan would obtain: 1) deep subsurface information on seismic discontinuities of regional extent, and 2) detailed seismic refraction information from shallow structural features. Geophones and explosive charges would be deployed to provide subsurface data in directions perpendicular and parallel to the structural welt. An eight-geophone seismic array would be deployed perpendicular to the trace of a subdued trough or rille; explosive charges near this array would be arranged to give information on the thickness of an inferred lunar regolith, on possible near-surface bedrock stratifications, and on the subsurface structure of the rille. Explosive charges would be remotely detonated, individually, after the manned surface exploration is completed.

A magnetics staff that would measure the natural remanent moment, polarity, and magnetic susceptibility of the lunar materials, and the total field at the time of measurement, has provisionally been added to the geophysical instrumentation.

Lunar materials may very possibly contain measurable remanent magnetism because: 1) all classes of known extra-terrestrial materials--the meteorites--contain remanent moments, and at least parts of the moments appear to be of extra-terrestrial origin (Dubois and Elston, 1967, 1968); and 2) two classes of "basaltic" achondrites, the eucrites and howardites, may be of lunar origin, the former possibly being derived from the mare and the latter from the uplands (Duke, 1964; Duke and Silver, 1967; Elston, 1968b). Measurements of remanence with the magnetics staff could be useful for lunar stratigraphic correlations, and could also enable discrimination of exotic extra-lunar and lunar materials in breccias associated with primary and secondary impact craters. Study of the remanence and polarity of lunar materials of different ages could shed light on the thermal history of the Moon.

MISSION PARAMETERS

Transportation and Exploration Systems, and Scientific Payloads

The same two-stage transportation system planned for the 3-day mission to the Marius Hills is assumed for the 5-day mission. The latter would place two men on the Moon in an Extended Lunar Module (ELM). Scientific payloads assigned to the launch vehicles are listed in table 1. The weights of some items have been estimated higher than weights listed in the 3-day mission to allow some latitude in instrument design.

The Extended Lunar Module (ELM) would have an intrinsic stay-time of 3 days on the lunar surface. Two additional days would be provided by fuel landed by the logistics support vehicle. The concept of a shelter-laboratory has been incorporated into the ELM by the inclusion of a small polarizing binocular microscope and ancillary sample-examination equipment. The microscope would be discarded before the return flight to earth. One of the two flying units (LFU) formerly assigned to the manned lander vehicle payload (Karlstrom and others, 1968) has been placed in the logistics support vehicle scientific payload (table 1) in order to allow the inclusion of a scientific payload on the ELM that can support foot-traverse operations both around the ELM and around stations visited by the remaining LFU. Thus, some scientific work could be carried out if the ELM is inadvertently landed well away from the logistics support vehicle.

Table 1.--Launch vehicle payloads charged to science

Manned lander vehicle (1,000-lb scientific payload)	Payload (lb)
1. Fuel and life support for a 2-day stay-time extension (3-day intrinsic stay-time)	500
2. Contingency Portable Life Support	120
3. Lunar Surveying System (LSS)	100
4. Magnetics Staff	5
5. Geologic tools; prenumbered sample-wrap and bags, and carrier	25
6. Sample examination equipment (binocular microscope with polaroid analyzer and polarizer; needle, glass slides, oils, vials)	5
7. Vacuum(?) return-sample containers (2)	50
8. Lunar Flying Unit (LFU)	180
9. Unassigned	15
	1,000

Table 1.--Launch vehicle payloads charged to science--Continued

Logistics support vehicle (2,800-lb scientific payload)	Payload (lb)
1. Fuel and life support for a 2-day stay-time extension	500
2. Contingency Portable Life Support System	120
3. Communication relays (2)	30
4. Lunar Flying Unit (LFU)	180
5. Lunar Roving Vehicle (LRV; includes remote control navigation equipment and stereo-facsimile camera system)	1,000
6. Lunar Surveying System (LSS; mounted on LRV)	100
7. Magnetics Staff (mounted on LRV)	5
8. Apollo Lunar Surface Experiments Package (ALSEP; loaded on LRV)	300
9. LRV loading equipment (for off-loading ALSEP and for transferring rocks to ELM)	50
10. Two 3-geophone seismic arrays (deployable from LRV; for deep refraction survey)	20
11. One 8-geophone seismic array (deployable from LRV; for shallow refraction survey)	10
12. Explosives (deployable from LRV; for Active Seismic Experiment)	80
13. LRV boom-mounted magnetometer (continuous reading, total field intensity type)	25
14. Gravimeters (2; 1 continuous recording for base station drift correction, and 1 deployable from LRV)	30
15. Heat-flow probes (possibly thermal-blanket type, includes transmitter; deployable from LRV)	60
16. LRV scientific instruments (automated for use in an unmanned operational mode)	87
Jet Propulsion Laboratory "petrographic" microscope	15[1]

[1] R. G. Brereton, personal commun., 1968.

Table 1.--Launch vehicle payloads charged to science--Continued

Logistics support vehicle--Continued		Payload (lb)
16. LRV scientific instruments--Continued		
X-ray diffractometer and spectrometer	23	
Water detector	5	
Drill/auger or "bulk" sampler	18	
Sample collector	26	
	87	
17. X-ray diffractometer--$\alpha K\alpha$ spectrometer (for use in lunar environment at base station)		60
18. Geologic tools (includes tongs, push-type core tubes, magnifying lens, sample bags, and carrier)		30
19. Outside worktable		10
20. Drill mounted on logistics support vehicle		50
21. Unassigned		8
		2,800

Time Allocations for Surface Operations

Stay-time, Extra-Vehicular Activity (EVA) time, the time-framework of the employment of the astronauts on the surface, and the nominal utilization of time in the ELM between periods of EVA are summarized in table 2.

Table 2.--Time allocations for surface scientific operations

Stay-time (maximum)	120 hr (5 days)
Extra-Vehicular Activities (EVA)	48 hr: 8 three-hour EVA periods/man; 1 EVA/day/man on the first and last day of the mission, and 2 EVA's/day/man on intervening 3 days of mission.

Table 2.--Time allocations for surface scientific operations--Continued

Nominal utilization of time in Extended Lunar Module (ELM)	2 hr/day/man for debriefing, conferences, and mission planning and preparation; 2 hr/day/man for scientific investigations in ELM (sample examination and return-sample selection); 6 hr/day/man for engineering requirements and housekeeping; 8 hr/day/man for sleep.
Drill mounted on logistics support vehicle	Deployment: 30 min. Monitoring and core removal, 10 min/hr of operation.
ALSEP	Off-loading, partial deployment and preliminary checkout at site: 20 min. Final deployment and checkout by ELM-based astronaut: 20 min.
Seismic geophones	3-5 min/geophone 3-geophone array, 15 min. 8-geophone array, 30 min.
Explosive charges	Emplacement: 5 min/charge.
Gravimeter	Automatic deployment and readout from LRV: 5 min/reading.
Magnetics Staff	Automatic deployment and readout from LRV at sample stations.
Heat-flow probes	Selection of site and emplacement of probe: 5 min/probe.
Lunar Surveying System (LSS)	Photographic panorama from LRV Stereometric film camera 4 min. Television camera

Table 2.--Time allocations for surface scientific operations--
Continued

Lunar Surveying System (LSS)--Continued	Photographic detail of rock exposure at sample station: Stereometric film camera, Television camera — 1 min.
Sampling	Traverse (grab or chip) sample, obtained during vehicle or foot traverse by tongs; includes brief description, wrapping and placing in box or bag: 2 min. Prime station sample; includes brief field and rock description, wrapping or bagging; location and orientation data obtained from employment of LSS: 10 min/sample.
X-ray diffractometer and $\alpha K\alpha$ spectrometer	Deployment and checkout at ELM: 15 min. Sample preparation, supply of instrument, and instrument monitoring: 15 min/hr of operation.
Lunar Roving Vehicle (LRV)	Deployment and checkout: 45 min.
Lunar Flying Unit (LFU)	Deployment and initial checkout: 30 min. Flight checkouts: 5 min. Refueling time: 15 min.

Times have been assigned for specific field operations, such as sampling, and the employment and emplacement of instruments, so that time-lines could be estimated for traverse and base-station EVA operations. The times that have been allocated to various operations are arbitrary, but are believed to be in approximately correct proportions in light of mission objectives, anticipated traverse capabilities, the desired scientific support system, and anticipated EVA suit constraints. Instrument checkout and monitoring times hopefully might be reduced, and some reduction in time also might be made with respect to the deployment and emplacement of seismic equipment and explosive charges. Gravity and magnetic measurements and film and television photographs would be automatically obtained at stations occupied by the astronaut. Because time is precious, and because the astronaut probably would not be able to scrutinize outcrops as closely and efficiently as on Earth, scientific operations during LRV traverses, including sampling, probably would be conducted principally from the driver's seat of the LRV.

Exploration Guidelines

Field exploration

The fieldwork presumably would be conducted as a detailed reconnaissance--a reconnaissance made possible by the traverse and flight capabilities of the LRV and LFU, and by the supporting scientific data acquisition equipment. At many and perhaps at most stations, small diverse samples, rather than large homogeneous ones, would be collected because compositional and age determinations of samples returned to Earth will require only small quantities of material, and because return sample payload will be limited. To effectively employ the traverse and automatic data collection capabilities of the LRV, it is here considered more important to briefly examine and to sample a relatively large number of features across the area that is traversed, than to examine in relatively great detail only a comparatively few features that may or may not be truly representative. The reconnaissance exploration presumably would provide a fairly large number of comparatively small "representative" and "special interest" samples collected from the diverse features across the area. Such a suite of samples, supported by photographic and descriptive information obtained during the course of the traverses and at the sample stations, should provide a reasonably broad foundation for evaluating and interpreting the geology of the area in light of supporting geophysical, chemical, and age data.

It is expected that during the course of the reconnaissance traverses, the astronaut would become familiar with a spectrum of features and materials, and that he would come to recognize, at some stations, features and materials that would require more detailed examination and more sophisticated sampling. Such stations would become prime sample stations. Anticipated prime sample stations along planned traverse routes have been identified on the basis of interpretations made from Orbiter photographs. Although some, or possibly even most, might remain as prime sample stations, changes are to be expected. The decision to occupy prime sample stations during the course of the individual traverses should be made by the astronaut.

Five LFU excursions would be possible, but only three have been scheduled. Two are held in reserve to permit revisiting LRV stations where critical relations warrant more detailed examination and sampling, or to occupy stations that the LRV cannot reach.

Traverse capabilities and operational guidelines

Nominal traverse capabilities and guidelines for surface exploration are summarized in table 3.

An attempt has been made to schedule mutually supporting scientific and operational activities. For example, the first LFU excursion has been coordinated with an LRV traverse. The LFU would be used for extended exploration only after the astronaut has adapted to the lunar environment and can operate the LFU confidently. The three planned LFU sorties visit spot localities that probably could not be reached by the LRV. The advantages of the LFU are: 1) travel time between stations would be very short, enabling correspondingly longer visits at each station; 2) it would provide access to stations that could not be reached by the LRV; 3) it would enable extension of the geophysical net; 4) it might serve as a rescue vehicle. The disadvantages of the LFU are: 1) high fuel consumption; 2) only a few stations could be visited; 3) geologic continuity would not be maintained between widely spaced stations; 4) exploration around stations visited by it would be limited to foot traverses.

Table 3.--Nominal traverse capabilities and operational guidelines

Capabilities

Lunar Roving Vehicle (LRV)	Nominal operating radius from ELM: 5 km. Nominal range: 15 km. Average traverse speed: 7 km/hr. Maximum speed: 15 km/hr. Nominal payload: 400 lb. Maximum payload: 800 lb.
Lunar Flying Unit (LFU)	Nominal two-stop operating radius: 5 km. Traverse time: negligible. Payload: 100-240 lb.
Astronaut (foot traverse)	Nominal cross-country speed: 1 km/hr. Maximum operating radius: 1½ km. Nominal operating radius from LRV, LFU, and ELM: 100 m.

Guidelines

1. One astronaut is to be within a 1½ km walk-back distance of the ELM when the other is on an extended traverse; or the two astronauts are to be within mutual support distance when concurrent LRV and LFU traverses are conducted beyond a 1½ km radius of ELM.
2. Concurrent LRV and LFU traverses, where practicable, are to be mutually supporting, both scientifically and operationally.
3. The more difficult LFU and LRV traverses should be carried out after operational proficiency in the lunar environment is attained, but before the very end of the mission when the astronauts may not be functioning optimally.

FIELD EXPLORATION

Scientific Support System

The desired scientific support system would include a surveying staff (the lunar surveying system, or LSS), a magnetics staff, navigational system, sample collecting equipment, sample examination and analysis equipment, and a scientific advisory support group. The purpose of the support system would be to make field operations as efficient as possible within the physical and scientific capabilities of man on the lunar surface.

Lunar surveying system (LSS)

The LSS would obtain location, orientation, and television and photographic data at field stations. The staff would be mounted on the LRV and LFU, and presumably would be used from the vehicular mounting whenever practible. Mounted on the LRV, it would provide continuous television photographic coverage during the course of the traverses, supplementing photography obtained from a navigational stereometric facsimile camera system intrinsic to the LRV.

Magnetics staff (MS)

The magnetics staff would consist of a magnetically balanced array of tiny flux-gate sensors. A staff designed for lunar use could weigh less than 1 pound, exclusive of telemetry and power source. The staff would be employed at stops of the LRV, and upon either manual or remote triggering, readings would be obtained essentially instantaneously.

Navigational system

The navigational system would keep track of the general location of the LRV during traverses. Stations located on Orbiter V photographs by inspection in the field, or by reference to television photographs at the Earth-based support facility, would augment the navigational systems data.

Sample-collecting equipment

Geologic tools would include a chisel-end bar for chipping and prying, hammer, trowel, drive tubes, prenumbered sample wraps and bags, and tongs that would permit sampling without dismounting from the LRV, and sampling without bending or kneeling while on foot traverses.

The hand tools would be affixed to an instrument carrier for foot traverses, and the carrier would be mounted on the LRV for use during the cross-country traverses.

Traverse examination and analysis equipment

Sample handling and analysis equipment to be used at the base station outside the ELM would include a work table, sample splitter, grinder, sample wrap and bags, two vacuum(?) return-sample containers, an X-ray diffractometer and $\alpha k \alpha$ spectrometer, a stand-mounted magnifying lens (with sunshade to prevent burning accidents), and containers for cores to be obtained from the Titan-mounted drill.

Equipment for examining samples inside the ELM would include a small polarizing binocular microscope for viewing rock surfaces and grains, a magnetized probing needle, mortar and pestle, glass slides and a few immersion oils, and sample vials, wrap, and bags.

Scientific advisory support group

A support group of geologists, who are assumed to have worked closely with the astronauts during mission-simulation exercises, would monitor the lunar field and landing-site operations. They would compile, evaluate, and synthesize data in support of the conduct of the mission, and for near-real-time mission planning.

Exploration Operations Framework

Scientific operations fall into four categories or groupings: 1) operations that are conducted near the ELM shortly after landing, 2) an ordered series of LRV traverses and LFU excursions, 3) scientific investigations that are conducted in the vicinity of the ELM during the course of the mission, and 4) investigations that are conducted in a shirt-sleeve environment in the ELM.

Operations conducted during the first "day" would include: sampling in the vicinity of the ELM for contingency purposes; checkout of field exploration systems; activation of "near-ELM" geophysical, analytical, and drilling equipment; and an LRV shakedown traverse to unload the ALSEP and to investigate nearby high-priority objectives.

The second phase of the exploration would involve a series of traverses and excursions to meet the general field exploration objectives. Stations would be described, photographed, and sampled; magnetics data obtained; and gravity, seismic, and heat-flow nets established.

Samples brought to the ELM would be selected for mineralogical and compositional analysis by the X-ray diffractometer and the $\alpha k \alpha$ spectrometer, and the data would be telemetered to Earth. Small chip samples representing each station visited would be set aside for return to Earth under non-vacuum conditions; these samples would provide a reference suite for post-mission analysis of the exploration traverses. Selected specimens would be described and identified in the ELM under shirt-sleeve conditions. On the basis of the compositional analyses, and the examinations in the ELM, specimens deemed to be from critical and important sample stations would be selected for return to Earth, possibly in vacuum containers if such a requirement still exists at this stage of lunar exploration.

Scientific operations in the ELM presumably would include microscopic examination and classification of the rocks with respect to conventions used for terrestrial rocks and meteorites. Common rock-forming minerals, and diverse materials of lunar and extra-lunar origin, might be provisionally identified under the microscope, with the aid of the scientific advisory support group on Earth. Microscopic and anlytical information on materials collected during the course of the mission would be important for near-real-time mission evaluation and planning by scientists and engineers on Earth.

Traverse Operations

Traverse operations, for convenience, are subdivided into operations that provide three levels or categories of data collection. They are: 1) visual and instrumental information gathered during the course of a traverse (vehicle or foot); 2) visual, instrumental, and sample information gathered at brief stops along a traverse (grab-sample stations); and 3) visual, instrumental, and sample information gathered during longer stops at features considered to be significant (prime sample stations). At grab-sample stations the geologic setting would be briefly described and readily obtainable materials related to the geologic setting would be collected. At prime sample stations field geologic relations would be described in moderate detail and samples that could be related in some detail to the stratigraphic and structural setting would be collected. Information to be gathered and instruments to be deployed or used in each of the three categories, are summarized in the Appendix.

Television and concurrently operating facsimile cameras are assumed to be functioning continuously during the LRV traverses. The LSS television camera would be aimed at features being described by the astronaut, both as he travels and at stations. The astronaut also would use the stereometric film camera on the LSS while delivering running commentaries and descriptions.

EXPLORATION PLAN

Summary

The exploration plan is summarized in table 4. The routes of the planned traverses, and anticipated station locations, are shown on plate 2. Traverse objectives, details of the individual LRV traverses and LFU excursions, and near-ELM activities, are listed in outline form in pages that follow.

Optimum and Nominal Traverses

Because there are a large number of variables, no single exploration traverse, or group of traverses, can unequivocally be

Table 4.--Summary of surface exploration plan

		Day 1	Day 2	Day 3	Day 4	Day 5
Morning EVA	Astronaut 1	LANDING	LRV Traverse II	LRV Traverse IV	LRV Traverse VI	LRV Traverse VIII
	Astronaut 2	Engineering system check-out Obtain contingency samples	LFU Excursion I and near-ELM activities	LFU Excursion II and near-ELM activities	Near-ELM activities: Attend drill, spectrometer; diffractometer; sort and analyze samples collected on previous traverses. Back-up LFU excursion	Near-ELM activities: Pack samples and cores for return flight; load samples in ELM; make final spectrometer and diffractometer analyses
Afternoon EVA	Astronaut 1	LRV Traverse I	LRV Traverse III	LRV Traverse V	LRV Traverse VII	Select LRV-VIII samples for return flight
	Astronaut 2	Near-ELM activities: Deploy and check out drill, spectrometer, diffractometer; deploy base gravimeter; analyze samples collected near ELM	Near-ELM actvities: Attend drill, spectrometer and diffractometer; sort and analyze samples collected on previous traverses; sample ALSEP site; complete deployment and checkout of ALSEP	LFU Traverse III	Near-ELM actitivies:	PREPARE FOR DEPARTURE
Scientific activities in ELM		Debriefing; examine selected samples collected on traverses; plan and prepare for traverses			Plan and prepare for departure	DEPARTURE

considered to be either optimum or nominal. A small change in one engineering parameter--for example, average traverse speed--can have far-reaching effects on the traverses and the time available for field examination and sampling at stations.

The individual traverses were developed by first identifying diverse features of potential interest, and then by connecting the potential stations by routes that would provide as large a variety of data as possible for a given stage of exploration. Most of the different types of features that have been recognized from Orbiter photographs are scheduled for examination and sampling within the first 3 days of exploration; work during the 4th and 5th days results principally in the completion of the field geophysical net, and in obtaining field observations and samples to assure that representative features and materials have been investigated.

The LRV traverses shown on plate 2 are considered optimum in light of assumed mission constraints. The station density and distribution are attainable if all the proposed field operations proceed without operational difficulties, and if the average speed of the LRV is 7 km/hr. The scheduled LRV traverses are maximum traverses, each of which lasts 3 hours. Although a fairly large number of grab-sample stations appear to be distributed along the individual LRV traverses, the sample station density is only about one station per kilometer of traverse, which is not dense sampling by Earth-based standards. It is conceivable that the LRV astronaut might normally stop his vehicle every kilometer or so for a variety of operational reasons, as well as for scientific reasons. Operational stops could become grab-sample stations, particularly if they are made at or near sites previously determined to be of interest.

The "optimum" traverses are presented here to show the kind of sampling that should provide near-representative field information and samples for this area of the Moon. To provide some reserve time, and thus to arrive at "nominal" traverses, a number of stations would need to be deleted and some traverses shortened.

Total travel and station time might be reduced by about one-quarter to one-third to arrive at a "nominal" level of effort. Deletions and reductions could be done in various ways, and at different places along the traverses. The final decisions as to which stations are to be bypassed and which parts of individual traverses are to be eliminated might best be made during the mission, and in light of data from preceding parts of the mission. The greatest flexibility in exploration might be obtained by near-real-time modifications of "optimum" traverses. The "optimum" traverses, moreover, could serve as references for adjustment that would result from changes in the operating parameters. For example, an increase in the average speed of the LRV would move the present "optimum" classification toward a "nominal" category.

Scientific Objectives and Tasks For the Individual Traverses

Scientific objectives and tasks for the individual LRV traverses and LFU excursions are summarized below.

LRV Traverse I:

Sample: materials of plateau-plain, crater at head of rille, rilles, fissure (punctured) cone, satellitic craters (exotic and local materials), dark-halo crater (exotic and local materials), and bright-halo craters (exotic and local materials).

Describe field relations with respect to: plateau-plain, fissure cones, narrow and broad rilles, dark- and bright-halo craters, satellitic craters, and small crisp-rim craters.

Investigate possible deposits of volatiles in dark-rimmed craters.

Look for signs of alteration near fissure cone and craters associated with rilles.

Obtain supporting LSS and magnetics staff data.

Begin development of gravity and seismic nets.

LRV Traverse II:

Sample: plateau-plain(?) material in rim of crater of uncertain origin; rim material enclosing large (1 km) subdued maar(?) crater north of landing site; satellitic crater materials (exotic and local materials, possibly in different swarms); wall and floor materials of small maar-like (crater mound) crater; dome materials; fissure cone materials; dark-halo crater materials; and rille material.

Describe field relations, as in LRV-I, plus relations in dome materials.

Investigate possible deposits of volatiles in small and large maar(?) craters and in dark-halo craters.

Look for alteration near fissure cone, dome, and maar craters.

Obtain supporting LSS and magnetics staff data.

Continue development of gravity and seismic nets.

LRV Traverse III:

Sample: maar crater, plains, dark-halo crater, ridge, rille, cone-on-ridge at head of rille, fissure cone, dome, and bright-halo crater materials.

Describe field relations, as in LRV I and II, plus descriptions of ridge, and rille and ridge associations.

Investigate possible deposits of volatiles associated with maar and dark-halo craters.

Look for alteration near fissure cones, domes, and rilles.

Obtain supporting LSS and magnetic staff data.

Continue development of gravity and seismic nets.

Emplace heat-flow probes.

LRV Traverse IV:

Sample: small crisp-rim crater in plains, low-dome, sharp-sided dome, and bulbous-dome materials; low-rimmed crater of uncertain origin, dark-halo and bright-halo materials.

Describe field relations, as in LRV I-III.

Investigate possible deposits of volatiles associated with maar(?) and dark-halo craters.

Look for alteration in dome areas.

Obtain supporting LSS and magnetics staff data.

Continue development of gravity and seismic nets.

Emplace heat-flow probe.

LRV Traverse V:

Sample: materials of satellitic craters, crisp-rim craters, fissure cones, dark-halo craters, funnel crater and block field, crater mound, bulbous dome, and crater of uncertain origin.

Describe field relations as in previous traverses.

Investigate possible deposits of volatiles associated with maar(?) and dark-halo craters.

Look for alteration in dome and maar crater.

Obtain supporting LSS and magnetics staff data.

Continue development of gravity and seismic nets.

Emplace heat-flow probe.

LRV Traverse VI:

Sample: materials of plains, domes, rilles, fissure cones, scarp, bright-halo craters, and satellitic craters.

Describe field relations as in other traverses.

Look for alteration in dome and rille areas.

Obtain supporting LSS and magnetics staff data.

Continue developing gravity and seismic net.

LRV Traverse VII:

Sample: materials of dark-halo crater, subdued crater, fissure cone, crater mound, dome, and crisp-rim craters.

Describe field relations as in other traverses.

Investigate possible deposits of volatiles in dark-halo and possible maar craters.

Look for alteration in dome and fissure-cone materials.

Obtain supporting LSS and magnetics staff data.

Continue development of gravity net.

LRV Traverse VIII:

Sample: materials of crisp-rim craters, shallow elliptical crater (satellitic?), bright-halo crater, dark-halo craters, bulbous-dome and low-dome material, crater mound wall and floor material.

Describe field relations as in other traverses.

Investigate possible deposits of volatiles in dark-halo crater and crater mound materials.

Look for alteration in dome areas.

Obtain supporting LSS and magnetics staff data.

Complete development of gravity net.

LFU Excursion I:

Sample: materials of wall and floor of maar(?) crater, and crater rim (impact) materials in dome field.

Describe field relations.

Obtain supporting LSS and magnetics staff data.

Continue development of gravity net.

LFU Excursion II:

Sample: materials of dome, plains(?), and dark-halo(?) craters.

Describe field relations.

Obtain supporting LSS and magnetics staff data.

Check for water-bearing materials.

Continue development of gravity net.

LFU Excursion III:

Sample: materials of fissure cones and impact(?) crater.

Describe field relations.

Obtain supporting LSS and magnetics staff data.

Continue development of gravity net.

Emplace heat-flow probes.

Outline of Exploration Traverses And Near-ELM EVA

LRV traverses, LFU excursions, and near-ELM EVA operations that would appear to meet general exploration objectives are outlined in the following pages. All exploration traverses are 3 hours long. Stations along the traverses are at places that appear to be favorable for rapid sampling of outcrops or of relatively fresh deposits of material.

LRV TRAVERSE I

Operation Objectives: Deploy: ALSEP, 4 explosive charges, and 8-geophone seismic array

Obtain: 2 gravity readings, 4 prime samples, and 5 grab samples (grab sample includes a magnetics staff reading and photography)

Travel Parameters: Traverse length: 4.7 km

Travel time: 45 min.

Station	Operations	Time at station (min.)	Cumulative station time (min.)
1	Deploy ALSEP	20	20
2	Prime sample, crisp-rim crater with blocks in bottom	10	30
3	Grab sample, small crater at head of narrow rille (linear trough)	4	34
4	Prime sample, craters excavating broad rille	10	44
5	Prime sample, satellitic crater cluster	10	54
6	Prime sample and gravity station, fissure cone	15	69
7	Grab sample, dark-halo crater	2	71
8	Grab sample, bright-halo crater penetrating rim of older crater	2	73
9	Gravity station; emplace 3 explosive charges	20	93

LRV TRAVERSE I--Continued

Station	Operations	Time at station (min.)	Cumulative station time (min.)
9-10	Deploy 8-geophone seismic array	30	123
	Grab sample along array (2)	4	127
10	Emplace explosive charge	5	132
11	Grab sample, bright-halo crater	2	134
Unassigned		1	

LRV TRAVERSE II

Operation Objectives: Deploy: 3 explosive charges

Obtain: 2 gravity readings, 4 prime samples, and 12 grab samples

Travel Parameters: Traverse length: 10.2 km

Travel time: 87 min.

Station	Operations	Time at station (min.)	Cumulative station time (min.)
1	Grab sample, rim material of subdued crater	2	2
2	Prime sample and emplace explosive charge in rubbly outcrop of large low-rimmed crater	15	17
3	Grab sample, rim material of large crater excavated by small craters	2	19

LRV TRAVERSE II--Continued

Station	Operations	Time at station (min.)	Cumulative station time (min.)
4	Emplace explosive charge (arrives at station 4, 45 min. after departure from ELM)	5	24
5	Grab sample, small satellitic crater	2	26
6	Grab sample, wall of larger satellitic crater	2	28
7	Prime sample, bottom of satellitic crater and emplace explosive charge	15	43
8	Grab sample, of crc, bh, and bc rim materials (3 samples)	6	49
9	Gravity station and prime sample, crater mound and smooth floor material	15	64
10	Grab sample, crisp-rim crater at base of small dome (2 samples)	4	68
11	Grab sample, dark-halo(?) crater	2	70
12	Grab sample, fissure-cone material exposed in small crater	2	72
13	Gravity station and prime sample, fissure-cone and low-dome material	15	87

LRV TRAVERSE II--Continued

Station	Operations	Time at station (min.)	Cumulative station time (min.)
14	Grab sample, sinuous rille material excavated by crater	2	89
Unassigned		4	

LRV TRAVERSE III

Operation Objectives: Deploy: 1 three-geophone seismic array, 2 explosive charges, and 2 heat-flow probes

Obtain: 2 gravity readings, 1 prime sample, and 14 grab samples

Travel Parameters: Traverse length: 11.1 km

Travel time: 99 min.

Station	Operations	Time at station (min.)	Cumulative station time (min.)
1	Emplace explosive charge	5	5
2	Grab sample, crater mound and floor materials (2 samples)	4	9
3	Grab sample, plains material in bright-halo ejecta	2	11
4	Grab sample, dark-halo(?) material	2	13
5	Grab sample, dark-halo crater	2	15
6	Grab sample, plains material in bright-halo crater ejecta	2	17

LRV TRAVERSE III--Continued

Station	Operations	Time at station (min.)	Cumulative station time (min.)
7	Deploy 3-geophone seismic array, emplace explosive charge, and grab sample	20	37
8	Grab sample, ridge material(?) in ejecta	2	39
9	Grab sample, ridge material in very narrow sinuous rille	2	41
10	Gravity station and prime sample, crater at head of sinuous rille; emplace heat-flow probe	20	61
11	Grab sample, small crater on edge of shallow-floored crater; gravity station	7	68
12	Grab sample, steep-sided-dome material at edge fissure cone(?)	2	70
13	Grab sample, edge of bulbous dome, emplace heat-flow probe	7	77
14	Grab sample, dark-halo(?) crater	2	79
15	Smooth low-rimmed crater, describe in passing	-	
16	Grab sample, crisp-rim crater	2	81
Unassigned		0	

LRV TRAVERSE IV

Operation Objectives: Deploy: 3 explosive charges, and 2 heat-flow probes

Obtain: 2 gravity readings, 5 prime samples, and 5 grab samples

Travel Parameters: Traverse length: 9.2 km

Travel time: 78 min.

Station	Operations	Time at station (min.)	Cumulative station time (min.)
1	Grab sample, crisp-rim crater in young crater rim material, bright-halo crater in plateau plains	2	2
2	Prime sample, crater-rim material in low-dome field; emplace heat-flow probe	15	17
3	Prime sample, steep-sided dome material	10	27
4	Prime sample, bulbous dome material; emplace heat-flow probe	15	42
5	Grab sample, crisp-rim crater in low-rimmed crater	2	44
6	Grab sample, wall of low-rimmed crater on northwest-trending lineament	2	46
7	Gravity station, grab sample, and emplace explosive charge, material of steep-dome field	12	58

LRV TRAVERSE IV--Continued

Station	Operations	Time at station (min.)	Cumulative station time (min.)
8	Grab sample, dark-halo(?) crater material on edge of steep-dome field and adjacent to north-trending lineament	2	60
9	Gravity station, emplace explosive charge, and prime sample, possible secondary crater	20	80
10	Emplace explosive charge and prime sample, rim of deep-floored low-rimmed crater	15	95
11	Emplace explosive charge	5	100
Unassigned		2	

LRV TRAVERSE V

Operation Objectives: Deploy: 1 heat-flow probe, and 1 explosive charge

Obtain: 2 gravity readings, 7 prime samples, and 7 grab samples

Travel Parameters: Traverse length: 8.6 km

Travel time: 74 min.

Station	Operations	Time at station (min.)	Cumulative station time (min.)
1	Grab sample, small crater cluster on fresh crater	2	2

LRV TRAVERSE V--Continued

Station	Operations	Time at station (min.)	Cumulative station time (min.)
2	Grab sample, crisp-rim crater in plains	2	4
3	Prime sample and emplace heat-flow probe, fissure(?) cone	15	19
4	Grab sample, rim material of dark-halo(?) crater	2	21
5	Prime sample, funnel crater and block field from adjacent crater	10	31
6	Prime sample, swarm of satellitic(?) craterlets	10	41
7	Gravity station and prime sample, dome materials in rim of crater	15	56
8	Prime sample, crater mound (?) and bulbous-dome material	10	66
9	Prime sample, rim material of subdued crater	10	76
10	Grab sample, rim material of subdued crater	2	78
11	Prime sample, fresh(?) bulbous-dome material	10	88
12	Gravity station, grab sample, and emplace explosive charge, rim material of old large satellitic crater cluster	12	100

LRV TRAVERSE V--Continued

Station	Operations	Time at station (min.)	Cumulative station time (min.)
13	Grab sample, freshly(?) slumped materials, possibly ejecta, in satellitic(?) crater	2	102
14	Grab sample, plains material in crisp-rim crater	2	104
Unassigned		2	

LRV TRAVERSE VI

Operations Objectives: Deploy: 2 explosive charges

Obtain: 3 gravity readings, 6 prime samples, and 8 grab samples

Travel Parameters: Traverse length: 8.3 km

Travel time: 72 min.

Station	Operations	Time at station (min.)	Cumulative station time (min.)
1	Grab sample, fresh crater rim material in plains material	2	2
2	Gravity station, prime sample, and emplace explosive charge, dome-plains contact	20	22
3	Grab sample, near end of small sharp rille	2	24
4	Grab sample, very narrow en echelon rilles in plain	2	26

LRV TRAVERSE VI--Continued

Station	Operations	Time at station (min.)	Cumulative station time (min.)
5	Prime sample, material near very narrow en echelon rilles in plains	10	36
6	Gravity station and grab sample, narrow rille (subdued trough)	7	43
7	Prime sample and emplace explosive charge, fissure-cone material	15	58
8	Grab sample, scarp in plains (2 samples)	4	62
9	Prime sample, crisp-rim crater material in low-dome terrain	10	72
10	Prime sample, craterlet chain on rim of subdued crater	10	82
11	Gravity station and prime sample, bright-halo material	15	97
12	Grab sample, satellitic craterlet cluster (2 samples)	4	101
13	Grab sample, rim material of subdued crater	2	103
Unassigned		5	

LRV TRAVERSE VII

Operations Objectives: Obtain: 3 gravity readings, 6 prime samples, and 2 grab samples

Travel Parameters: Traverse length: 8.0 km

Travel time: 69 min.

Station	Operations	Time at station (min.)	Cumulative station time (min.)
1	Grab sample, sharp dark-halo(?) crater	2	2
2	Prime sample, bright wall material of subdued crater	10	12
3	Prime sample, floor and wall(?) material of subdued fissure cone	15	27
4	Gravity station and prime sample, rim, wall, and floor material of crater mound	20	47
5	Prime sample, wall material of subdued fissure cone	10	57
6	Gravity station and prime sample, fresh(?) steep-sided dome material	15	72
7	Grab sample, material of crisp-rim crater in plains	2	74
8	Gravity station and prime sample, crisp-rim crater in plains	15	89
Unassigned		22	

LRV TRAVERSE VIII

Operations Objectives: Obtain: 3 gravity readings, 7 prime samples, and 7 grab samples

Travel Parameters: Traverse length: 8.6 km

Travel time: 76 min.

Station	Operations	Time at station (min.)	Cumulative station time (min.)
1	Gravity station and grab sample, crisp-rim crater in plains	7	7
2	Grab sample, crisp-rim crater in plains	2	9
3	Grab sample, shallow elliptical satellitic(?) crater	2	11
4	Gravity station and prime sample, bright-halo crater	15	26
5	Prime sample, crisp-rim crater in rim of dark-halo(?) crater	10	36
6	Prime sample, freshly(?) exposed outer wall of subdued crater	10	46
7	Prime sample, crisp-rim crater in smooth floor material of subdued crater	10	56
8	Grab sample, exposure in low-dome slope adjacent to subdued crater	2	58

LRV TRAVERSE VIII--Continued

Station	Operations	Time at station (min.)	Cumulative station time (min.)
9	Gravity station and prime sample, exposure in steep-dome material	15	73
10	Grab sample, bulbous-dome material	2	75
11	Prime sample, crater-mound and smooth floor materials	15	90
12	Prime sample, dark-halo crater	10	100
13	Grab sample, freshly(?) exposed material in mound	2	102
14	Grab sample, crisp-rim crater in low-dome material	2	104
Unassigned		0	

LFU EXCURSION I

(coordinated with LRV traverse II)

Operations Objectives: Deploy: communications repeater and 1 heat-flow probe

Obtain: 3 gravity readings, 2 prime samples, 2 grab samples, and magnetics staff readings

Travel Parameters: Traverse length: 9.4 km

Number of stops: 2

Distance between stations: 1.8 km, 3.2 km, and 4.4 km

LFU EXCURSION I--Continued

Station	Operations	Time at station (min.)	Cumulative station time (min.)
ELM	Check Titan drill	10	10
ELM	LFU preparation	30	40
ELM	Gravity station	5	45
1	LFU checkout and flight; land at plains-crater slope contact	5	50
1	Gravity station	5	55
1	Emplace heat-flow probe	5	60
1	Prime sample (3) and grab sample (3), crater floor, slope, and wall materials	45	105
2	LFU checkout and flight; land on rim crest of impact(?) crater	5	110
2	Deploy communications repeater	10	120
2	Gravity station	5	125
2	Prime sample and grab sample, crater rim materials	30	155
2	LFU checkout and flight; land at ELM	5	160
ELM	Debriefing; sample sorting; refuel LFU	20	180

LFU EXCURSION II

(coordinated with LRV traverse IV)

Operations Objectives: Deploy: 1 heat-flow probe, 1 explosive charge, and 3-geophone seismic array

Obtain: 2 gravity readings, 6 prime samples, 6 grab samples, and magnetics staff readings

LFU EXCURSION II--Continued

Travel Parameters: Traverse length: 10.8 km

Number of stops: 2

Distance between stations: 2.8 km, 3.2 km, and 4.8 km

Station	Operations	Time at station (min.)	Cumulative station time (min.)
ELM	LFU checkout and flight; land in dome area near smooth, dark-rimmed crater	10	10
1	Gravity station	5	15
1	Prime sample (3) and grab sample (3), bulbous-dome material, local plains in subdued dome, dark-halo(?) crater material	45	60
2	LFU checkout and flight; land in dome area near bright-halo crater	5	65
2	Gravity station	5	70
2	Emplace heat-flow probe	5	75
2	Deploy 3-geophone seismic array	15	90
2	Emplace explosive charge	5	95
2	Prime sample (3) and grab sample (3), low-dome and crater wall and rim materials	45	140
2	LFU checkout and flight; land at ELM	5	145
ELM	Debriefing, sample sorting and analysis; refuel LFU	35	180

LFU EXCURSION III

(coordinated with LRV traverse V)

Operations Objectives: Deploy: communications repeater, 2 heat-flow probes, and 1 explosive charge

Obtain: 2 gravity readings, 3 prime samples, 3 grab samples, and magnetics staff readings

Travel Parameters: Traverse length: 10.0 km

Number of stops: 2

Distance between landings: 3.3 km, 1.8 km, and 4.9 km

Station	Operations	Time at station (min.)	Cumulative station time (min.)
ELM	LFU checkout and flight; land on rim of fissure cone	10	10
1	Gravity station	5	15
1	Deploy communication repeater	10	25
1	Emplace heat-flow probe	5	30
1	Prime sample (1) and grab sample (1), fissure-cone material; panoramic description	30	60
2	LFU checkout and flight; land on fissure-cone material near impact(?) crater	5	65
2	Emplace explosive charge	5	70
2	Gravity station	5	75
2	Emplace heat-flow probe	5	80
2	Prime sample (2) and grab sample (2), fissure-cone and impact crater materials	45	125

LFU EXCURSION III--Continued

Station	Operations	Time at station (min.)	Cumulative station time (min.)
ELM	LFU checkout and flight; land at ELM	5	130
ELM	Debriefing, sample sorting, sample analysis, drill monitoring	50	180

NEAR-ELM EVA

Specific Objectives: Equipment: Service Titan-mounted drill; supply diffractometer and spectrometer with samples

Samples: Select and sort samples for analysis in spectrometer, diffractometer, and ELM; select and pack samples for return to Earth

Fieldwork: Investigate dark-halo crater a short distance south of ELM; obtain local geophysical measurements

Operations (sequenced to obtain optimum efficiency)	Estimated time	Total time (min.)
Maintain drill, remove cores and pack cores	10 min/hr	30
Supply spectrometer and diffractometer with prepared materials	15 min/hr	45
Confer with Scientific Support Group with respect to sorting, selection, and analysis of samples collected on LRV and LFU traverses	As needed	105
Investigate local geology; collect and analyze local samples	As needed	

NEAR-ELM EVA--Continued

Operations (sequenced to obtain optimum efficiency)	Estimated time	Total time (min.)
On 4th day, 2 LFU excursions, each nominally 90 min. long, would be available for detailed examination and sampling of 4 prime sample stations. The 4 may be stations that could not be reached by the LRV, or LRV stations that need to be revisited	--	--

RESULTS OF EXPLORATION

If man on the lunar surface is provided with some reasonable traverse capability, adequate Extra-Vehicular Activity (EVA) time, and a scientific support system that minimizes routine and mechanical field operations, then detailed reconnaissance geological and geophysical field investigations can be conducted in a geologically complex area such as the Marius Hills. This study suggests that an area within a 5-km radius of the ELM could be reasonably well explored during a 5-day mission using operational and mobility constraints currently under consideration by NASA.

The roving vehicle traverses would enable examination and sampling of a fairly large number of diverse features and types of material (table 5), and geologic continuity would be maintained along the lines of traverse. A smaller variety of materials would be sampled during the LFU excursions (table 5). Because the astronaut's surface mobility will probably be limited, LFU excursion time has been allocated for collection of prime samples, and the weight of samples that might be transported to the ELM by the LFU is fairly high with respect to the number of stations occupied (table 6). The potential scientific value of a given sample, however, is not necessarily a function of its size or weight. Additionally, in the interest of returning a scientifically useful, representative

Table 5.--Number of samples obtained from inferred volcanic and crater units during an optimum mission

LRV TRAVERSES (8)

	sr, lt	nr	cf	cm	fc	sd	bd	ld	pp
Volcanic materials probably not modified by impact (see pl. 3)	4, 3*	1	1	2, 3	6	2, 4	2, 1	1	4
bh									5, 2
crc							2	2, 1	7, 1
dh						2		2, 1	4, 1
cc, (lunar and extra-lunar)						1		1	5, 2
c	1	1			1	2, 3	1	3, 2	5, 2
bc									4, 1
bcs									
Subtotals - - - - - -	5, 3 / 8	2 / 2	1 / 1	2, 3 / 5	1, 6 / 7	6, 8 / 14	4, 2 / 6	8, 5 / 13	34, 9 / 43

Grand total - - - - - - - - - - - - - 99 (62 grab samples; 37 prime samples)

LFU EXCURSIONS (3)

	sr, lt	nr	cf	cm	fc	sd	bd	ld	pp
Volcanic materials probably not modified by impact (see pl. 3)					2, 2	1, 1	1, 1	1, 1	1, 1
bh								2, 2	
crc						1, 1			
dh									
cc, (lunar and extra-lunar)									
c					1, 1			1, 1	
bc								1, 1	
bcs								1, 1	
Subtotals - - - - - -					3, 3 / 6	2, 2 / 4	1, 1 / 2	6, 6 / 12	1, 1 / 2

Grand total - - - - - - - - - - - - - 26 (13 grab samples; 13 prime samples)

* First number listed in box refers to grab samples; second number refers to prime samples. Where only one number appears, if on left side it refers to grab samples, if on right side--to prime samples.

Table 6.--Estimated weight (lb) of samples transported to ELM from an optimum mission, and returned to Earth

Weight (lb) of samples transported to ELM

	Grab samples (3/4 lb each)	Prime samples (4 lb each)
LFU (3 excursions)	10	52
LRV (8 traverses)	48	160
Subtotals	58	212
Total	270	

Weight (lb) of samples to be returned to Earth

Samples packed in 2 containers outside the ELM	Bagged samples	
	Reference suite of chip samples; bagged outside ELM	Samples examined and bagged in ELM
80	20	20
Total	120	

suite of samples, the sizes of individual prime samples would probably have to be selectively reduced before the return flight to Earth.

As shown in table 6, an estimated 270 lb of samples could be obtained during the optimum traverse operations, about half of which would be selected for transport to Earth. In any extended lunar surface mission where the return-flight payload is seriously restricted, return-sample selection will be of great scientific importance and operationally time-consuming. A four- or five-to-one ratio between samples collected and samples transported to Earth would probable be wasteful because of nonproductive time involved in sample collection, and in later handling, selection, and trimming. A ratio of about two- to three-to-one, however, would allow the traverse astronaut some latitude in the initial selection of both diverse and representative materials at individual stations, yet would probably keep the size and number of samples handled and examined at the ELM within the capabilities of the ELM-based astronaut. To minimize later handling, selection, trimming, and packing, grab samples should each weigh 1/2-3/4 lb, and prime samples 3-4 lb.

A successful mission will, it is believed, in no small part rely on the examination and sampling of a variety of different materials at a variety of locations--a procedure that will increase the chances of obtaining representative information for the inferred volcanic and impact crater units, and that will also increase the chances of observing field relations critical to an understanding of the stratigraphy, structure, and history of the lunar materials. Success will depend on the complimentary scheduling of LRV traverses and LFU excursions for the conduct of geologic investigations, and for the establishment of gravity, seismic, and heat-flow nets across the area.

A 5-day mission will produce at least twice as many samples as a 3-day mission (table 7), in addition to providing for a more comprehensive geological and geophysical survey. The increased returns are partly brought about because the 2 additional days of

Table 7.--Comparison of sample collections of the 3- and 5-day missions

	Geologic units									
3-day mission:[1]	sr, lt	nr	cf	cm	fc	sd	bd	ld	pp	Total
LRV (4 traverses)					4	6	3	8	11	32
LFU (2 excursions)		1			3				1	5
								Total		37
5-day mission:										
LRV (8 traverses)										
Optimal	8	2	1	5	7	14	6	13	43	99
Nominal[2]	6	1	1	3	5	9	4	9	30	68
LFU (3 excursions)										
Optimal					6	4	2	12	2	26
Nominal[2]					5	3	2	10	2	22
						Total optimal				125
						Total nominal				90

[1] From Karlstrom and others (1968, table 2).
[2] Nominal operations are assumed to be about 1/4-1/3 less efficient than optimal operations for LRV traverses, and about 1/10-1/5 less efficient for LFU excursions.

stay-time are available solely for exploration, unimpeded by base station systems checkouts that are a part of the first and last days' operations. However, 5 days may approach the useful human surface stay-time for a mission using the ELM, because rest and sleep facilities as presently planned in the ELM are minimal.

In summary, the Marius Hills contain diverse features that are small enough (and close enough to each other) to be traversed and sampled during several 3-hour LRV exploration traverses. Assuming an average traverse speed of 7 km/hr for the roving vehicle, a 5-km radius of surface operations approaches the upper limit of efficient surface traverses. Unless either traverse speeds or EVA times are increased, a marked increase in the radius of operations--for example, to 10 km--would reduce to nearly the vanishing point the number of stations that could be occupied and the time available for field geological and geophysical investigations.

The exploration matrix summarizes a mission plan that is designed to investigate a complex field problem through the investigation and sampling of a fairly large number of fairly small features, all of which occur in a fairly small area. If parts of one or two comparatively large features were to be explored, and if only a few stations had to be occupied, the nominal radius of LRV traverses could lie between 5 and 10 km with EVA time and average traverse speeds unchanged. Point localities at relatively great distances from the ELM would of course be most efficiently explored by LFU excursions. Efficient use of a surface exploration system characterized by limited-range roving and flying vehicles necessitates choosing scientific sites that exhibit diverse features, or parts or intersections of features, small enough for critical problems to be investigated.

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APPENDIX

Geologic and geophysical operations conducted during the course of foot and vehicle traverse

Procedures

A. Descriptions and commentaries on:
   1. Land-form characteristics
      a. Physiography and topography
      b. Texture and structure of surface materials (patterned ground; rubble fields; outcrop; regolith; flow fronts)
      c. Reflectance and color
   2. Compositional characteristics
      a. Rock description and classification
   3. Structure and stratigraphy
      a. Character of small-scale cratering (morphology; symmetry; distribution; trends)
      b. Large- and small-scale stratigraphy (includes soil horizons and fossil soil horizons in crater rim deposits)
      c. Large- and small-scale bedrock structure
   4. Interpretation
      a. Local and areal stratigraphic relations
      b. Origin and relative age of features and materials

B. Sampling (prime, and grab or chip)
   1. Representative material
   2. Special interest material

C. Instruments and instrumentation
   1. Geologic tools
      a. Tongs; hammer and trowel-scoop, with extension handle; drive-tubes; prenumbered sample-wrap and sample bags; sample box; instrument carrier
   2. Geologic support instruments
      a. Lunar Surveying System (LSS)
      b. Magnetics Staff

Procedures--Continued

C. Instruments and instrumentation--Continued

3. Field geophysical instrumentation

a. 3-geophone seismic array, and explosive charges

b. 8-geophone seismic array, and explosive charges

c. Gravimeter (mechanical deployment from LRV; automatic readout)

d. Heat-flow probes (deployed from LRV)

e. Magnetometer (continuous recording; boom-mounted on LRV)

Use of Procedures

In transit

A. 1, 3, 4

B. --

C. 2a, 3e

Grab-sample locality

A. 2, 3, 4

B. 1, 2

C. 1, 2, 3 (as designated in traverse plan)

Prime-sample locality

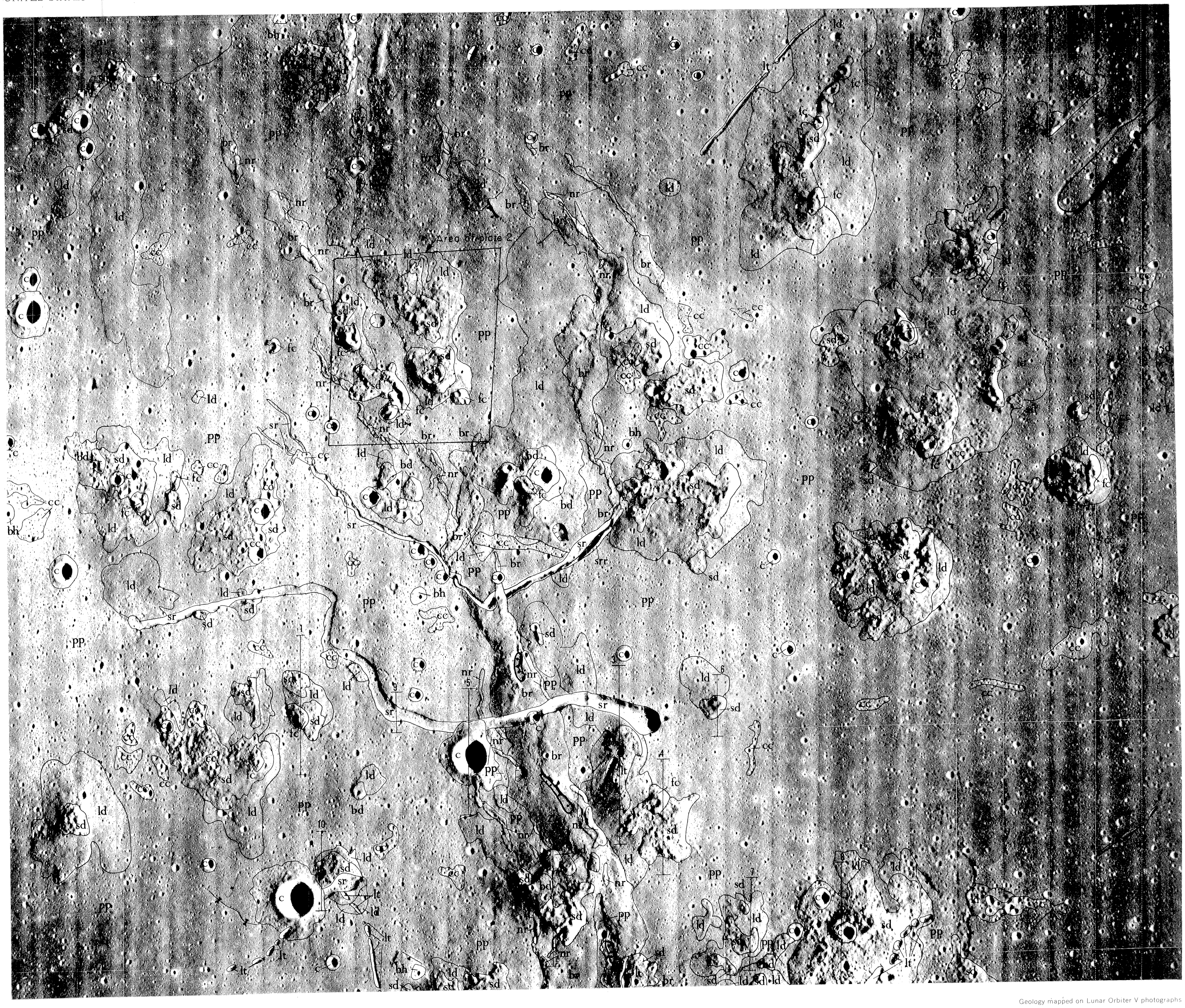
A. 2, 3, 4

B. 1, 2

C. 1, 2, 3 (as designated in traverse plan)

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

INTERAGENCY REPORT: ASTROGEOLOGY 14
PLATE 1



Geology mapped on Lunar Orbiter V photographs

Photobase from Langley Research Center
uncontrolled photomosaic

PRELIMINARY SMALL-SCALE GEOLOGIC MAP OF THE MARIUS HILLS REGION

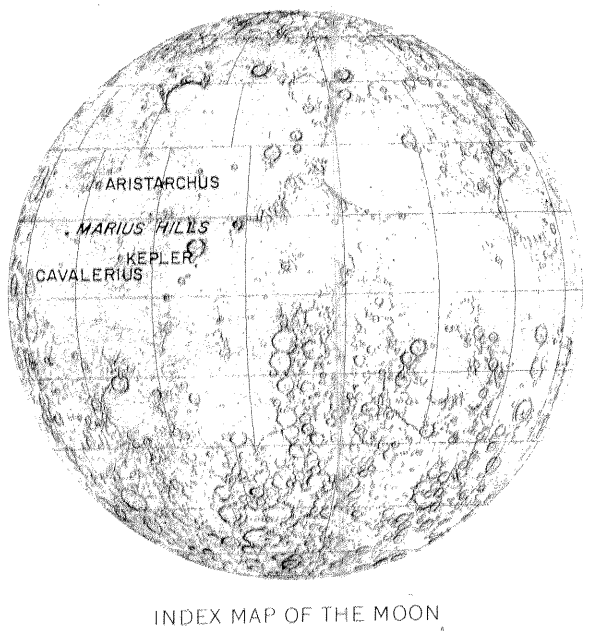
By
John F. McCauley

1968

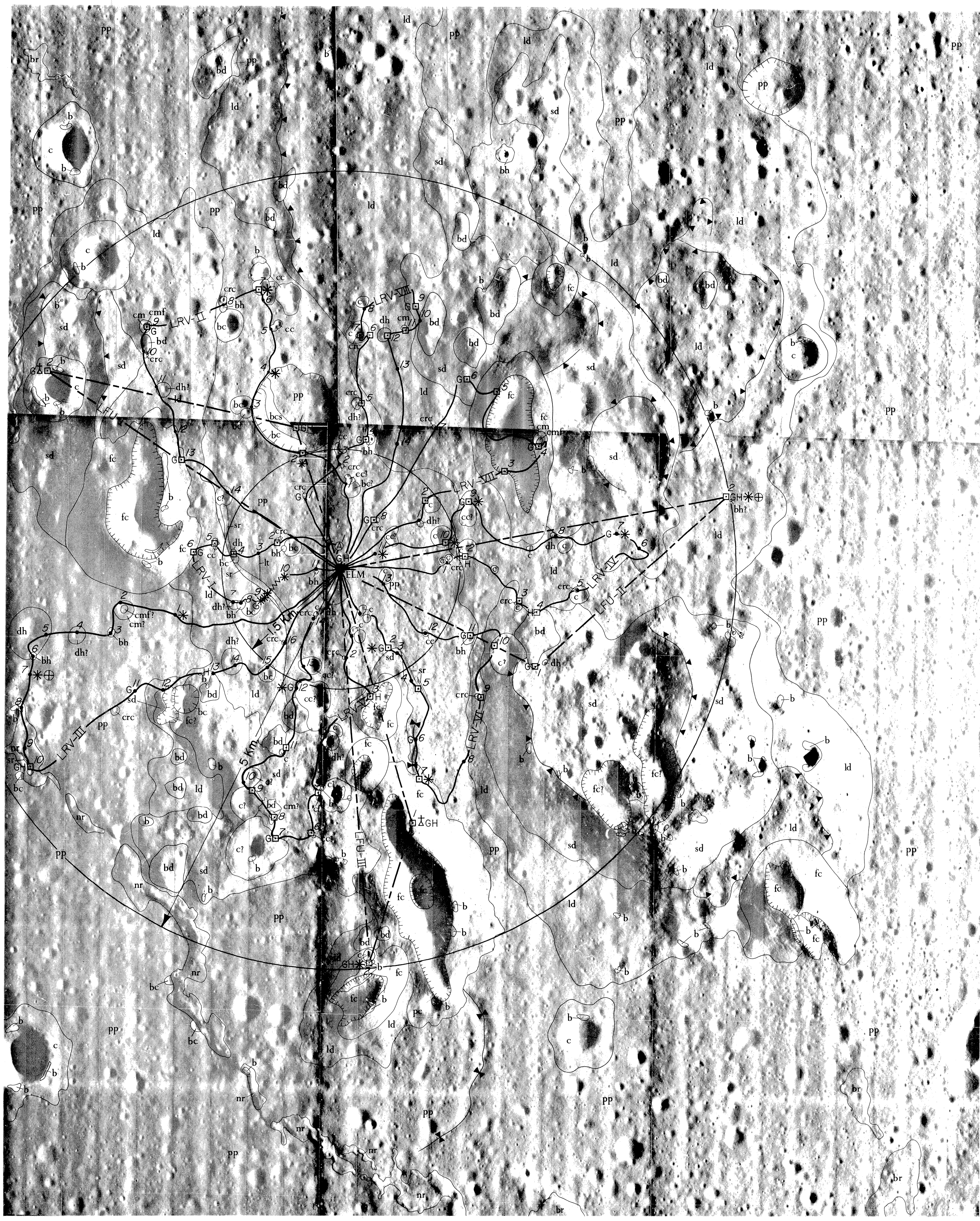
N

APPROXIMATE SCALE 1:200,000

5 0 5 10 15 20 25 KILOMETERS



INDEX MAP OF THE MOON



Photobase from Langley Research Center
uncontrolled photomosaic

Geology mapped on Lunar Orbiter V photographs, H-216, 217.

PRELIMINARY LARGE-SCALE GEOLOGIC MAP OF PART OF THE MARIUS HILLS REGION

By
John F. McCauley
1968

GEOLOGIC DETAIL ADDED ALONG TRAVERSE LINES

By
Donald P. Elston
1968

N

APPROXIMATE SCALE 1:25,000

1 ½ 0 1 2 3 4 5 KILOMETERS

STRATIGRAPHIC UNITS

Marius Group
(Inferred endogenetic materials)

fc

Fissure or punctured cone material

Material of steep-flanked relatively smooth, conical structures having single to multiple linear depressions with intervening septa at or near the summits. Most cones and summit depressions are elongate in plan and oriented parallel to regional structure. Heights up to 300 meters above surrounding plains. Generally superposed on steep-sided domes (sd). Pyroclastic deposits surrounding structurally controlled vents. If features are analogs of similar appearing cones in Hawaii and other differentiated terrestrial volcanic provinces, the composition may be trachytic.

cm | cmf

Crater mound materials

cm, material of small, shallow, low-rimmed craters that occur on the summits of broader topographic swells.
cmf, smooth filling material that occupies floors of crater mounds.

cf

Funnel crater material

Material of small, cone-shaped depression enclosed by darkish halo; elevated rim is not apparent.

nr

Narrow-ridge material

Material of steep-sided relatively small, narrow ridges; contacts mostly marked by scarps. Often superposed on broad ridge (br). Internal structure braided to en echelon in pattern. Locally appears to partly bury craters on the plateau plains (pp). Mostly viscous fissure flows; locally may be intrusive beneath impact regolith.

br

Broad-ridge material

Material of smooth textured linear ridge of complex topographic form. Contact with adjacent plains marked either by gentle break in slope or by low scarp. Numerous smaller gentle scarps often occur within larger ridge. In southern and central part of map, trend is north-south; in north trend is north-northwest. Intrusive features which may, however, be locally extrusive. Probable surface expression of major deep seated north-south trending structures that interconnect the Marius Hills, Aristarchus Plateau and Rümker Hills.

sd

Steep-sided-dome material

Material of steep sided rough textured domes generally perched upon low domes (ld). Contact marked by gentle to steep scarp; more rectilinear in plan than low domes. Heights generally from 200-300 meters above surrounding plains. Composed of numerous small ribs and spurs that are oriented north-northeast or north-northwest along the prevailing local structural trends. May be extrusive structures resulting from differentiation of the more primitive viscous magmas that produced the mare material (m) and the low domes (ld).

bd

Bulbous-dome material

Material of smooth-textured domes; steeply convex upward in form. Smaller domes tend to be equidimensional; larger are more irregular and show influence of structural control. Intrusive or more probably extrusive structures formed from very viscous lavas of intermediate composition.

ld

Low-dome material

Material of smooth-textured gently tumescent structures as much as 100 meters higher than surrounding plains. Contact located at gentle break in slope. Convex upward in profile. Some roughly circular in plan. Most, however, are elongated in north-south direction. Lack of flow front morphology suggests a laccolithic origin.

pp

Plateau-plain material

Material of smooth to gently undulating cratered plains lying between domes and cones of Marius Plateau. Average elevation on the order of several hundred meters above the adjacent maria. Probably consists of volcanic flows, interbedded pyroclastic deposits and a moderately thick impact regolith.

Dark mare plains material
(Procellarum Group)

m

Mare material

Dark cratered plains material typical of the central regions of Oceanus Procellarum. Detailed descriptions given by McCauley (1967b).

Crater units
(Inferred exogenetically modified materials)

bh

Bright halo crater material

Bright rim, interior slope, and floor materials of small widely separated craters. Material of relatively recent impact craters surrounded by bright blankets of pulverized bedrock and shock lithified regolith.

cc

Crater-cluster material

Material in and around clusters of closely spaced to overlapping small to medium-sized craters, generally with subdued rims. Mostly material of secondary craters from Kepler, Aristarchus, and Cavalerius.

crc

Crisp-rim crater material

Material of small to very small craters that exhibit sharp elevated rims and narrow rim materials; floors appear hemispherical, and some contain bulbous clots; a few craters are partly enclosed by bright-halo material.

dh

Dark-halo crater material

Material of small craters that exhibit low to moderately elevated, rounded rims which are enclosed by apparently smooth, darkish-halo rim material.

c

Crater material

Exterior rim deposits, interior slope, and floor materials of moderately subdued widely scattered craters. From crater lip to limit of rim deposit profile is concave upward. Mostly material of impact craters modified by later seismic and impact events.

bc | bcs

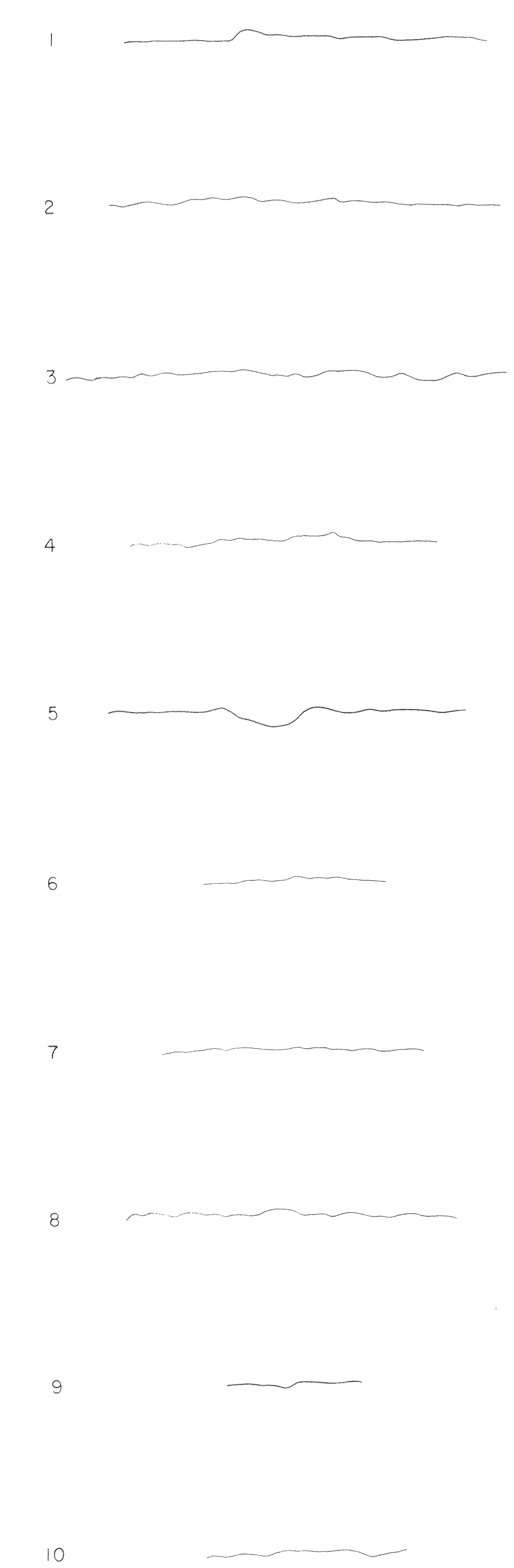
Partly buried crater materials

bc, subdued-rimmed crater material. Partly buried or overridden by narrow ridge material (nr). Numerous craters of similar form are present on all units but are not mapped unless partly buried. Probably mainly material of older impact craters degraded by micrometeorite bombardment and mass wasting.
bcs, ridged slump(?) material. Possibly derived from adjacent crater wall in a large (1 km) subdued maar(?) crater north of landing site (LRV traverse II).

TOPOGRAPHIC PROFILE

Vertical and Horizontal Scale

1:160,000



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sr, srr — Sinuous rille

Contact marks edge of sinuous depression with smooth interior slopes and either a "V" shaped profile or, in the case of the largest sinuous rille, a broad rather flat floor. Estimated gradient from high end about 0.2 meters per kilometer. Unit srr marks elevated rim that flanks part of the northernmost example on plate 1. Includes narrow straight-walled rilles and subdued trough-like depressions in area of traverse exploration.

lt — Linear trough

Steep-sided linear depression or closely spaced circular to elliptical depression.

b

Bedrock or block field

Exposures of bedrock on steeply sloping surfaces or block fields surrounding moderately fresh craters.

Contact
Dashed where indefinite

Buried contact

Inferred fault

Subdued trough or rille-like depression

Crest of scarp, barbs point downslope.

Rimless circular depression

Irregular summit depressions

5 — Topographic profile line

EXPLANATION FOR MISSION TRAVERSES SHOWN ON PLATE 2

● ELM

LRV-I — Lunar Roving Vehicle traverse

LFU-I — Lunar Flying Unit excursion

• Grab sample and(or) instrument reading

⊡ Prime sample

G Gravity station

H Heat-flow probe

✳ Explosive charge

Communication repeater

⊗ Three-geophone seismic array

Eight-geophone seismic array

Ⓐ ALSEP
(Apollo Lunar Surface Exploration Package)

EXPLANATION FOR GEOLOGIC MAPS OF THE MARIUS HILLS REGION