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# The Case for Planetary Sample Return Missions

## Origin and Evolution of the Moon and its Environment

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## Introduction

The Apollo missions established the Moon as a cornerstone in planetary science: insights gained from this coign of vantage have stimulated research and influenced ideas for the Earth and other planets subsequently investigated using spacecraft. The history of lunar studies emphatically demonstrates the enormous progress in knowledge and understanding—a giant leap—that is made when samples from another planet become available for study in sophisticated laboratories. A few pebbles kicked loose are enough to start an avalanche, and the lunar samples are used as test beds for hypotheses about planetary, and even solar, evolution. The Moon is more accessible than any other body in the Solar System and is a potential home for a permanently occupied base with multiple purposes; it remains an important target for future work in planetary science.

We advocate the collection of more samples from a variety of sites on the Moon. The collections could be undertaken solely as a scientific program to explore the Moon or could be part of a program leading to the establishment of a lunar base. Such an advocation has a firm scientific base, and there have been several proposals since Apollo for lunar sample-return missions [*LAPST*, 1985; *Wilhelms*, 1985; *NCOS*, 1986]. We already know much more about the Moon than we do about other planets, in particular, from studies of the Apollo and Luna sample collections. Although we may have samples from other planets, brought to us as meteorites, we cannot be sure where they came from or how one specimen relates to another. The lunar samples have field contexts that permit much greater confidence to be put in the inferences made from them; at a minimum the context is that they definitely come from the Moon. Therefore the reasons for collecting more samples from the Moon are quite different from those for collecting from other bodies that are so far unsampled by spacecraft, such as Mars or asteroids; it is not a first-cut, exploratory effort, but one intended to answer some of the many questions about the characteristics of the Moon, its evolution, and its environment. These answers will significantly advance our understanding of planetary bodies in general, including the Earth, as did the Apollo results.

The Apollo and Luna collections, important as they are, are from a small area of the Moon, essentially the central nearside, and from a limited set of terrain types; their collection was influenced by the exigencies of the moment. Geological studies show the diversity of lunar terrains and the great range of relative ages of the unsampled terrains; without samples from them, our knowledge of the Moon and its evolution will remain rudimentary. Terrestrial geosciences benefit from continual sample collection and analysis; by comparison, our study of the Moon has been minimal. Literati still learn from Shakespeare; planetologists continue to learn from the Moon.

## General Context of Sample Collection

A collection of samples from the Moon is useful from three independent points of view: that of pure science, that of the environment (past and present) of the Moon, and that of planning the logistics for a lunar base. For lunar science and the Moon's environment, the characterization of the materials that make up various geological units, determining their ages, and constraining the processes that made the rocks and the units are paramount. Moreover, the Moon is used as a touchstone for the interpretation of planetary geologic processes in general; the better we understand the evolution of this relatively simple object, the better we can interpret the histories of, and the processes operating on, other Solar System objects. For a lunar base, a characterization of the units, and in particular the regoliths formed on them, for habitation and resource potential is dominant. We can already select targets for sample return from existing data, but we assume that by the time sample return missions are ready, a lunar polar orbiter mission will have flown [e.g., *LGO Science Workshop*, 1986]. Such a mission will provide chemical, mineralogical, and petrological maps of the entire lunar surface and will advance our understanding of the Moon, provide a basis for selecting new target sites, and elicit new problems. These advances will actually make new sample returns even more desirable.

Previous papers in this series [*Drake et al.*, 1987; *Gooding et al.*, 1989] have listed the advantages that sample returns confer over in situ analyses. Most of these advantages apply to lunar samples, and indeed we still study lunar samples collected 20 years ago. The unmanned sample returns of the Soviet Luna series (16, 20, 24) have shown how useful these were for the Moon, for instance, the basalt fragments collected on Lunas 16 and 24 have been important in establishing not only chronology but the processes of basalt production and evolution of the Moon. The Luna missions actually had very limited sample returns, collecting only a small regolith sample at each site, and are a pointer to what might be accomplished by slightly more ambitious missions. Sampling can be performed at varied levels of sophistication, from simple grabbing of material at the landing site to complex automated or teleoperated rovers, and with varied degrees of other instrumentation appended.

Many questions could be answered with a simple sample collection, while others might require a great degree of sophistication. For example, on some flat mare terrain, a regolith sample would provide the essential chemistry of the terrain and might provide enough basalt particles to satisfy most analytical requirements, e.g., radiometric dating of lava flows. In contrast, at a terrain of complex domes of possible volcanic origin, several regolith samples from various spots, as well as small rock samples selected after some chemical screening by an instrumented rover, would be needed to understand the geological context of the features and crustal processes. We suggest that some fairly simple collection without much mobility, but with the ability to rake both small rocks and collect regolith within arms length of the lander, would be satisfactory for many purposes. In this paper, we discuss mainly sample collection, but a lander could also carry geophysical instruments, perform in situ measurements, and make other observations about the Moon and its environment.

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*Editor's Note: This is the third in a series of articles published in Eos on scientific value of sample returns from Solar System bodies.*

## Questions, Samples and Solutions

The analysis of samples is the key to answering many questions about the Moon, and improves our inchoate understanding of that body. These questions range from those of local importance to those of global and fundamental importance, and from scientific to technological. In the following paragraphs, we outline some of the general kinds of questions that can be addressed by a sample return, and why they are significant. Subsequent sections will outline sample return techniques, and will discuss some specific sample return sites and the questions that they address.

*Origin of the Moon* A fundamental constraint on the origin of the Moon is its chemical composition. The Moon is a differentiated body, so its surface has a composition different from its interior. Geophysical constraints and current sample data provide some information on the lunar bulk composition [*Hood and Jones*, 1987; *Mueller et al.*, 1988]. However, to see through the differentiation requires as much knowledge as possible about the surface composition itself (its average and its variability), as well as about the rocks that exist in the crust. Regolith samples from a large number of locations would enable an accurate calibration of the global geochemistry data to be obtained from a future lunar orbiter and lead to knowledge of both a global average composition and lateral regional and local variations for a large number of chemical elements. Rock samples are needed to understand the specific processes of differentiation that are also required to read through the plexus of crustal compositions to the lunar bulk composition.

*Magmatic History of the Crust* Igneous rocks are the most direct guide to the internal workings of the Moon, providing information on what actually happened and when it happened. There is a paucity of igneous rocks from the lunar highlands in the current sample collections, yet there are enough to show that the production of the crust comprised a complex and prolonged set of events. Most highlands rocks are breccias, but even these preserve some fragments of igneous rocks, and breccia components help us to establish the probable nature of precursor rock types. Average compositions of specific volumes of the lunar crust can be obtained from impact melts sampled from craters. Melt sheets from large basins, like the one sampled at the Apollo 17 landing site, contain clasts of deep-seated igneous rocks and can be targeted for sampling. Selected spots in the highlands, including those with anomalous compositions (as determined from orbital data), would provide significant samples that can elucidate the materials and processes of lunar crustal formation.

*Characteristics of Lunar Mare Basalts* Many of the dark plains units on the Moon are crystallized lava flows; other dark patches are probably composed of glass beads and shards erupted as pyroclastic deposits. Mare basalt magmas formed by internal melting of the Moon and provide information on the thermal history of the Moon, its internal composition, and the processes of magma generation and modification. Remote observations show that a myriad of distinct mare flows occur on the Moon, with a wide range of compositions and relative ages. Most of these were not sampled by the Apollo or Luna missions, so although we have a general idea of their compositions and relative ages, we lack data on the all-important minor-element chemistry and radiogenic isotopes, which permit absolute dating; these data are among the fundamental tools of modern studies of petrogenesis. For most of the lava flows, we lack even the major-element data that is required to use the results of experimental petrology to constrain the depths of origin of the magmas. Sample returns from mare plains of varied compositions and ages would considerably advance our knowledge of the evolution of the lunar interior and the thermal history of the Moon.

*Time Calibration of Lunar Stratigraphy* The stratigraphic sequence of events on the Moon is rather well known from numerous detailed mapping studies that started prior to Apollo and continue at present [*Wilhelms*, 1987]. A calibration of this sequence with absolute time is partially available from the Apollo and Luna samples, which allow radiogenic dating of specific units. However, the limited coverage of the sampling missions is not sufficient to date most of the mapped units. For example, further sampling of specific units for radiometric dating would ensure a better understanding of whether or not there was a steady declining bombardment in early lunar history or a late (3.8-3.9 Ga) resurgence of bombardment, of the duration of mare volcanism, and of the ages of specific craters of stratigraphic importance. Further details are provided in the following paragraphs.

Few lunar samples, even from the highlands, show ages older than 3.9 Ga. The limited sampling is seen by some workers as permitting the interpretation that these ages are dominated by one or a few events. Sampling from a greater number of specific units, particularly from areas distant from the Apollo and Luna sites and stratigraphically as old as possible, would resolve this question, which has important ramifications for the early dynamical environment of the Moon.

The interpretation of the thermal evolution of the Moon requires a thorough understanding of the timing of lunar volcanism. The youngest samples collected on the Apollo and Luna missions are more than 3.0 Ga old, yet flows stratigraphically younger have been identified from geological and remote sensing studies; how much younger cannot be certainly known without samples of them to permit radiometric dating.

Clast-poor impact melts can be dated isotopically and provide a precise age for a cratering event. The youngest basin, Orientale, was created after Imbrium, but exactly how much later is not known; it is possibly as much as 100 million years younger, but could be as little as a few hours younger. Its units include some interpreted as impact melts, and its age could be determined precisely and unambiguously in a way that older basins, whose extant deposits do not include clearly exposed undisturbed melt units, cannot. Other large craters that have been used as younger stratigraphic markers, such as Copernicus and Tycho, could also be dated, allowing precise correlation of the stratigraphic sequence with absolute ages.

*The Regolith and the Sun's History* The Moon's surface is a complicated, powdery blanket of broken rock, mineral, and glass fragments. This debris, called regolith, was produced by meteoroid impacts that fragmented rocks, melted soils, and mixed the regolith vertically and, to a lesser extent, laterally. Most importantly, the regolith has been exposed to the solar wind and to solar flares for billions of years. The lunar regolith is the zone of interaction between the solid Moon and the extralunar environment. Regolith processes are by far the most dynamic of those occurring on the Moon today, and their study provides a framework for predicting what to expect when we land on other planetary bodies. In principle, it is also possible to use lunar regolith samples to unravel the Sun's history. For example, Apollo data indicate that the $^{15}N/^{14}N$ ratio of solar wind-implanted gases on lunar dust grains has increased with time, probably due to nuclear reactions in the Sun [*Clayton and Thiemans*, 1980]. David McKay, Johnson Space Center, Houston, Tex., refers to the lunar regolith as a solar telescope with a tape recorder. The problem is that the tape recorder has a complicated playback button. Much more work and many more core samples are needed before we can determine with confidence when identifiable layers in the regolith formed, information essential to quantitatively decipher secular changes in the Sun, and before we are able to quantify regolith dynamics of the present and the past.

*Origins of Lunar Paleomagnetism* A surprising result of the study of Apollo samples was that some samples cooled in the presence of a relatively strong magnetic field, even though the current magnetic field at the lunar surface is negligible [*Hood*, 1986]. In addition, several geologic features, such as high-albedo surface swirls, appear to be associated with high-intensity remnant magnetic fields; the origins of both the swirls and magnetic anomalies remain unknown. Sample returns from carefully selected areas on the Moon can address these problems. Samples of oriented mare basalts from flows of various ages can settle the question of whether there was a peak in magnetic intensity between 3.9 and 3.6 Ga ago; such studies would help address the question of a possible early core dynamo and hence, may lead to a better determination of the presence of a lunar core. Sample returns from the enigmatic swirls can help resolve both the origins of the swirls and their associated magnetism. Finally, it will be important to sample impact melt glass lining the floors of small fresh craters; these samples can test the idea that transient magnetic fields are generated during hypervelocity impact events.

*Characterization of Lunar Resources* A great deal about the surface chemistry and mineralogy and their variations over the entire Moon will be learned following the flight of a polar orbiter. Samples from specific sites will then be needed to evaluate their potential in detail, including any possible water trapped in permanently shadowed crater floors near the lunar poles [*Arnold*, 1979], or particular mineral or chemical resources. One of the major resources contained in the lunar regolith are minable quantities of solar wind gases including hydrogen (for the manufacture of rocket propellant) and the terrestrially rare isotope $^3He$, which ultimately may be used in nuclear fusion reactors on the Earth [*Wittenberg et al.*, 1986]. The evaluation of gas resources in the

**TABLE 1. Geologic Reconnaissance Sites Where Objectives Can be Accomplished by Simple, Unmanned Sample Returners**

| Target | Objectives | Landing Point | Comments |
|---|---|---|---|
| Maria | Characterize diverse mare basalts in terms of age and composition. Determine boundary conditions on lunar thermal history; when did mare volcanism start and stop? Calibrate crater densities with isotopic ages. Determine chemical differences between near- and far-side maria. Determine lateral and vertical heterogeneity of lunar mantle. | 1. In Flamsteed 3°S, 44°E | Surveyor I shows thin regolith; age about 1 Ga |
| | | 2. Near Lichtenberg 32°N, 67°E | Basalts embay rayed crater; age about 1 Ga |
| | | 3. Tsiolkovsky 20°E, 130°S | Apollo 11 composition and age |
| | | 4. Mare Ingenii 36°S, 165°E | Reiner Gamma-type swirls overlie basalts |
| | | 5. Mare Moscoviense 28°N, 148°E | Typical far-side mare fill |
| | | 6. Mare Smythii 3°N, 90°E | High-Ti, very young (<2 Ga) |
| | | 7. Mare Marginis 12°N, 90°E | Young (<2.5 Ga); high Th |
| | | 8. Mare Australe 38°S, 91°E | Old mare covered by Imbrian age light plains |
| | | 9. Schickard 55°E, 45°S | Old maria covered by Orientale light plains |
| | | 10. Imbrium flows 29°N, 29°W | Young (1–2 Ga); high-Ti and KREEP-rich |
| | | 11. Mare Serenitatis 20°N, 20°E | Spectral standard, near major age (I-E) boundary |
| Crater Melt Sheets | Determine melt compositions for crater target. Determine projectile signatures. Isotopic ages for crater events to calibrate relative time scale for Moon and other planets. Determine melt homogeneity and clast provenance. | 12. Copernicus 10°N, 20°E | Major stratigraphic horizon, complex target |
| | | 13. Eratosthenes 14°N, 12°E | Major stratigraphic horizon |
| | | 14. King 5°N, 121°E | Far-side crust, very young |
| | | 15. Tycho 43°S, 10°E | Young major crater; complex rock types in target |
| | | 16. Giordano Bruno 36°N, 103°E | Youngest large crater on Moon |
| Basin Melt Sheets | Determine melt composition as a sample of the crustal average. Determine lateral heterogeneity of lunar crust. Isotopic age of basin impacts to calibrate geologic time scale. Samples of crustal rock types as clasts within basin melts. Determine projectile signatures for ancient large impacts. | 17. Orientale 25°S, 96°W | Youngest multiring basin on the Moon |
| | | 18. Humboldtianum 55°N, 77°E | Interesting "middle-age" basin on NE limb |
| | | 19. Schrödinger 74°S, 125°E | Young, 2-ring basin near south pole |
| Highlands | Characterize chemistry and petrology of a variety of highlands areas. Determine magmatic and impact events in highlands evolution. Sample anomalous regions to determine differences with average highlands. Isotopic dates for magmatic events in highlands history. Address thermal evolution, cratering history. | 20. Near Mutus 66°S, 30°E | "Average" ancient near side highlands |
| | | 21. Near Lebedinsky 10°N, 165°W | "Average ancient far-side highlands |
| | | 22. Van De Graaf 26°S, 170°E | KREEPy basalts or Mg-suite |
| | | 23. Ptolemaeus 10°S, 12°W | KREEPy basalts or Mg-suite |
| | | 24. Hertzsprung floor 4°S, 124°W | Mg-suite pluton (?) |
| | | 25. West of Tsander 7°N, 153°W | Mafic ferroan rocks of ancient mare basalts |
| | | 26. Gruithuisen Gamma 36°N, 41°W | Spectral anomaly; age and composition |
| Lunar Resources | Sample and characterize sites for future resource exploitation. Assess pyroclastic deposits for volatiles, high-Al regions, and possible volatile deposits at poles. Characterize compositions and ages of resource deposits; physical processes responsible for their existence. | 27. Rima Bode 13°N, 4°W | Major regional pyroclastic deposit; high Ti |
| | | 28. Sulpicius Gallus 19°N, 10°E | Major regional pyroclastic deposit; high Ti |
| | | 29. Aristarchus Plateau 26°N, 51°W | Regional pyroclastic deposit; appears Kreep-rich |
| | | 30. North of Orientale 0, 110°W | Nearly pure ferroan anorthosites |
| | | 31. Permanently shadowed areas near poles at 90°N and 90°S | Sample only if LO finds evidence of water ice in polar regions |

regolith cannot be accomplished from orbit; sample returns are required. Samples might also be needed for engineering purposes (maturity of regolith, geotechnical properties) and for characterizing a site for the potential of building a lunar base.

*Geology and Petrology of Complex Sites* Although many lunar features are at least superficially rather simple, and thus sampling could be simple, others are more complex and require a sophisticated level of sampling to ensure adequate elucidation rather than additional confusion. The formation of giant ringed basins, so important in lunar stratigraphy and well illustrated by the Orientale basin, cannot be understood with samples from a single location. A wide variety of locations would need to be sampled, covering the radi-

**TABLE 2. Geologic Field Sites That Require Intensive Field Work With Human Interaction**

| Target | Objectives | Landing Point | Comments |
|---|---|---|---|
| Cratering | Determine details of crater and basin formation. Study central peaks and basin rings to determine origin(s). Study melt sheet homogenization, clast provenance, particle motions during cratering flow. Study walls, terraces, and slump blocks. Investigate continuous deposits; primary versus local ejecta fractions as a function of radial range. Reconstruct stratigraphy of target. Investigate absolute ages; shock metamorphism of crater materials. Projectile types and changes with time. | 32. Copernicus 10°N, 20°W | KREEP/Mg-suite target; central peaks |
| | | 33. Tycho 43°S, 11°W | Gabbronorites in central peak; melt sheet surface |
| | | 34. Aristarchus 23°N, 48°W | Gabbro in central peak, high Th; KREEP intrusives? |
| | | 35. Aristillus 34°N, 1°E | Mare basalt/KREEP target; ray material spectrally distinct |
| | | 36. Apennines/Conon 22°N, 2°E | Excavated through Imbrium ejecta to pl bedrock; KREEP-LKFM transition zone |
| | | 37. Eudoxus 44°N, 16°E | Alpes Fm., Imbrium deposits; what is origin of knobby basin deposits? |
| | | 38. Montes Pyrenaeus 15°S, 40°E | Nectaris ring and melt sheet; pure anorthosite outcrops |
| | | 39. Orientale floor 15°S, 85°W | Melt sheet, mare basalt ponds, and Montes Rook Fm. |
| | | 40. South Pole-Aitken basin massifs 25°S, 155°E | Largest basin on Moon, chemically anomalous |
| Volcanism | Characterization of vent and flow systems. Determine eruption and emplacement styles. Determine chemical differentiation through time. Determine origin of volcanic landforms. Determine details of assimilation in mare magmas; search for mantle xenoliths in basalt flows. Variability of mantle sources in space and time. Investigate possible intrusions and ore bodies. | 41. Marius Hills 12°N, 55°W | Central vent volcanos; sinuous rilles |
| | | 42. Hortensius domes 7°S, 28°W | Small basaltic shield volcanos |
| | | 43. Rümker plateau 41°N, 58°W | Similar to Marius Hills but smaller complex |
| | | 44. Herigonius rilles 12°S, 36°W | Sinuous rille and vent system atop wrinkle ridge |
| | | 45. Aristarchus plateau 24°N, 50°W | Dark mantle; light plains with high Th content (KREEP basalt?); Schröter's Valley sinuous rille complex |
| | | 46. Ina ("D-caldera") 19°N, 5°E | Small collapse feature associated with very young basalt flows |
| | | 47. Alphonsus vents 13°S, 2°W | Small cinder cones in floor-fractured crater |
| | | 48. Near Lassell 14°S, 10°W | Small cones and mare flows |
| Highlands | Determine small-scale geologic setting of ancient crust, plutonic intrusions, and ancient volcanics. Search for blocks displaying primary igneous layering. Determine composition and origin of anomalous materials. Sample and investigate all plutonic units identified remotely. Determine provenance of lunar meteorites. Characterize cratering process at all scales. | 49. Silver Spur 25°N, 4°W | Layered materials in Apennines; igenous or sedimentary layering? |
| | | 50. Montes Caucasus 32°N, 7°W | Uplifted pl crust in rectilinear fault blocks |
| | | 51. Tsiolkovsky peak 20°S, 129°E | Uplifted far-side crust in crater central peak |
| | | 52. Mons La Hire 28°N, 25°W | Part of Imbrium ring; spectral anomaly |
| | | 53. Gruithuisen domes 36°N, 40°W | Rhyolitic domes or basin massifs? |
| | | 54. Hansteen Alpha 12°S, 50°W | Spectral anomaly; volanic or basin massif? |
| Geologic oddballs | Unusual morphologic features indicate either rare geologic processes or unknown facets of common ones. Determine ages, compositions of units. Determine origin(s) of landforms. Search for exotic processes and materials. | 55. Struve L 21°N, 76°W | Orientale basin secondary; melt-lined floor? |
| | | 56. Donut crater in Humboldt 26°S, 83°E | Concentric crater, possibly a secondary |
| | | 57. Crater in Barbier 24°S, 158°E | Volcanic complex or basin secondary crater? |
| | | 58. Reiner Gamma 6°N, 59°W | Swirl material, magnetic anomaly; comet impact? |
| | | 59. Marginis swirls 15°N, 90°E | Swirl material, magnetic anomaly; comet impact? |

al extent and variety of units of a basin. This requires either multiple landings or a sophisticated rover capable of traveling hundreds of kilometers. On a smaller scale, volcanic and tectonic features, including vent complexes, domes, and wrinkle ridges, still require sampling from more than a single spot and require mobility of a sample collector. These features are important to sample if lunar volcanic processes, or the genesis of other complex landforms, are to be understood.

## How to Sample

The unresolved problems outlined above will not yield their solution easily. They require an integrated program designed to explore the Moon at increasing levels of detail and complexity. Such a program involves a series of orbital missions, surface exploration missions, sample returns, network science, and ultimately, detailed geologic field work on the Moon.

We distinguish reconnaissance from field study in surface scientific activities. Reconnaissance is the quick and superficial examination of a given site or region with the aim of understanding what types of processes and events are to be studied. Field study involves extensive and protracted work in which specific scientific questions dealing with geologic processes and history are formulated and answered. Both are needed but require different hardware and philosophies of surface operations.

Reconnaissance sampling can be performed by an inexpensive series of simple spacecraft of the Soviet "Luna"-class [*Johnson*, 1979]. Because many lunar units are geologically complex and difficult to interpret, this phase of sampling should be restricted to targets where interpretation of the returned samples is expected to be relatively straightforward. Such targets include samples of compositionally uniform but distinct mare basalt units, the melt sheets of large craters and basins, and regional chemical provinces identified from orbit. These missions will also guide future exploration, such as the selection of a lunar base site. The long-range goals of human colonization and use of the Moon require that we perform an adequate reconnaissance to plan the next generation of geological study.

We envision these simple, sample-return vehicles as being much like the Luna spacecraft that returned samples from three localities on the Moon. Reconnaissance samples could also be obtained by automated rovers operated from the Earth. The cost effectiveness of these two approaches needs to be determined; both methods of sample collection may be necessary. Either spacecraft must be capable of collecting two types of samples—raked rocks and regolith.

*Rake Samples* Much was learned from walnut-sized rocks collected by pulling a rake through the lunar regolith during the Apollo 15, 16, and 17 missions. The rake collected samples larger than 1 cm, each large enough to allow mineralogic, chemical, and isotopic studies. For each landing site for which we propose sample-return reconnaissance missions, about 100 rake samples would give a reasonable sampling of the rocks present. Extrapolating from the Apollo rake samples, A. Binder (unpublished manuscript, 1984) estimated that a spacecraft would have to rake about 5 $m^2$ to obtain 100 fragments 1–4 cm in size, a mass of about 1 kg. To ensure collecting 100 rocks, the lander ought to be capable of raking about 10 $m^2$. If the sampling arm could collect over a range of 180° and was hinged 1 m above the surface, it would need to be at least 2.7 m long to sample the required area.

*Regolith Samples* Some regolith would be contained in the rake sample. This material would be useful scientifically, but would be compromised because friable rake samples tend to break up during sampling and transport to Earth, possibly leading to unrepresentative regolith compositions and physical characteristics. A bulk regolith sample would better characterize the site and serve as ground truth for calibrating the orbital geochemical data. A 200-g sample would probably serve this purpose. Also, to understand the regolith stratigraphy at the site and the depositional mechanics of possible pyroclastic deposits, a core sample should also be taken. For a core 2 cm in diameter and a regolith density of 2 $g/cm^3$, a 150-cm core would have a mass of 900 g. Thus 1100 g of regolith would be returned. For the rake, bulk regolith, and core samples, the spacecraft would return a total payload of 2.1 kg.

This sample-return spacecraft would be almost entirely autonomous, programmed to collect the samples, store them, and then return to Earth. It could also carry geophysical instruments and deploy them on the Moon. The cost effectiveness of combining sample-return and geophysical missions needs to be evaluated.

Human involvement in intensive geologic field study of promising areas on the Moon is necessary for complicated areas. Such work is guided by the results from orbital and surface reconnaissance and combines geologic field work with sample collection. Examples of targets include the central peaks of craters, where complex outcrops occur, megablocks of brecciated highland crust that occur as crater ejecta and are exposed within crater walls, in situ mare basalt exposures such as occur within the walls of sinuous rilles and craters, crater and basin ejecta deposits, and study of the genesis of specific lunar landforms such as volcanic vents and wrinkle ridges. A Luna-type sample return from such targets might produce more confusion than enlightenment; direct human involvement and control is required at this level of study.

## Sites to Sample

The Moon is unique among planetary bodies in that we already possess enough information to identify some specific sites where fairly detailed and sophisticated questions can be answered by sample return missions. We present a list of such sites in Tables 1 and 2; the locations of these sites are shown in Figure 1. We emphasize that these lists are tentative and should be extensively revised and

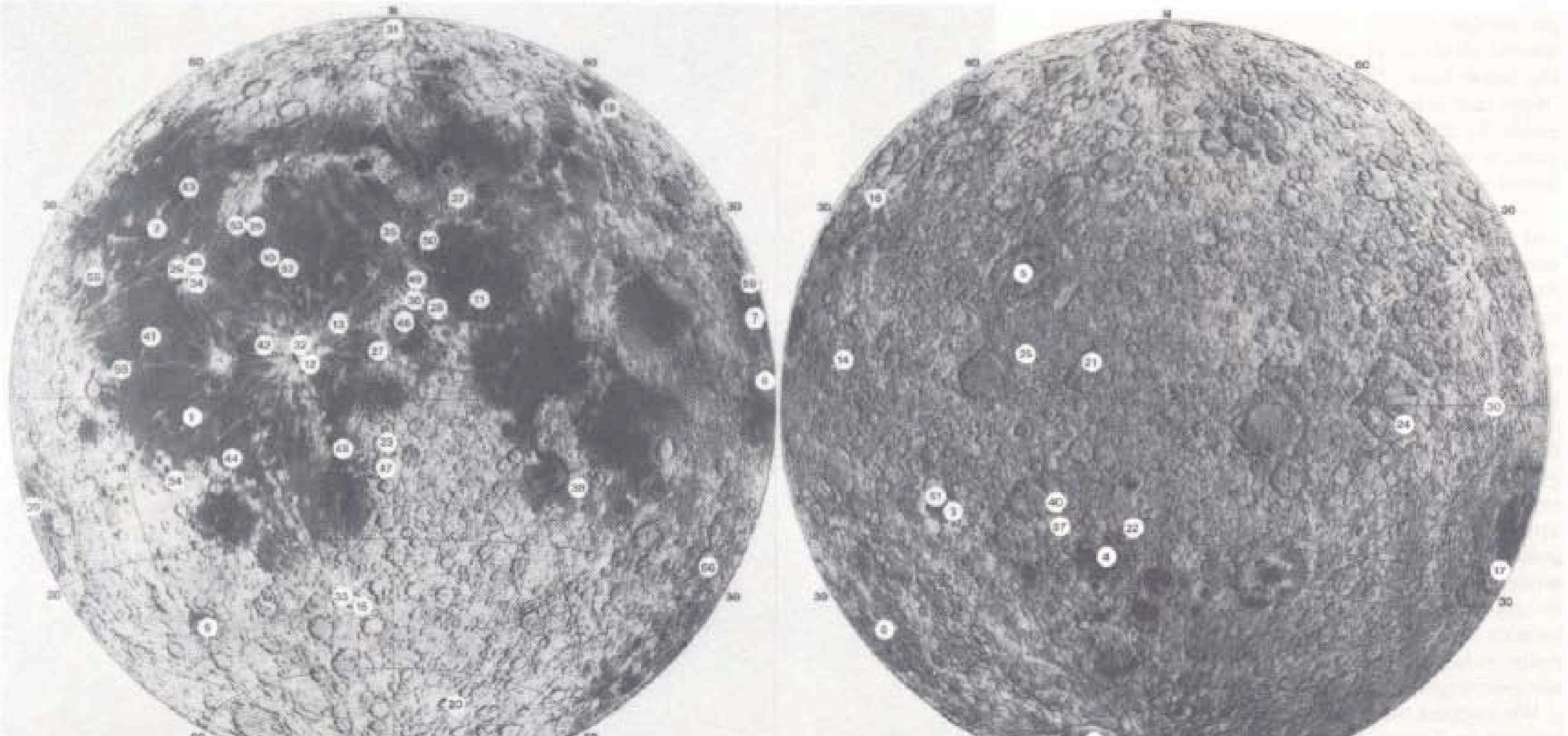

*Fig. 1.* Map of the Moon (equal-area projection) showing the locations of recommended sites for sample-return missions. Numbers refer to sites listed in Tables 1 and 2.

prioritized after the acquisition of global remote sensing data. Moreover, we do not advocate that all of these sites be visited within a single program series or even several mission programs. The lists presented here are shown as examples to indicate the diversity of geologic processes and units from which sample return missions can contribute significant scientific results.

*Sample Sites for Luna-Type Spacecraft* A series of relatively simple sample return missions can be planned to address the need for geologic reconnaissance of the Moon. A series of landing sites can be identified from the global remote sensing data returned by the Lunar Observer and other possible orbital missions from which a Luna-type sample return will provide both first-order scientific information and a guide to the detailed planning of future geologic field work.

Sites that we identify for a series of Luna-type sample return missions are presented in Table 1 and Figure 1; examples are shown in Figure 2. This mission series serves the most pressing reconnaissance needs. Among the problems to be addressed are the mare basalt inventory on the Moon (sites 1-11) and the calibration of the lunar relative time scale through the sampling of crater and basin impact melt sheets (sites 12-19); these same sites permit the determination of regional lateral variations in crustal compositions by using impact melts as crustal probes. The early magmatic history of the crust may be addressed by sampling regions on the Moon identified from the orbital data as being petrologically interesting (sites 20-26). This series of missions can characterize the resource potential of identified lunar prospects, such as regional pyroclastics, volatile-rich areas, and zones composed of relatively "pure" rock types (sites 27-31).

The suggested sites of Table 1 are tentative, and a more detailed and revised list should be prepared after global remote sensing data are obtained. The ability to fly simple sample-return missions should be a required element of the infrastructure supporting lunar base. These missions provide important scientific data, but they also will guide future, more detailed geologic investigations to be conducted as the base is established and expanded.

*Sample Sites Requiring Intensive Exploration and Field Study* As the geological reconnaissance of the Moon progresses, we will undoubtedly encounter scientific questions of such detail and complexity as to require the acquisition of additional data through intensive field study. In contrast to the missions previously described, these studies will require long site visits, intensive work capabilities, and the option to revisit the site. The goal is to understand lunar processes and evolution at whatever levels of detail may be appropriate. The key element that distinguishes this type of study from reconnaissance is human interaction during the work. Human presence may take the form of actual human field geologists or robotic teleoperations; either method proceeds along the same methodological lines [*Spudis and Taylor*, 1988].

We suggest targets for intensive field investigation in Figure 1 and Table 2; some examples are shown in Figure 3. At this level of study, we are asking fundamental questions about the basic geologic processes of the Moon and we are deciphering the detailed history of selected regions. The mechanics of

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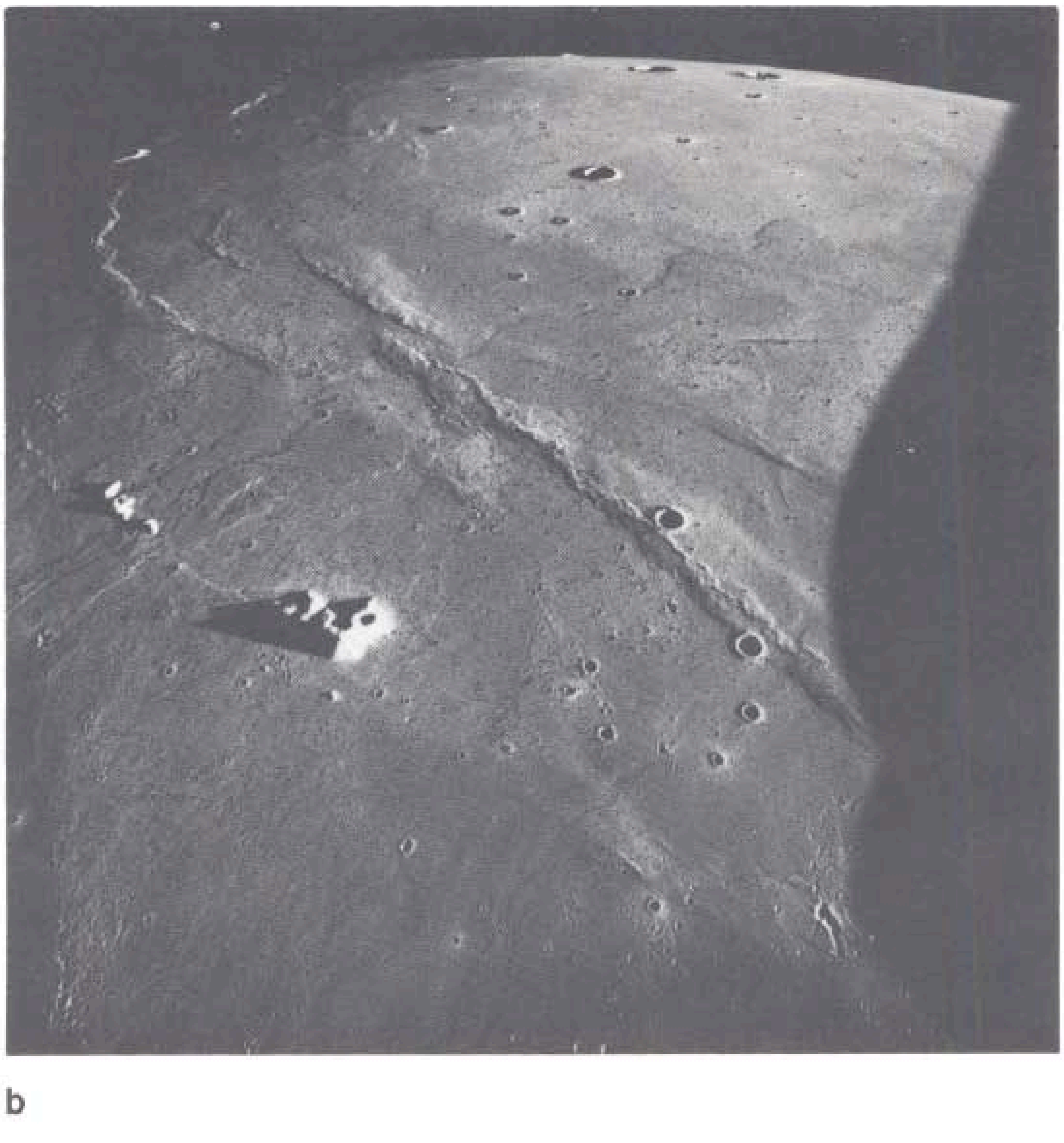

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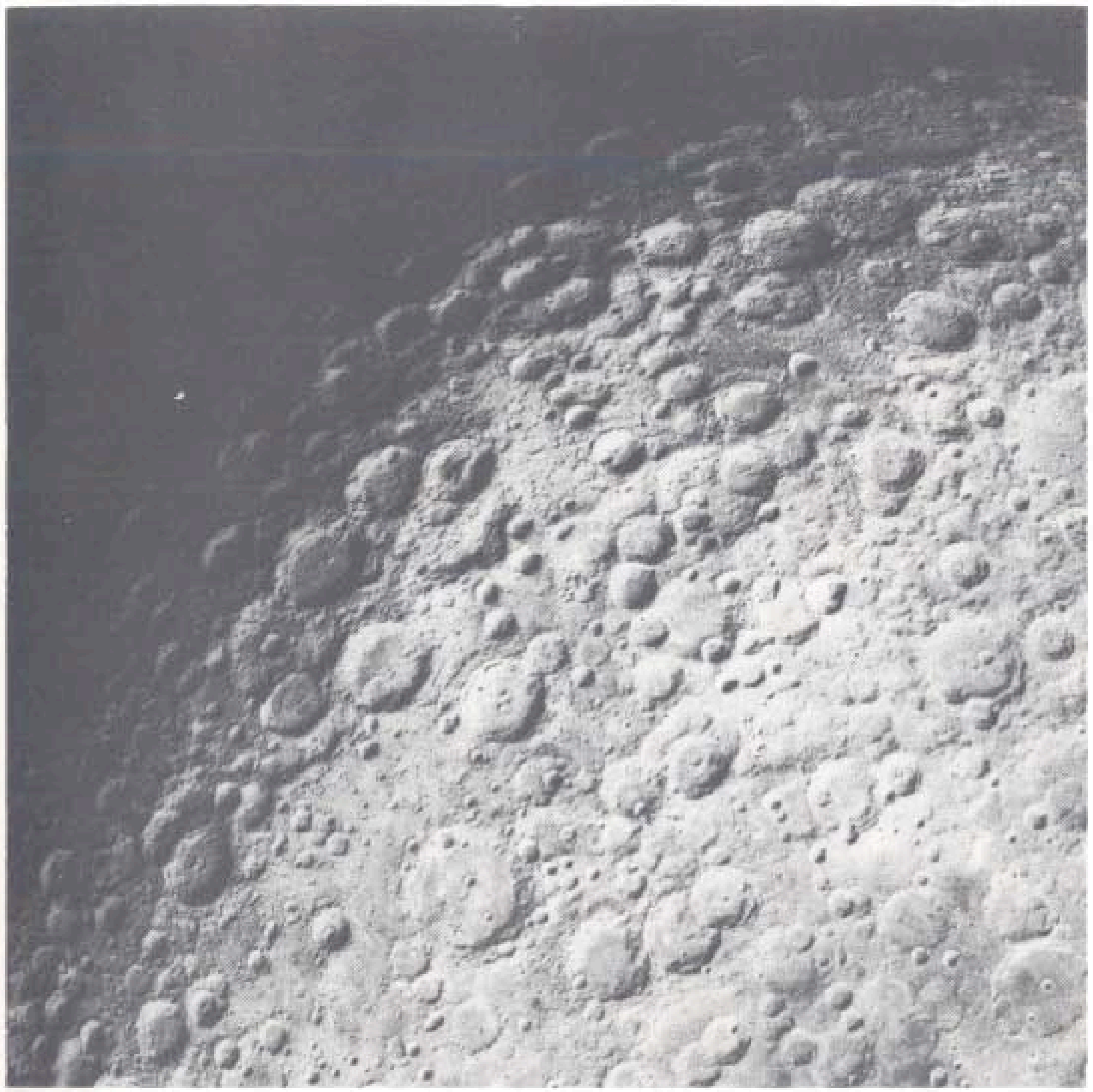


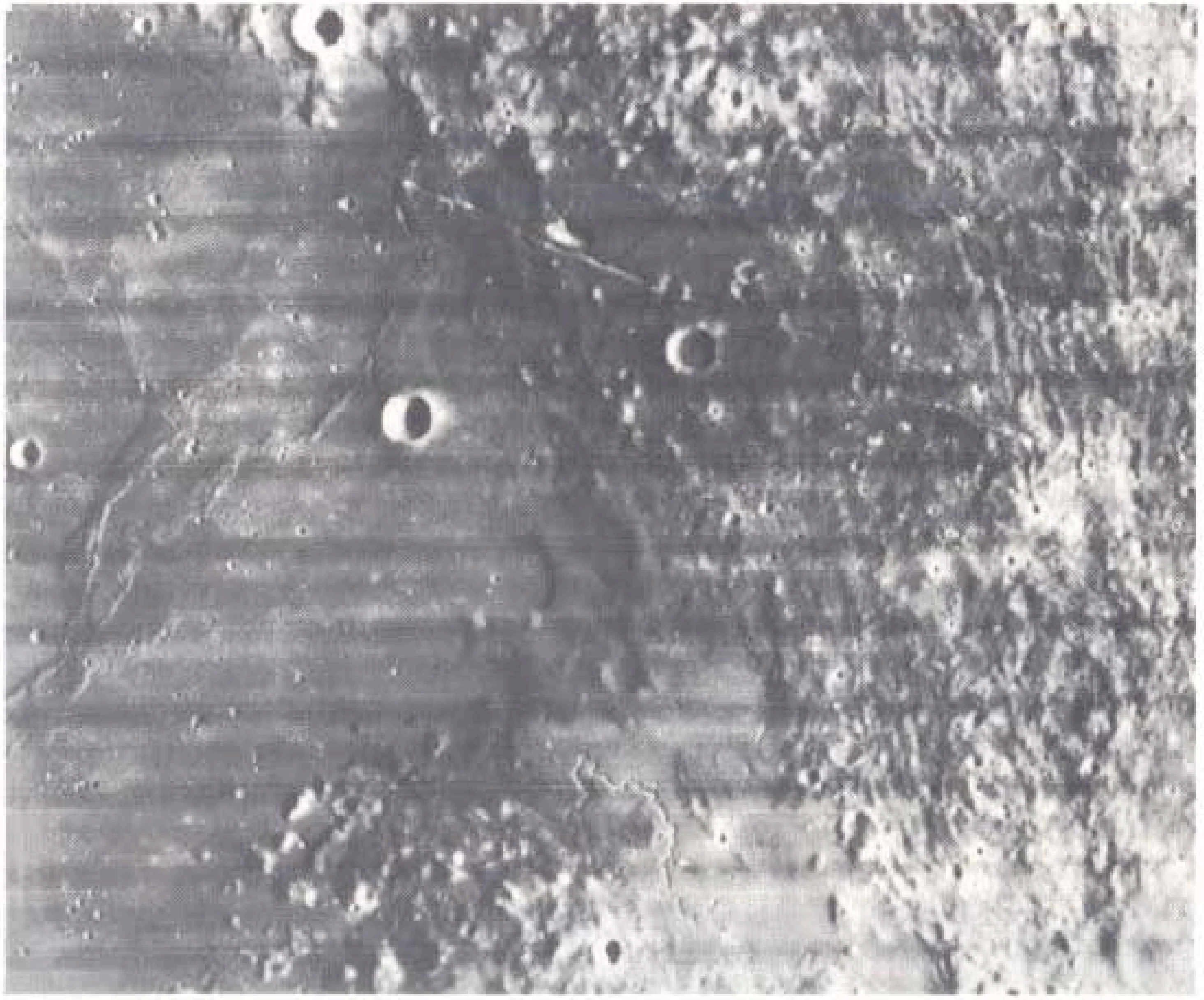
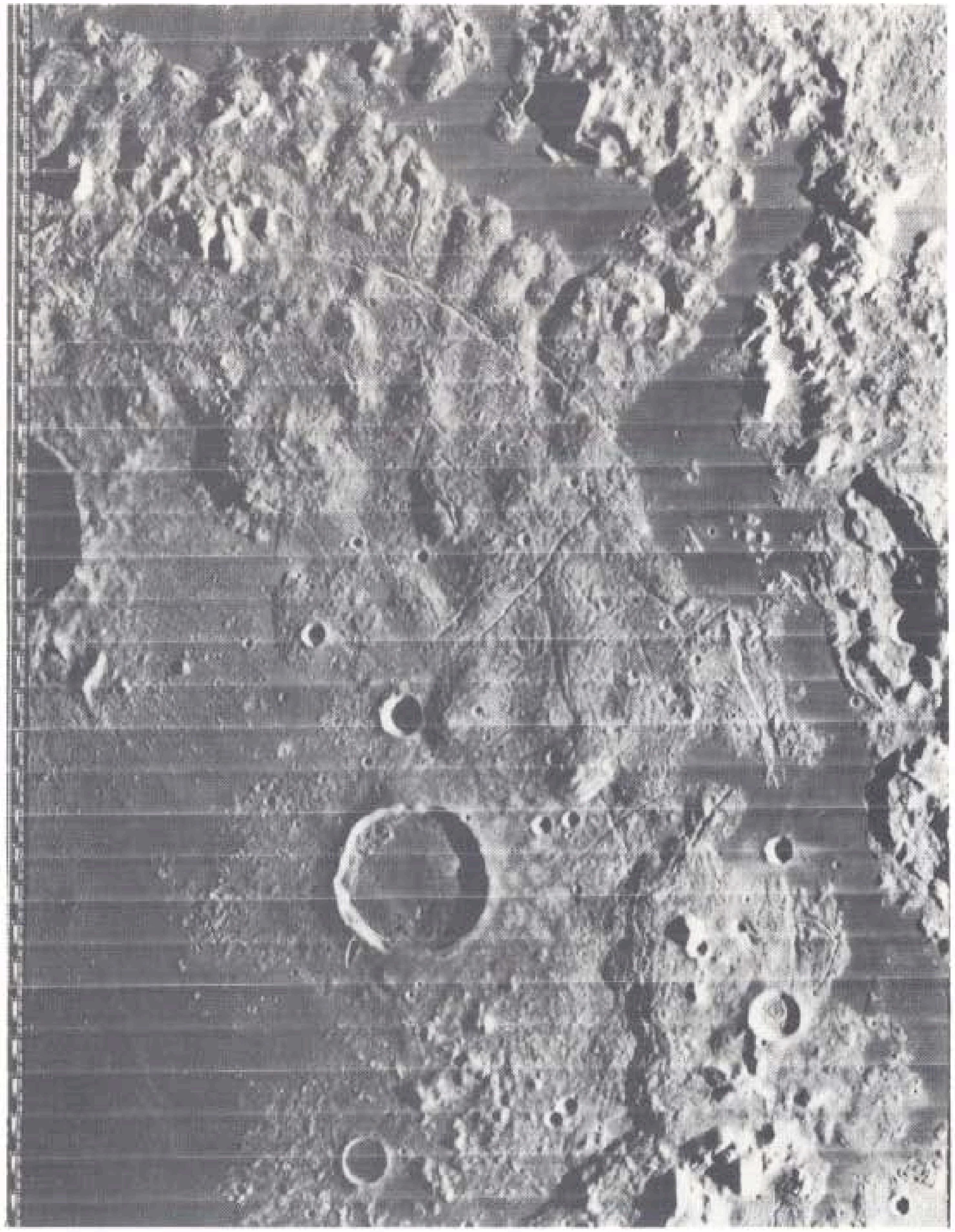


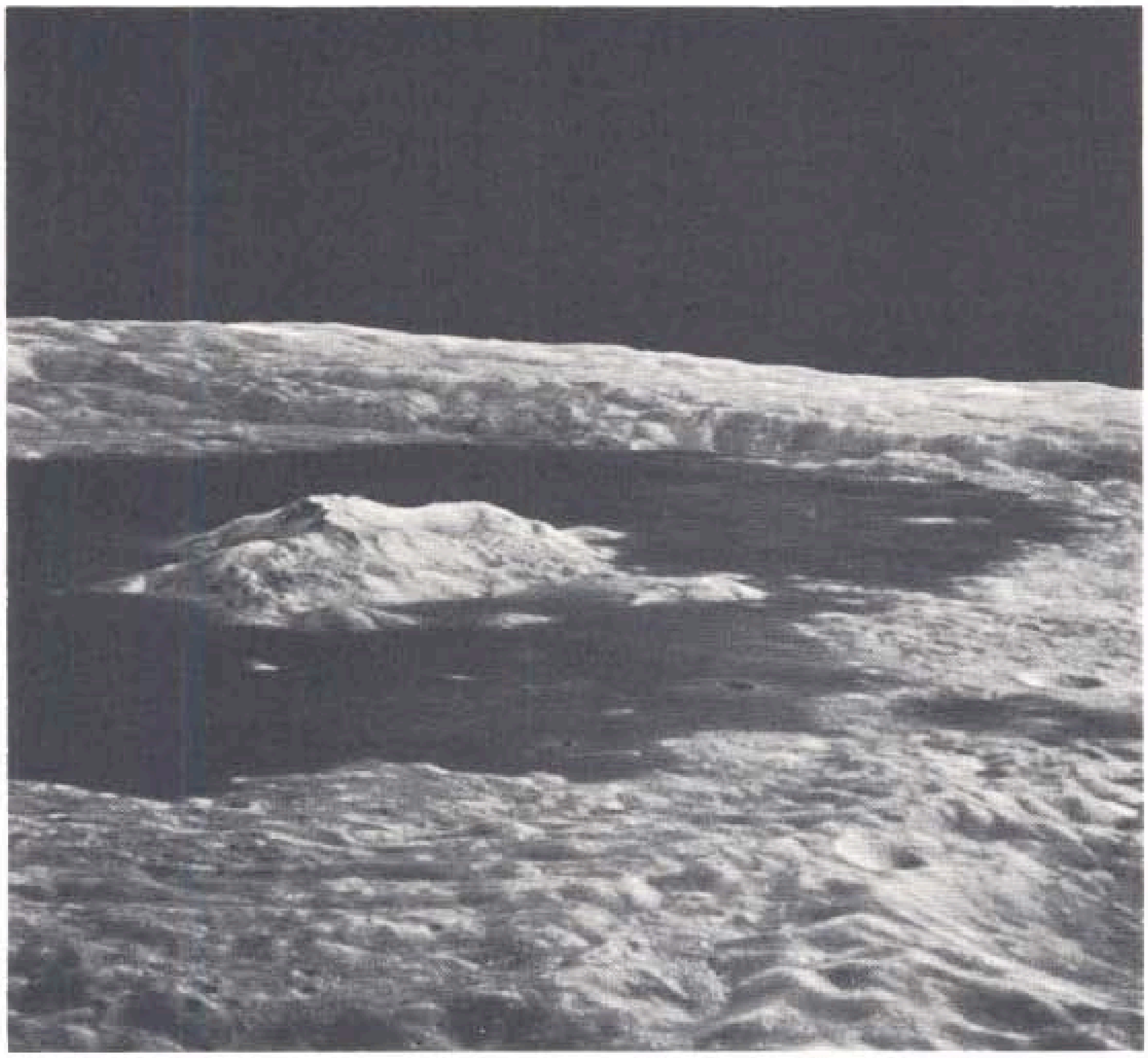
*Fig. 2.* Some examples of simple, reconnaissance landing sites—see Table 1 for description and Figure 1 for location. (*a*) Mare Ingenii (site 4) on the far side. Orbital data show that this maria is geochemically anomalous, possibly rich in KREEP. Swirl material covers the mare in part and could be included in the sample return. South looking oblique; large filled crater at left center is Thomson (112 km diameter). AS15-91-12375. (*b*) Young mare basalt flows in Mare Imbrium (site 10). Well-developed flow lobes outline a relatively young basalt flow (about 1.5 Ga) with relatively KREEP-rich composition. North looking oblique; field of view at bottom about 100 km. AS15-1555 (metric). (*c*) Ancient cratered highlands of the far side (site 21). We have no documented samples of the far side and none of relatively pristine highlands (uncontaminated by recent basin ejecta). South looking oblique; prominent crater near center with Y-shaped central peak is King (77 km diameter). AS 16-3032 (metric). (*d*) Rima Bode region (site 27). Dark deposits discontinuously mantle the highlands; these deposits are probably pyroclastic glasses, similar to those sampled by the Apollo 17 astronauts. Such units are important to sample both to understand volcanic processes and the lunar mantle and also to evaluate the resource potential of these volatile rich glasses. North at top; framelet width 12 km. LO IV-109 H2.



a

b

*Fig. 3.* Some examples of complex sites requiring intensive field study—see Table 2 for description and Figure 1 for location. (*a*) Orientale basin floor (site 39). Fractured deposit consists of basin impact melt sheet, samples of which could both date the Orientale impact and provide a crustal average composition. Mare basalt ponds of Lacus Veris (dark plains) could be studied to decipher basin volcanic history. Crater Kopff (lower center; 42-km diameter) has unusual morphology and could result from an impact into a still partially molten basin melt sheet. North at top; framelet width 12 km. LO IV-187 H2. (*b*) Aristarchus Plateau (sites 29, 34, 45). This site is extremely complex and diverse including Imbrium basin deposits (Alpes Formation), plateau lavas (KREEP-rich, possible KREEP basalt), dark pyroclastic deposits, and the crater Aristarchus (40-km diameter), which is both a geochemical anomaly (high Th) and shows evidence for highland gabbroic rocks exposed in the central peaks. South looking oblique. AS15-2609 (metric). (*c*) Tsiolkovsky crater, far side (sites 3, 51). Crater is 190 km in diameter and floor is covered by relatively old mare basalts (crater density comparable to Apollo 11 site); basalts are Ti-rich (from Apollo gamma-ray data). Central peak averages about 30 km in diameter and rises a spectacular 3400 m above the crater floor; based on analogy to terrestrial craters, materials exposed within this peak complex probably come from depths of greater than 10 km in the Moon. East looking oblique. AS15-91-12383. (*d*) Mare Marginis on the east limb (site 59). In addition to the mare deposits, which are relatively young (about 2 Ga) and KREEP-rich, high-albedo swirl deposits cover the surface. The origin of these features, which are accompanied by intense magnetic anomalies, is unknown; they could represent the site of a very recent cometary impact. Grooved terrain (top center) is antipodal to Orientale basin and could be related to that event, either as antipodal ejecta or catastrophic seismic shaking. Crater at bottom center is Al-Biruni (78 km diameter). East looking oblique. AS16-122-19591.



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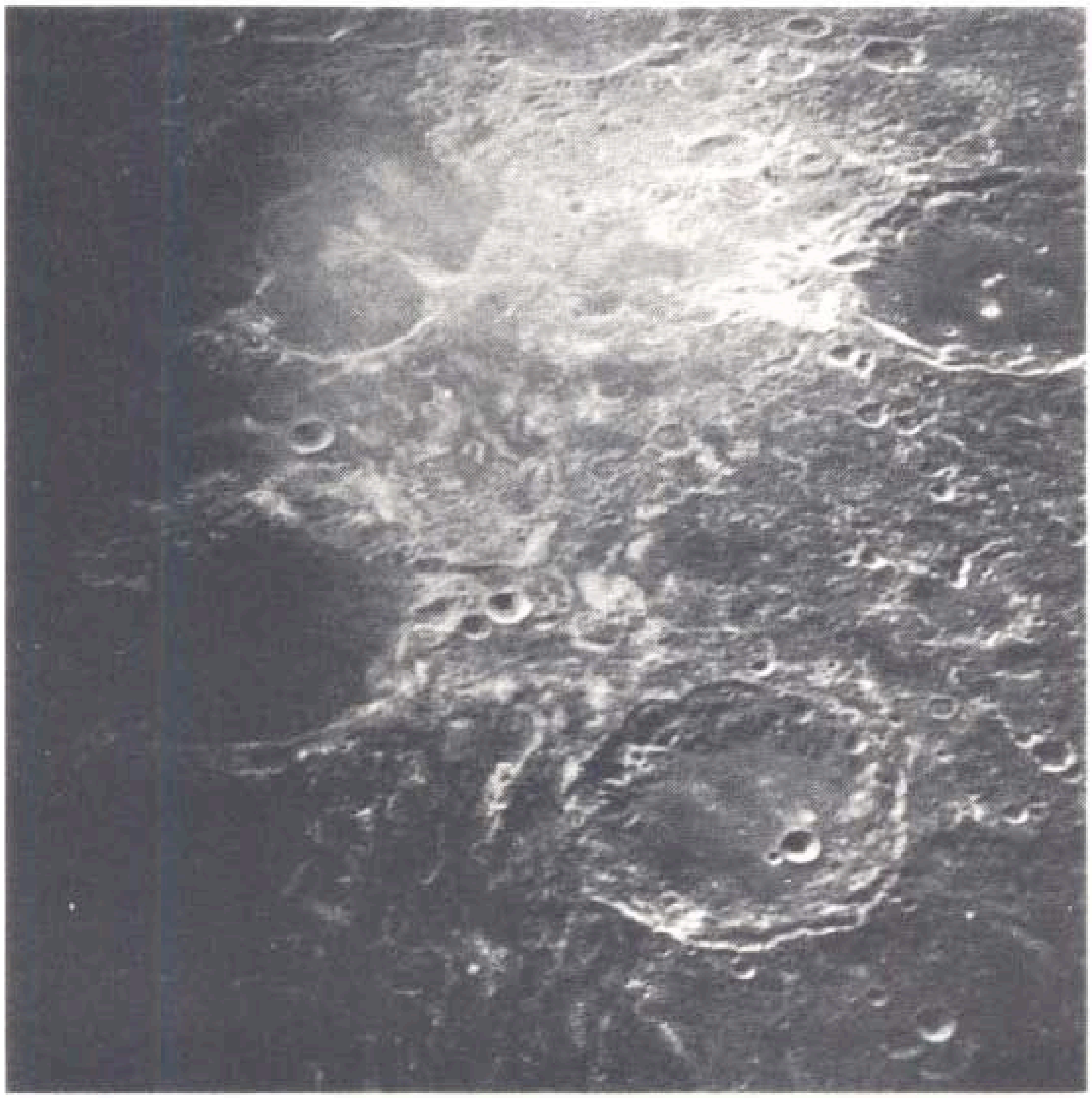

d

formation of large craters and basins (sites 32-40) may be addressed by the study of the geology of these structures; such work includes understanding the detailed stratigraphy and structure of the crater targets, the relative amounts of primary and secondary ejecta in the continuous deposits, the nature of the impact melting process, and the enigmas of central peak and basin ring formation. Many large craters appear to be our best access to deep-seated plutonic complexes that make up the crust; lunar igneous processes are on display within the central peaks and walls of large craters. Basin interiors may yet yield evidence of rocks excavated from the upper mantle of the Moon; the structural relations of rocks exposed within basin rings may likewise provide some constraints on ring genesis.

The processes and products of lunar volcanism are suited for protracted field study (Table 2; sites 41-48). Field study of vent structures and products, sinuous rilles, and small domes and shields will allow a more complete reconstruction of the epoch of mare flooding. The problems of landform genesis posed by lunar geomorphology require intricate, close-up inspection. For example, the origin of wrinkle ridges has long vexed lunar students and cross-sectional exposures occur on the Moon (associated with superposed impact craters or volcanic vents; Table 2, sites 41 and 44). These sites would be ideal candidates for field study to understand the mechanisms of wrinkle ridge formation and hence, regional tectonic history.

One of the most exciting capabilities resulting from extended human presence on the Moon is the one to examine bizarre and enigmatic features. Such landforms include craters with cracked or concentric floor fill, bulbous domes in highland areas, irregular depressions within the maria (possible vent sites), and unusual high albedo swirl-like markings. These features span the Moon globally and in time and are probably hints to the existence of rare processes (sites 58 and 59) or unknown facets of common ones, such as impact cratering (sites 55-57). Early reconnaissance by Luna-type spacecraft would not solve the questions raised by these features, but may be helpful in the planning of later, more advanced field study.

Each of the targets listed in Table 2 requires intensive investigation, but this need not be done on separate missions. The long geologic traverse described by *Cintala et al.* [1985] includes at least 29 stops that study a wide range of lunar processes and geologic units, including virtually all the processes listed in Table 2. Such a traverse could take years to complete but would provide an abundance of information pertinent to fundamental problems in lunar science.

## Conclusions

The Moon is one of the most important planetary bodies: it is a natural laboratory for the study of planetary geological processes, it provides us with a guide for the interpretation of the history of other terrestrial planets, including our own Earth, and its proximity enables us to use it as a stepping stone to the rest of the Solar System. The six manned Apollo and three unmanned Luna sample-return missions have provided us with a tantalizing peek at the geologic evolution of our surprisingly complex Moon. The sampling of the Moon is far from being complete; the results from each Apollo and Luna mission required a significant revision to our concepts of lunar history and there can be no doubt that additional samples from carefully selected sites will result in more revision. Because of its accessibility, the Moon is the most likely place for extended human presence in space beyond low Earth orbit; we must understand the evolution and history of the Moon to maximize our potential use of that body. The return of additional samples from the Moon is an essential step in our inexorable drive into space.

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