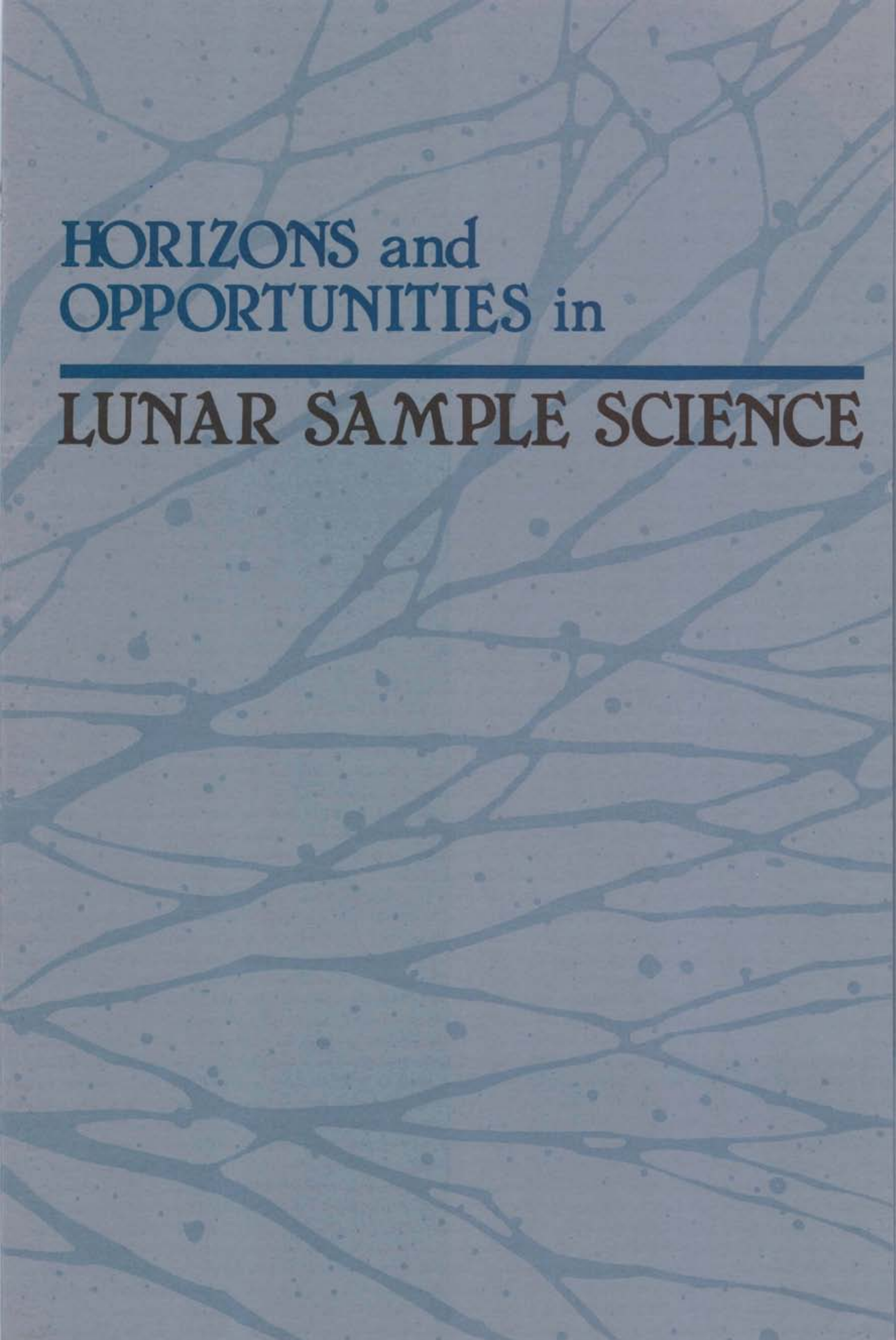
HORIZONS and OPPORTUNITIES in LUNAR SAMPLE SCIENCE



HORIZONS and OPPORTUNITIES in

LUNAR SAMPLE SCIENCE

BY

LUNAR AND PLANETARY SAMPLE TEAM (LAPST)

MEMBERS
Lawrence A. Taylor, Chairman; University of Tennessee
Randy Korotev; Washington University
David S. McKay; Johnson Space Center
Graham Ryder; Lunar & Planetary Institute
Paul Spudis; U.S. Geological Survey, Flagstaff
G. Jeffrey Taylor; University of New Mexico
David Vaniman; Los Alamos National Lab
Paul Warren; University of California Los Angeles

LPI TECHNICAL REPORT 85-04

Compiled in 1985 by the
LUNAR AND PLANETARY INSTITUTE

The Institute is operated by Universities Space Research Association under Contract NASW-3389 with the National Aeronautics and Space Administration.

This report may be cited as:
Lunar and Planetary Sample Team (LAPST) (1985) Horizons and Opportunities in Lunar Sample Science. LPI Tech. Rpt. 85-04. Lunar and Planetary Institute, Houston. 44 pp.

This report is distributed by:

LIBRARY/INFORMATION CENTER

Lunar and Planetary Institute
3303 NASA Road 1
Houston, TX 77058-4399
Mail order requestors will be invoiced for the cost of postage and handling.

Frontispiece. *Mission commander Dave Scott samples mare basalt bedrock at the rim of Hadley Rille during the Apollo 15 mission on August 3, 1971. On the boulder rests the gnoman (sun compass) and rock hammer; the gouge in the boulder just below the mid-point of the rock hammer is the location of pyroxene (quartz-normative) basalt sample 15596 (seen in sample bag in Scott's left hand, at right). The large blocks in the background are rille basalt outcrops; this is the only location on the Moon where bedrock was directly sampled during the Apollo missions. Lunar Module pilot James Irwin (who took the picture) is seen reflected in the Scott's sun visor. NASA photo AS15-82-11146.*

CONTENTS

INTRODUCTION

The Moon is the cornerstone of planetary science. Lunar sample studies have been fundamental in developing our understanding of the early evolution and continued development of planetary bodies, and have led to major revisions in our understanding of processes for the accumulation of planetesimals and the formation of planets. Studies of lunar samples have increased our understanding of impact cratering, meteoroid and micrometeoroid fluxes, the interaction of planetary surfaces with radiations and particles, and even the history of the sun. The lunar sample research program has obviously been especially productive, but by no means have all the important answers been determined; continued study of lunar samples will further illuminate the shadows of our knowledge about the solar system. Further, the treasures returned through the Apollo program provide information that is required for a return to the Moon, beginning with new exploration [Lunar Geoscience Observer (LGO)], followed by intensive study (new sample return missions), and eventually culminating in a lunar base and lunar resource utilization.

The few years during and following Apollo were a hectic time for lunar science. Since then, considerable maturation of the science and distinct changes in the mode of operation have developed. Funding (and hence the number of investigators) has naturally declined. Studies have become far more problem-oriented than descriptive. Many sample investigators have shifted their sights away from planetary evolution, for which the Moon holds considerable information, toward processes and materials in the pre-planetary solar nebula, for which the Moon has no direct evidence. Nonetheless, unique scientific opportunities are still supplied by the samples returned from the Apollo and Luna missions and by lunar meteorites. These 382 kg of samples constitute a priceless resource that still has enormous scientific potential. Continued interaction between NASA and the scientific community, especially through the advice of groups such as the Lunar and Planetary Sample Team (LAPST), is essential in maintaining the current level of excellence of the program.

LAPST has reviewed its role, the role of the sample research community, and the perceived role of future researchers over the next decade in ensuring the effective use of lunar sample studies in space exploration and exploitation. The review encompasses: (1) lunar sample science; (2) lunar materials applications; (3) lunar sample studies and their relation to future space missions; and (4) lunar sample curation. Plans in all four areas are summarized in this document.

1

LUNAR SAMPLE SCIENCE

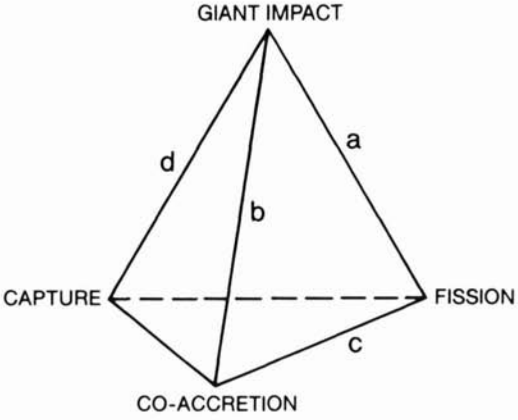
Much more scientific research will focus on lunar samples because many outstanding problems of lunar origin and evolution remain. Progress toward their solution will be made with new and improved techniques, new samples (e.g., previously unstudied or newly-sawn breccias, and the lunar meteorites of the Antarctic), new ideas, and integration with other lunar-related studies (e.g., remote-sensing, LGO). The recent emphasis on multidisciplinary, coordinated efforts has proven particularly rewarding and will continue to be effective. The proven means of exchanging ideas and stimulating studies by workshops, topical conferences, and the annual Lunar and Planetary Science Conference will continue to improve our understanding of the Moon and, by extrapolation, the rest of the solar system, including Earth.

OUTSTANDING LUNAR SCIENCE PROBLEMS

Origin of the Moon

Although the Moon's origin has not yet been determined, solid constraints have been placed on the problem. Several hypotheses are feasible, including coaccretion of the Moon and Earth, blasting off of material from Earth by a huge impact, and fission from the Earth. The capture hypothesis and its variants are largely discounted because of dynamical and chemical problems.

One of the most important constraints on the problem of lunar origin is the Moon's bulk chemical composition and how this compares with the composition of Earth's mantle as it was 4.5 b.y. ago. Important parameters include the Mg/(Mg + Fe) ratio and the abundances of refractory lithophile (e.g., U, rare earth elements),



ORIGIN OF THE MOON

This diagram depicts how the Moon might have formed. Besides the three traditional hypotheses—fission, co-accretion, and capture—a relatively new idea is that a single giant impact played an important role in the Moon's origin. The classical capture hypothesis pictures Earth's gravitational field capturing the Moon after it had formed elsewhere in the solar system. Although this has been ruled out on chemical and dynamical grounds, variants of it are possible. Co-accretion, or double-planet, models are plausible, though dynamical and chemical arguments have also been raised against them. The fission hypothesis requires that the Earth rotate fast enough to spin off a blob of material from which to form the Moon. The fission model's main flaw involves getting the fledgling Earth to spin at the rate needed, once every 2.5 hours. The giant-impact hypothesis solves many of the dynamical and chemical problems suffered by the other models. It depicts the Moon forming as a result of an oblique impact by an object the size of the planet Mars. Huge quantities of melted and vaporized projectile and Earth are propelled into orbit, forming a ring of material from which the Moon forms.

Although it is possible that one of these processes was responsible for the Moon's origin, it seems likely that two or more acted in consort. Some possibilities are indicated by the letters a through d:

(a) A large object might strike Earth in just the right way to cause Earth to spin much faster, causing the fission process to operate.

(b) A giant impact might put a substantial amount of material into orbit, but continued accretion of planetesimals by the Earth-Moon system would cause growth of both, thereby being a combination of the giant impact and co-accretion.

(c) Similarly, if the Moon fissioned by some mechanism other than a giant impact, continued accretion could still take place.

(d) Approach by a large planetesimal might not cause vast amounts of Earth to be blasted into orbit, yet might result in capture of considerable amounts of the projectile, a process that resembles traditional capture. Clearly, there are many other, more complicated stories, such as fission induced by a giant impact, followed by continued accretion. A great deal of research needs to be done to understand the dynamical and chemical consequences of a giant impact by itself and in combination with other models.

volatile (e.g., K, noble gases), and siderophile (e.g., Fe, Ni, Ir) elements. Lunar sample research has proven that the Moon is depleted in volatile and siderophile elements compared to Earth's mantle, but the precise extent of depletion and the values of other compositional parameters are not known well enough to test models for lunar origin. A great deal of information about the Moon's volatile content can be extracted from lunar samples. For example, volcanic glasses have concentrations of volatile elements, such as Zn, Cd, and S, and primitive Pb isotopes on their surfaces, and some individual glass beads have bubbles in them. Determining the nature of the gas in these bubbles might shed light on the mechanisms by which volatiles were lost from the Moon and on whether these gases came from deep in the Moon. This, in turn, could help evaluate which theory of lunar origin is most likely to be correct.

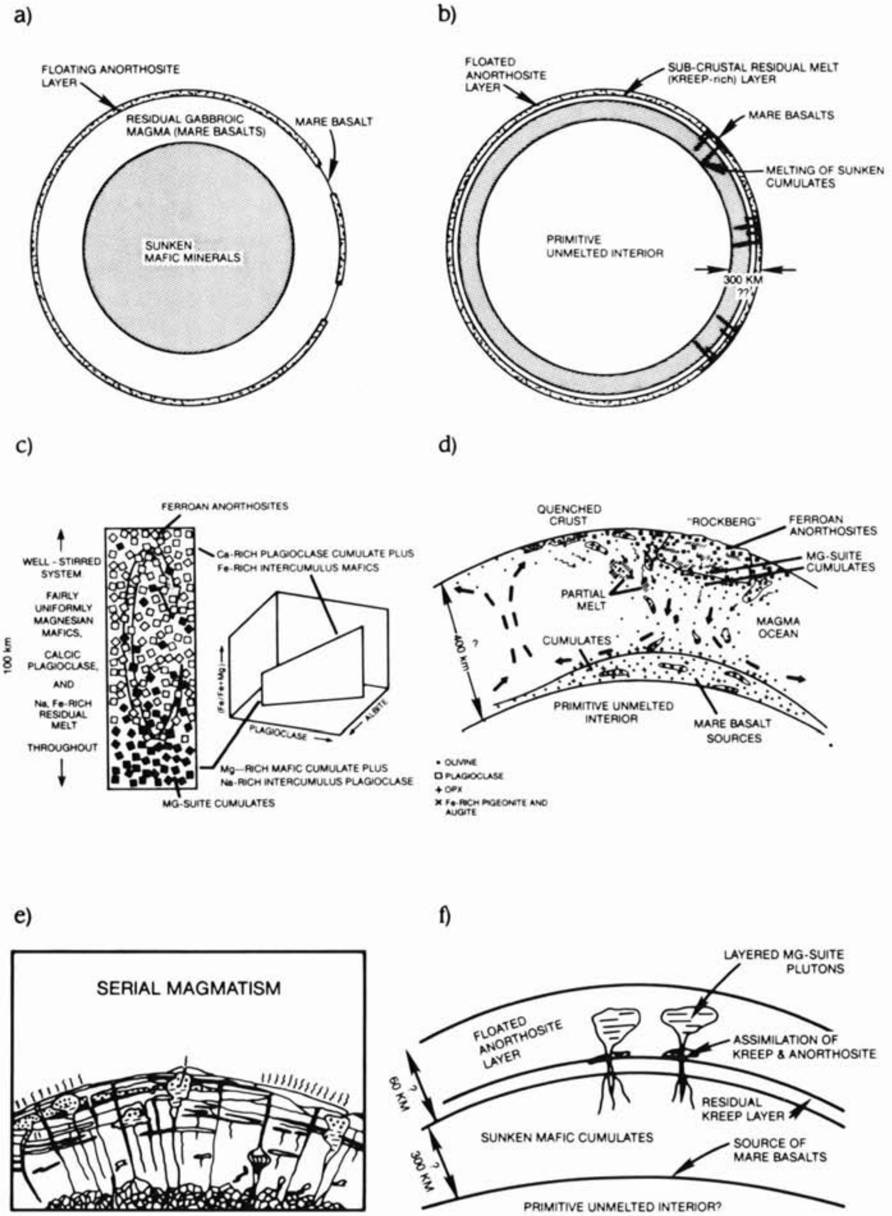
Determining the Moon's bulk composition is far more complicated than simply analyzing hundreds of lunar samples. It requires unraveling lunar evolution to understand how elements were partitioned into the Moon's crust, mantle, and core.

We must determine how many rock types are present on the Moon, how they formed, and how they relate to one another. In short, calculating the Moon's bulk chemical composition requires a thorough, quantitative understanding of lunar igneous evolution. Similarly, to compare the Moon's composition to that of Earth's mantle, we must know the composition of the mantle and how it has changed over geologic time. Research on the evolution and composition of Earth's mantle and crust is being pursued actively; this must be factored into any interpretation of lunar origin.

Crustal Formation and Early Evolution

The Moon is not a uniform body: even the first sample studies showed that within the first hundred million years, extensive melting resulted in the Moon's differentiation to produce a low-density crust 60 to 100 km thick, overlying a higher-density mantle. The simplest concept of this differentiation is of a globe-encircling "magma ocean" in which buoyant materials (plagioclase-rich) floated and dense materials crystallized at or sank to the bottom. However, some workers claim that such an ocean is not a requirement, and that large scale partial melting could have effectively produced the differentiation. Continued sample studies have shown that the lunar crust consists of a complex variety of igneous and brecciated rock types. New discoveries are continually being made as breccias are dissected and studied in detail and other small fragments are investigated. They show that the crust evolved (after the initial differentiation) by episodes of remelting, intrusion of magmas from mantle melting, extrusion of volcanic lavas, and continual and heavy meteorite bombardment for over 400 million years. Further petrographic, chemical, isotopic, and age studies of newly-revealed fragments, particularly those of igneous origin, are necessary to increase our understanding of the crust and the processes involved in its formation. One important determination that remains to be made is that of a precise crystallization age for ferroan anorthosites, which are likely to have crystallized in the earliest differentiation and are inferred to be the oldest of lunar rocks. Initial isotopic ratios for the same rocks are required to properly evaluate the bulk composition, formation, and earliest evolution of the Moon. Significant opportunities remain in acquiring ages and isotopic data for other igneous rocks, and in furthering our understanding of the significance of isotopic data on shocked rocks, which have disturbed isotopic systems. In addition, new petrographic observations and measurements will allow the inference of cooling rates and, hence, will give some idea of the relative depths of origin of even small samples, allowing a three-dimensional picture of the crust. An understanding of the igneous history of lunar crust is significant not only in its own right, but also for crustal genesis and magmatic processes in general, and is essential before we can accurately assess the bulk composition of the Moon. Deciphering the genesis of the crust is also requisite to understanding the heat sources that controlled the evolution of the Moon.

Few lunar highlands samples are primary igneous rocks; most are complex mixtures (breccias, impact melts, and soils). Certain loosely-defined compositions recur among samples from different landing sites: samples of a polymict norite ("low-K Fra Mauro" or LKFM) occur as breccias or glass components, and rocks with a low-K, magnesian, and feldspathic composition are common as granulitic breccias and glasses. No igneous examples of these are yet known, and they are assumed to be mixtures, many multigenerational, of older igneous rocks. However, modeling



Summary of evolution of the magma ocean concept. The figures show in generalized form a sequence of some ideas on the differentiation of the Moon. They are not a complete set, nor do they attempt to include thermal factors or varied ideas on the complexity of mare basalt sources. They generally follow the sequence from the recognition of a plagioclase-rich crust (a), the recognition of KREEP (b), the identification of Mg-rich plutonics in the crust and their sodic nature (c), the variety of Mg-suite rocks and the lack of a simple igneous trend between them and ferroan anorthosites (d and f), and the possibility that no ocean is required at all (e).

of their compositions as mixtures of known pristine igneous rocks on the Moon fails. The same problem is evident for the composition of highlands regolith samples. It is obvious that we have not yet identified as a primary igneous rock at least one of the important components of the lunar crust. The discovery and analysis of these components is an important goal of future sample dissection and study; even the continuing discovery of more extreme compositions of breccias is rewarding.

At present we cannot claim that we have a very complete understanding of the igneous history of the lunar crust. A far more complete understanding will result from continued sample investigation with petrographic, chemical, isotopic, and age analyses.

Production of Evolved Rocks

By terrestrial standards, "evolved" rocks (lithologies such as granite, diorite, etc.) are uncommon at the surface of the Moon. This difference probably reflects the Earth's greater intensity, longer duration, and different styles of differentiation (both chemical and physical). However, many of the lunar soils and polymict breccias appear to consist largely of a component ("KREEP") with high concentrations of the heat-producing elements Th, U, and K, as well as other incompatible elements such as REE and P. A few undiluted ("pristine") samples of the KREEP component exist as igneous-textured volcanics. Despite their high contents of incompatible elements, KREEP-rich rocks (including pristine ones) have moderate Fe/Mg ratios

---

(a) 1969 model, after J. A. Wood and others. Entire Moon is molten, mafic cumulates sink and plagioclase floats to give the highlands crust. Residual liquid is Fe, Ti-rich, has negative Eu anomaly, and escapes to produce mare basalts.

(b) 1970-1974, aggregate of several sources. Essential difference from Wood model is that the mare basalts form from remelting of sunken cumulates, thus reconciling the Eu anomaly of the basalts with their lack of saturation with plagioclase, and with the age relationships. Also, in this conceptual stage much less of the Moon was generally considered to undergo total melting, leaving a primitive unmelted interior.

(c) 1975 model, from Wood and others. With the realization that the crustal rocks were more complex, with high Fe, Ca anorthosites (ferroan anorthosites) and high Mg, Na norites and troctolites forming a chemical trend opposite from that observed in terrestrial layered intrusions ("Steele and Smith trend"), more complex petrogeneses were considered. The Wood model considered a well-stirred crustal magma in which a residual melt provided Fe-rich intercumulus mafics to plagioclase-rich materials and Na-rich intercumulus feldspar to mafic-rich materials. This model did not address mare basalt source origins.

(d) 1978 model, from J. Longhi and others. With the replacement of the simplified "Steele and Smith trend" with the realization that Mg-suite crustal rocks formed a "normal" trend but distinct from ferroan anorthosites, even more complex models were required. Longhi envisaged "rockbergs" with plagioclase-rich materials accumulating over down-flowing regions of a magma ocean, and Mg-suite rocks forming by complex assimilation and fractionation. This model derives both ferroan anorthosites and Mg-suite rocks from a single magma ocean.

(e) 1983 model, from D. Walker and others, who envisaged that the magma ocean was unnecessary and that the whole scheme could be produced by serial magmatism from partial melting of the lunar interior. The mare basalt Eu anomaly, considered as a prime driver for the magma ocean concept (by removal of plagioclase by flotation) was explained instead by complications in the fractionation of mare basalts with mixing of residual liquids (open system).

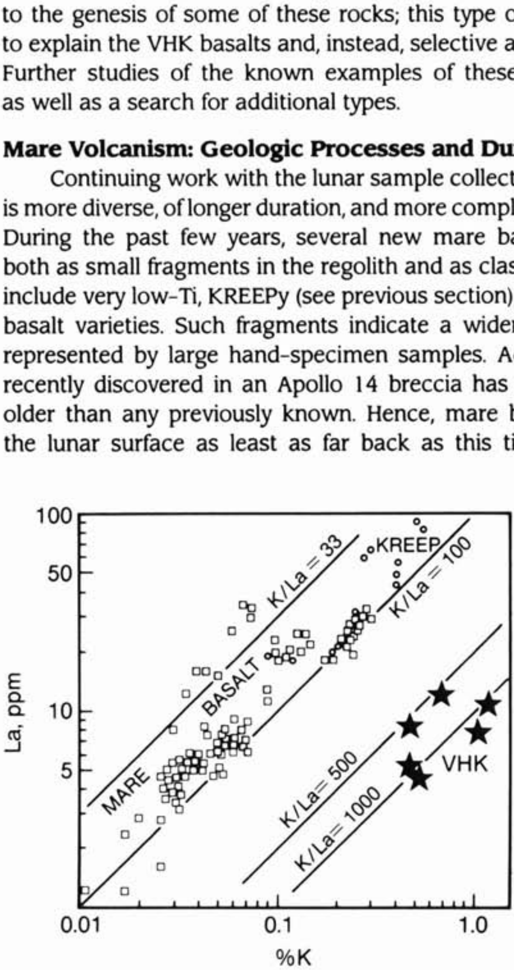
(f) 1980-1985, aggregate of several sources (e.g., P. H. Warren and J. Wasson; O. B. James). Many favor the magma ocean to produce the floating ferroan anorthosites and to have some role in the source of mare basalts. However, acknowledging the younger age of many Mg-suite rocks, the fact that they are not floatable, and their diversity has led to the suggestion that they are produced from partial melting in the interior, but have been affected by assimilation during ascent. The Mg-suite magmas form differentiated, layered intrusions within the ferroan anorthosite crust.

and Si contents. The Moon's early intense magmatic activity, its "magma ocean" epoch, must have resulted in pockets of extremely differentiated residual melt rich in incompatible elements. This material, which was probably later remelted and redistributed by volcanism and impacts, is presumably related to KREEP. According to some magma ocean hypotheses, the residual melt originally collected mainly at the base of the Moon's crust. The means, timing, and setting of the evolution of the residual melt into KREEP are important problems that can be addressed through further sample studies.

Recent sample studies, particularly those focused on lithic fragments from Apollo 14, have uncovered numerous "new" evolved lunar lithologies including pristine granites, a new type of Al-rich mare basalt with very high K concentrations (VHK basalt), and a series of anorthosites and troctolitic rocks with far higher KREEP contents than other lunar rocks of similar major element composition. Assimilation of KREEP-like residual melts by more primitive melts has been suggested as a key to the genesis of some of these rocks; this type of model does not seem adequate to explain the VHK basalts and, instead, selective assimilation is under consideration. Further studies of the known examples of these evolved rock types are needed, as well as a search for additional types.

Mare Volcanism: Geologic Processes and Duration

Continuing work with the lunar sample collection shows us that mare volcanism is more diverse, of longer duration, and more complex than we had previously thought. During the past few years, several new mare basalt types have been discovered both as small fragments in the regolith and as clasts within highland breccias. These include very low-Ti, KREEPy (see previous section), very high-K, and aluminous mare basalt varieties. Such fragments indicate a wider diversity of basalt types than is represented by large hand-specimen samples. Additionally, one mare basalt clast recently discovered in an Apollo 14 breccia has a crystallization age of 4.2 b.y.—older than any previously known. Hence, mare basalts were being extruded onto the lunar surface as least as far back as this time, during the period of intense



Very high potassium (VHK) basalts have far higher concentrations of alkalis (K, Rb, and Cs) than other lunar rocks with similar contents of typical incompatible elements such as lanthanum. One petrographic model suggests that VHK basalts formed when normal mare basalt magma partially assimilated granite.

bombardment. Direct sample studies are complemented by remote-sensing observations of the lunar highlands, which indicate that an abundant, mare basalt-like component might be admixed into large regions of the terra crust. Both discoveries suggest extensive mare volcanic activity on the early Moon. Future study of small basalt fragments from the highlands holds the potential for discovery of more varieties of old mare basalts to clarify early volcanic processes and lunar thermal history.

The youngest mare basalt episodes require further clarification from studies of the lunar sample collection. Stratigraphic and crater density studies of mare units have shown that there are regional basalt deposits that embay rayed craters and have very low crater density; both of these observations suggest emplacement ages that are much later than the ages of sampled mare basalt types thus far identified and dated. Some of these mare units occur near the Apollo 12, 14, and 15 landing sites; detailed examination of coarse-fines (i.e., samples 1-10 mm in size) from these sites should be performed to recognize exotic basalt samples thrown there by impacts onto very young basalt units. Remote-sensing data for these young mare units will guide us in this search by providing gross compositional information (e.g., high Ti, KREEP-rich) that will aid in the identification of exotic basalts. If such samples could be identified, we would be able to characterize these basalts petrologically and chemically, and could possibly obtain radiometric dates for unvisited lunar mare regions. New data on young mare flows would not only give us an improved and more detailed understanding of lunar geologic history, but would also provide new constraints on thermal history and evolution.

A given mare basalt suite comprises individual samples of varied composition that are related by surface fractionation. To identify the magma that was actually erupted requires understanding the fractionation process and any assimilation effects. While the former is at least generally understood for those basalt suites containing many samples, it is poorly understood for those with single or few individuals, yet the erupted magma is the one that recorded the conditions of partial melt, ascent, and eruption processes for lavas on the Moon. Cooling rates, and hence some estimation of lava flow thicknesses, have been partly derived quantitatively for only a few specific suites, and could profitably be addressed for the others. An investigation of chilled margins and heterogenous textures, observed in a few samples, and of the small metabasalt fragments that were apparently produced by one lava and reheated by another, would also provide information on flow processes. Assimilation has been demonstrated recently for some basalts, and its effects for all mare basalt suites needs to be investigated. Such studies will lead to a reassessment of the significance of the isotopic and trace element data for mare basalts—data that have been used to infer source regions. Some magmas ascended and erupted from great depths with very little, if any, crystal fractionation (e.g., volcanic glasses), whereas others underwent extensive fractionation. The reason for these differences has not been investigated. The problem requires assessment of samples not yet analyzed in order to determine whether some volcanic glasses have fractionated flow derivatives, and whether the fractionated flows were actually erupted as such or have fractionated on the surface.

Geologists are interested not only in the history and compositional diversity of lunar maria, but also in the processes of magma generation, transport, and eruption styles. Both erupted lava flows and pyroclastic deposits are represented in the sample collection. New work, both theoretical and observational, could aid us in understanding how lunar magmas are formed and extruded. We still do not know what volatile phases are responsible for lunar magma vesiculation. Additional work on volatile coatings and trapped bubbles in pyroclastic glass will provide increased understanding of gas involvement in eruptive processes. In conjunction with geologic and geophysical data, studies of lunar volcanic products (both lavas and pyroclastics) could lead to an improved knowledge of eruptive feeder dikes and vents. A few mare basalts contain xenoliths, composed of both cumulate rocks from depth and wall rocks broken off during magma transport. Such samples would be of great value in reconstructing eruptive conditions during mare basalt emplacement. Pyroclastic samples can be used to calibrate remote-sensing data and to reveal the extent of early lunar pyroclastic activity, the heights of the eruptive column, and the stratigraphic relationships between pyroclastic deposits and mare basalts or major impacts.

Mare Volcanism: Mantle Implications

An important reason to study mare volcanism is to assess mantle source compositions, depths, and melting processes. We do not fully understand how some of the inferred characteristics (e.g., Eu anomalies at depths of 400 km) can be reconciled with the early differentiation, nor do we have much knowledge about the effects of fractional crystallization, assimilation, and contamination processes on the measured chemical compositions and isotopic systems of the basalts. (This problem is also common to studies of terrestrial basalts.) Progress can be made with additional sample studies. For example, continued searching among coarse fines (1-10 mm in size) and in breccias will almost certainly lead to the discovery of additional types of mare basalts. This has been demonstrated by recent studies of Apollo 14 breccias; mare basalts with exceptionally high K_2O contents (~5 wt%) and others with exceptionally old ages (~4.2 b.y.) have been described. Discoveries such as these fill gaps in our knowledge of lunar basalts and, hence, of the lunar mantle and of lunar igneous processes.

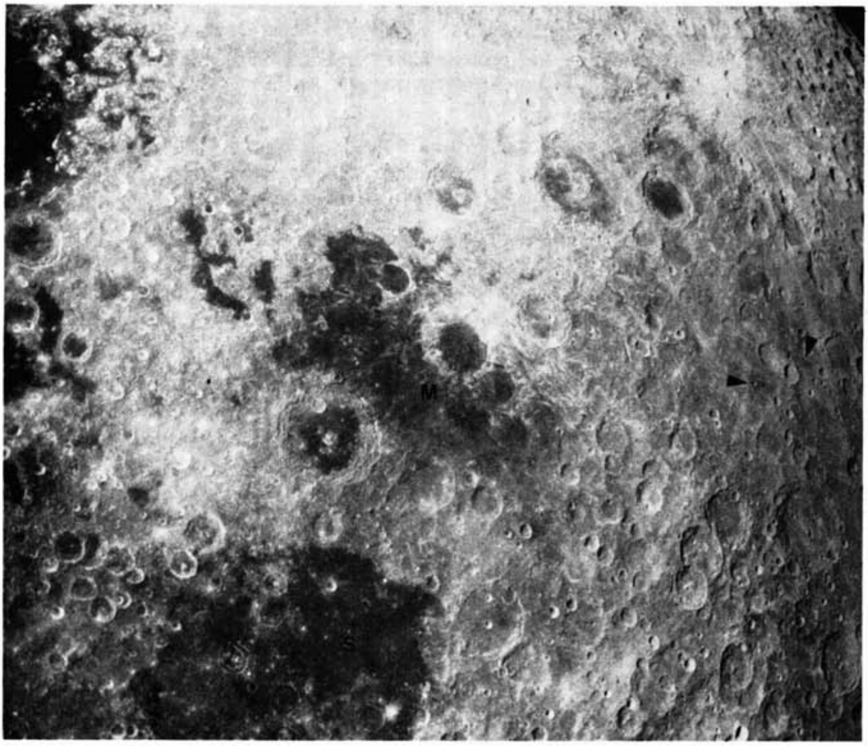
Individual lava flows are not uniform in composition because crystals sink or float as the flow crystallizes. It is important, therefore, to obtain samples that have compositions closest to that of the lava before it began to crystallize. In general, such samples are the finest-grained ones in a given flow, though in practice many samples must be analyzed and an assessment made as to which are the most likely to be representative of the parent magma. Such assessments have been made for suites of basalts from mare landing sites, but more data are needed for suites from other localities, e.g., Apollo 14.

Lunar volcanic glasses do not suffer from problems associated with solidification of lava flows. Furthermore, they are more primitive and have evidently experienced much less fractional crystallization at depth in the Moon than have mare basalts. Consequently, these samples contain a more direct record of the nature of the lunar mantle. Much additional work needs to be done to determine the full range in compositions of lunar volcanic glasses. Age data must also be obtained to establish the variations in glass composition with time.

Learning more about the origin of mare basalts will lead to a much improved understanding of the initial lunar differentiation into crust and mantle. It will help determine the extent to which the Moon was melted when it formed, an important constraint on models for lunar origin. Finally, obtaining a more complete understanding of mare basalt genesis will increase our knowledge of planetary volcanism in general.

Regional and Vertical Variations in Geology

To date we have samples from nine specific locations on the lunar surface (six Apollo sites and three Luna sites), all of which are from a restricted region of the lunar nearside. In addition, we have identified four Antarctic meteorites from unknown regions of the Moon. It is hard to imagine interpreting the regional and vertical variations in Earth's crust from so few locations. However, the Moon is a more primitive body whose major differentiation was complete before 4.2 b.y. ago, and emplacement of regional lava flows had slowed dramatically by 3.0 b.y. ago. The Apollo samples show both global consistency in that similar rock types



Oblique view of the Mare Marginis (M) - Mare Smythii (S) region of the Moon. The highlands light plains at right display dark-halo impact craters (arrows). Photogeologic study suggested that these craters have excavated a mafic, low-albedo substrate from beneath the highland plains; these deposits were interpreted as mare basalts emplaced prior to the end of heavy bombardment on the Moon (~3.9 b.y. ago). Subsequent spectral data for these features confirmed the basaltic nature of the dark-halo crater ejecta. This evidence, in conjunction with the discovery of ancient mare basalts in highland breccias, suggests that mare volcanism began on the Moon much earlier than previously thought. The bright-rayed crater at the top is Giordano Bruno, which some have suggested as the source crater for lunar meteorite ALHA 81005.

occur at most sites, and regional diversity in that the proportions and compositions of rock types vary from site to site. Local differences in composition at an Apollo site as a function of geologic features have been evaluated, and relationships to major mare and highland features and to individual craters have been suggested. However, larger scale variations are observed from site to site. The significance of these large scale variations will be understood when we can examine variations on a global scale. Orbital geochemical data have provided maps of elemental compositions of a limited equatorial region of the Moon. These maps show that the highlands are heterogeneous and complex. Among highlands sites, the Apollo 16 and Luna 20 samples have anorthositic norite bulk compositions, while the Apollo 14, 15, and 17 samples are noritic. The samples are enriched to varying degrees in KREEP. The lunar meteorites, from an unknown location, contain negligible KREEP and have intermediate anorthositic norite bulk composition.

Mare basalts are also distributed in a heterogeneous manner. Major differences occur in ages and in the amount of Ti (as the mineral ilmenite). The basalts from Apollo 12, 15, and Luna 24 are poor in Ti, while those from Apollo 11 and 17 are rich in Ti. But remote-sensing data such as Earth-based spectroscopy indicate the presence of high- and intermediate-Ti basalts in the west that have not yet been identified among samples.

Studies of lunar cores provide information on local vertical variations in compositions and rock types. This stratigraphic variation shows the evolution of the regolith with time. For example, mare basalt-containing layers were found at depth in the Apollo 16 cores, while such samples are rare at the surface.

Stratigraphic information on a regional scale may be obtained by relating lunar samples to their geologic context. As an example, the interpretation of a basin-produced impact melt sheet at the Apollo 17 landing site allows us to reconstruct the petrology and chemical composition of part of the crustal target of the Serenitatis basin. Similarly, samples collected from the rims of craters during the Apollo missions provide direct information on the nature of subregolith rock units in the vicinity of the landing sites.

Lunar sample studies can provide additional insight into the diversity of lunar samples and on the evolution of the regolith. It is also desirable to have better data on regions distant from the landing sites. Of particular interest are materials that appear to be exotic to a site, such as mare basalts in Apollo 16 soils or highlands samples at Apollo 11. The lunar meteorites are providing some information and will continue to enhance our knowledge, but they are extremely rare and their source locations are unknown. The Lunar Geoscience Observer (LGO) will produce global maps of chemical and mineralogic compositions that can lead to a global synthesis and a better understanding of the significance of returned samples.

Lunar Regolith

We have learned much about the characteristics of the lunar regolith from the samples returned during the Apollo program, but several important questions remain unanswered. Most importantly, we need to address in detail the question of whether the lunar regolith has changed over geologic time and how such changes, if found, reflect changes in the solar system environment or in lunar geologic conditions.

Much of the returned regolith in the Apollo collection consists of soil samples from near surface regions, which could still be considered active in terms of micrometeorite reworking, solar wind interactions, etc. These samples could therefore be termed "recent" regolith samples. In contrast, a few returned samples were not collected from the currently active zone, but were instead collected from quiescent regions not presently affected by micrometeorites or solar wind. These samples could potentially record conditions in space (micrometeorite environment), conditions on the sun (solar wind and flare composition and relative intensities), and conditions on the Moon (volcanic or internal activity, cometary impacts, reimplanted transient atmospheres, etc.). Regolith samples of this type exist in cores, with the oldest material located at the bottom of the deep drill cores. Ancient samples are also found in trenches (orange glass, soil 61221, etc.), and soil from beneath boulders may qualify as semi-ancient regolith. Finally, soil "sealed" into lunar regolith breccias may be the most ancient of all regolith samples in our collection.

Regolith samples currently exposed at the lunar surface are generally rich in agglutinates, solar wind constituents, and other indices of maturity, while soils from the bottom of cores and from trenches often have lower maturity. Differences in grain size properties between these regolith types seem to exist. Many regolith breccias from Apollo 15 and 16 are of much lower maturity than the typical soils at these sites. This lower maturity could reflect a relatively lower micrometeorite flux in past times, or a relatively larger flux of big meteorites that caused a greater turnover and burial rate, thus preventing the buildup of surface maturity indices. Some lunar breccias contain rare gas ratios that differ significantly from current soil values; it is uncertain whether this reflects a difference in solar composition or a difference in indigenous lunar gas abundances.

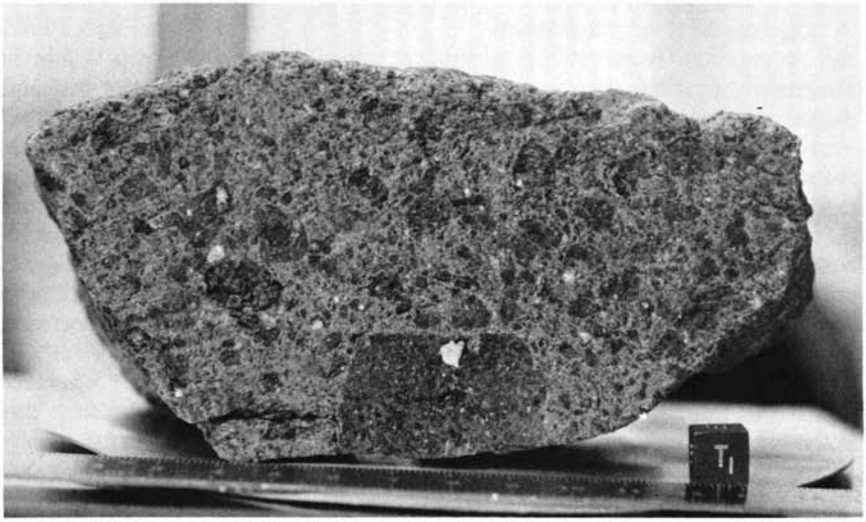
An important reason for further study of lunar regolith samples is to determine the record of cosmic dust, comets, and asteroids that is preserved in the lunar regolith. For example, soil 61221 has been called a cometary soil, but we do not know if in fact it reflects a cometary impact. We need to analyze soils for a gas record that might be related to a cometary projectile. In addition, some soils may carry a record that relates them to specific large asteroid impacts. For example, it is possible that if a large iron projectile impacted, remains of the iron would be trapped in the regolith and preserved. In addition analysis of ancient regolith samples could possibly tell us much about lunar geologic history. These samples must be studied to determine whether ancient regoliths contain rock types or glasses that are not common in recent regolith samples.

Finally, lunar regolith samples must be compared to meteorite regolith samples in order to learn whether they tell the same story of solar activity, whether they both contain records of micrometeorite impacts, and whether they contain similar volatile gas contents. Comparisons of ancient lunar regolith and meteorite regolith samples could allow us to deduce the properties of the parent bodies of meteorite regolith samples.

Cratering Mechanics and History

All lunar samples have been affected by impact. We have reached our current understanding of impact processes through a variety of approaches, including experiments, theoretical calculations, and investigations of terrestrial and lunar impact craters. It is clear from these studies that much remains to be learned about the impact process at all scales. Little is known about the origin, composition, and initial conditions of the early lunar crater and basin projectiles. Continued work on lunar impact melts is required to understand the chemical properties of these projectiles. Formation of impact melts, shock zoning, partition of energy, and comminution of ejecta are all topics that have been studied theoretically and experimentally. The lunar samples contain records of these processes, if the samples can be related to a geologic context. The problem may also be inverted: presuming we understand the process of impact melting, what do lunar impact melts tell us about their original igneous precursors in the lunar crust? In particular, geochemical modeling of low-K Fra Mauro basalt, a lunar impact melt of noritic bulk chemistry, cannot be successfully reproduced by mixtures of known lunar pristine rock types.

The impact history recorded by the lunar samples has enabled us not only to decipher the geologic history of the Moon, but also to model the history of unsampled planets (e.g., Mars) by extrapolation. Continued work may enable us to find lunar rocks with ages outside the currently accepted bounds of lunar activity. Such samples would give us more information on the cratering history of the Moon, which at present is incompletely understood. For example, was the early lunar cratering rate steadily declining with time, or was a terminal "cataclysm" responsible for the formation of most basins? Continued work on dating samples with a basin origin may allow us to either resolve which of these ideas is most likely, or, more probably, may indicate that some more complex history was responsible. Such questions are



This is a "mug shot" of 14305. This lunar breccia is one of the two "FSR" (football-size rocks) collected during the first EVA about 1150 m southwest of Cone Crater. It has been the subject of extensive "pull-apart" activities. The numerous clasts in such breccias provide "new" samples for study. This rock has been an especially productive one, yielding clasts that include the oldest dated mare basalt (4.23 aeons) and several new rock types, most notably very high potassium (VHK) basalt. Such studies of breccias, although quite work intensive, are currently in progress and hold promise for significant new discoveries.

directly relevant to the geologic history of all planetary bodies for which relative ages of stratigraphic units are determined by crater counting.

OUTLOOK FOR LUNAR SAMPLE STUDIES

The supply of lunar material returned by the Apollo missions is still remarkably intact after 15 years of intense study. There is every reason to expect that continued study of the samples will produce new and interesting results and that progress on many of the outstanding problems can be realized from sample study.

Because of the complex nature of most lunar rocks and regolith, the samples require more exhaustive study than would be made on a similar mass or volume of terrestrial material. Except for the mare basalts and some rare highland rocks, the lunar rocks and soils are all polymict: any hand-specimen breccia contains fragments of many rocks, including other breccias. Thorough study of all the rock types present in a single lunar breccia sample can be as work-intensive as the study of an entire terrestrial stratigraphic section or igneous complex. Thus, there remains much work to be done in the study of lunar breccias. Although most large breccia samples have been studied in survey mode, only a few have been the subjects of thorough, multidisciplinary studies. None has been totally disaggregated and consumed. Every new saw cut through a breccia exposes clasts. Nearly every breccia sample that has been rigorously studied has yielded clasts of rock types that are different or outside the compositional range of previously known rock types. The study of lunar breccias as a means of understanding some fundamental lunar processes is far from complete.

Thousands of 2-4 mm rocklets were sieved from the regolith samples, but only a small fraction has been studied. The 2-4 mm sample collection is likely to contain fragments of rocks exotic to the immediate sampling site. It may also provide the best estimate of the distribution and variety of rock types contributing to the <1 mm fines. Although these rocklets weigh only 10-50 mg each, they are similar in size to the quantity of material actually analyzed in breccia matrix and clast studies and, hence, are equally valuable. Various "high-grading" (i.e., selective sampling) expeditions have been conducted; however, a careful cataloging survey is necessary to fully realize the potential of these samples.

Many lunar cores have not yet been opened, and most of those that have were never systematically studied by more than one or two techniques. The last core to be opened, 64001/2 in 1981, was collected nine years earlier at Apollo 16. It probably contains the best samples of Descartes material. However, it was also found to contain totally unexpected layers enriched in material of mare origin. Other new discoveries are likely to be made when the cores are opened and when more detailed studies of the presently opened cores are completed.

Recently, four meteorites that are of lunar origin have been found in Antarctica, and more may be discovered during future expeditions. In addition, the U.S. might be able to obtain more material from the three Soviet Luna missions; moreover, the distinct possibility of future Soviet missions to the Moon could provide us with new samples. Even though these two sources have only yielded small amounts of material, their value is far greater than their mass because they provide samples from areas of the Moon not approached by Apollo missions.

There are continuing opportunities for fruitful research in several areas of analysis. Specific needs include greater access to geochronological analysis capability and sophisticated beam analysis techniques. As lunar sample research progresses, uncovering new, significant information requires intensive examination and analysis of increasingly large amounts of materials. Increased competition for sophisticated analytical techniques has made them less and less available for lunar studies. (It is ironic that it was the requirements of lunar sample analysis that brought great improvements in analytical capabilities, and these same capabilities are now only sparingly available to lunar studies.) There is a general need for Ar-Ar dating of small samples, especially for glasses that cannot be analyzed using isochron techniques. A major advance in dating of U-Th-bearing zircons was recently made by using ion beam instrumentation. Progress in determination of distribution coefficients for trace elements among phases opened opportunities for analysis of coexisting phases by ion microprobe techniques, but the availability of ion probe instrument time is severely restricted in U.S. laboratories. There are opportunities for discoveries in lunar science in the areas of geochronology and ion beam techniques. Funding should be made available to make appropriate facilities more readily available to lunar researchers who have identified problems that could be resolved by these techniques.

There is much to be discovered in the existing Apollo samples. Even some previously well-studied Apollo samples have already become, effectively, "new" samples in light of new ideas, theories, emphasis, and techniques that apply new state-of-the-art equipment.

NEW INSTRUMENTS

Technological advances have led to the development of new types of analytical instruments and to improved sensitivities of existing ones. Each improvement results in additional research on lunar samples because investigators can make analyses not previously possible. Development of the Lu-Hf dating method at the U.S. Geological Survey in Denver is an example of how improved sensitivity of an established technique led to a new type of analysis. The principles of Lu-Hf dating were known for years, but could not be applied until mass spectrometers became capable of measuring minuscule amounts of Lu and Hf. Once it became possible to do the analyses, investigators requested lunar samples.

The improved resolution of the ion microprobe at Australian National University allowed dating of individual zircon crystals in lunar highland rocks. Zircon is resistant to thermal alteration and, consequently, retains a record of its igneous origin rather than of younger metamorphic events. This work yields valuable new insights into the early evolution of the lunar crust.

A project is being funded jointly by the National Science Foundation (NSF) and NASA to develop a high-flux X-ray probe at Brookhaven National Laboratory. The system will be used to measure the distribution of trace elements on a microscopic scale by collimating the intense X-ray beam from the Brookhaven synchrotron and measuring X-rays fluoresced in the sample. Once this facility is in routine operation (by the end of 1986), we can expect many new analyses to be made on individual mineral phases in lunar samples.

As data are acquired from new and improved instruments, it frequently becomes apparent that our basic understanding of geochemistry and mineral behavior lags behind. Laboratory experiments to measure the geochemical behavior of appropriate elements are performed. Appropriate analog studies are essential. With this new quantitative information, data will be reinterpreted, an exercise that usually leads to new questions and to more refined analyses of samples. Each iterative process takes a few years to complete. The result is always a better appreciation for the complexities of lunar history.

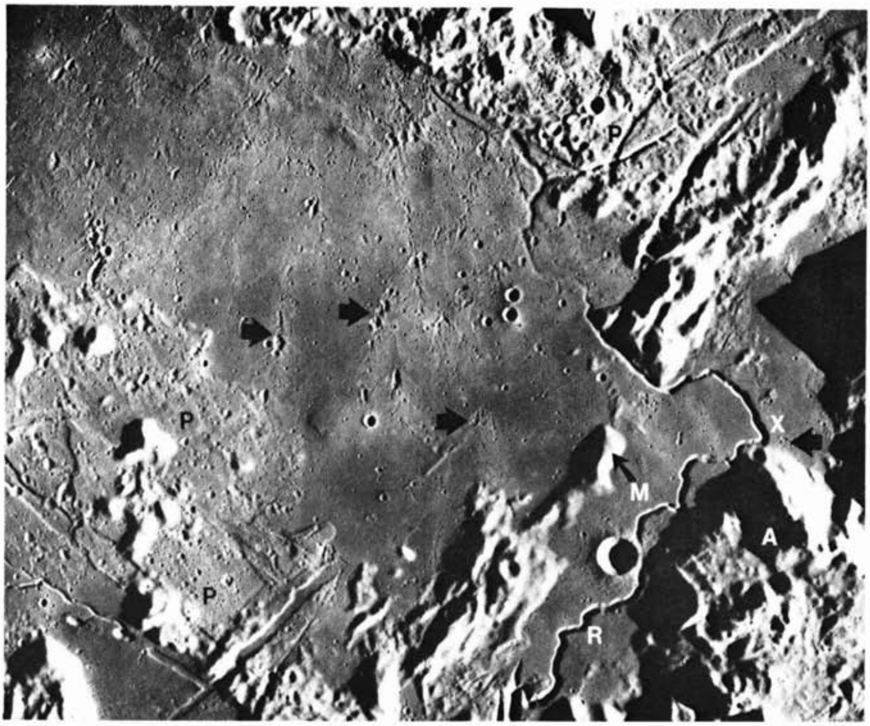
WORKSHOPS

Through the Lunar and Planetary Institute, LAPST has sponsored several workshops in recent years that have been successful in focusing attention on unsolved problems and in stimulating research on lunar samples. We plan to organize in the near future at least four workshops, each concentrating on a specific problem area that would benefit greatly from more attention. These problem areas are the Apollo 15 landing site, the genesis of mare basalts, the controversy surrounding the magma ocean concept, and the origin of KREEP.

Apollo 15 Workshop

The geology of the Apollo 15 site remains poorly known, in contrast to our understanding of the geology and samples of the Apollo 16 and 17 landing sites. The Apollo 15 landing site is situated on the rim of the Imbrium basin, a feature that represents a paramount event in lunar geologic history. Within the Apollo 15 samples and site photographs is recorded a variety of lunar processes and historical events, many of which are only dimly perceived at present. The petrology and stratigraphy of the Apollo 15 site are directly relevant to the composition, formation, and origin of the lunar crust, to the mechanics and ejecta depositional processes of large basin and crater impacts, and to mare volcanic processes.

The Apollo 15 site encompasses a remarkably complete stratigraphic section, ranging from pre-Imbrian to Copernican, which is unique among the Apollo sites. One of the major outstanding problems is the petrology of the Apennine Front (pre-Imbrian/Imbrian section). We have not yet established exactly how much of the material sampled at the Front is from the highlands, nor have we determined its characteristics. We also do not know its range of composition or its average. One reason for this is that few large samples of highlands rocks exist among the samples, and small samples (including coarse-fines from the regoliths) were largely ignored in the Apollo mission days, partly because of time constraints. The regolith throughout the site contains highlands components, mostly in a cryptic form. Up to the present time, petrographic population studies and synthesis of chemistry (mixing models, etc.) have not been properly directed at defining the nature of the highlands materials. If the terra components can be isolated and identified, we can go forward to decipher the events and processes that formed them. The common pre-mission interpretation of the Apennine Front implied an Imbrium and Serenitatis basin origin for massif material. The sample suite has not yet been investigated adequately or synthesized to assess the validity of this interpretation, or to determine whether other sources also provided Front material. There is direct evidence for some deeply-derived, lower



The Apollo 15 landing site and environs. The site (X) lies on a small inlet of Upper Imbrium age mare basalt that embays the Apennine Mountains (A), which form the main ring and ejecta deposits of the Imbrium basin. Light plains (P) are the Apennine Bench Formation; the composition of this regional unit, determined by remote-sensing, corresponds to pristine, Apollo 15 KREEP basalts, and the unit has been interpreted as post-basin volcanic KREEP lava flows. Dark-mantled deposits (M) discontinuously cover portions of the highlands; these deposits may be the ultimate source of volcanic pyroclastic glasses collected at the Apollo 15 landing site. Numerous secondary crater clusters and chains (big arrows) are superposed on the mare and were formed by ejecta from the Aristillus and Autolycus impacts; these impacts of debris may have supplied exotic debris to the site. Hadley Rille (R) is one of the largest lunar sinuous rilles; current interpretations suggest this feature is a lava channel or tube that was the conduit that supplied mare lava in this region.

crustal or perhaps even upper-mantle samples in the collection, but their context has not been adequately discussed. Finally, basin-related rocks and ejecta, once properly identified and studied, can tell us much about multi-ring basin formation.

More detailed study of Apollo 15 KREEP basalt samples, again all rather small samples (the largest is 7 g), can also shed light on the development of KREEP (at Apollo 15, lower Imbrian—3.85 b.y. old). The Apollo 15 KREEP basalts are rare among lunar KREEP samples (being "pristine" igneous rocks), but their geologic context may be known better than that of other Apollo KREEPy rocks. Only poorly deciphered as yet are their stratigraphy relative to other highland units, their variability in composition, petrology, and age, and their ultimate origin. Some workers remain unconvinced of their origin as volcanic flows, suggesting instead that they are impact melts.

Mare volcanic processes (upper Imbrian and lower Eratosthenian) may be profitably studied from the perspective of Apollo 15. Particularly interesting (and enigmatic) are the pyroclastic glasses. Green glass occurs as clods, some of which are rather pure and likely to represent original deposits, yet the stratigraphy of green glass (both internally and relative to other units), the nature of their eruptional mechanisms and depositional processes, and their ultimate origin are still poorly understood. Several different types of green glass with slightly (but significantly) different chemistries exist, but it is not yet known whether they were deposited sequentially or simultaneously. It has not been established whether a single near-pure clod of green glass contains one or more than one group; the relevant analytical work has not been performed. Other pyroclastic glasses, yellow and red, are disseminated around the site and are also poorly understood. Relationships among glass groups and other geologic units have not been deciphered because of a lack of data on trace element chemistry, ages and radiogenic isotopic ratios, and stratigraphic context.

It might be thought that the mare basalts at the Apollo 15 site are reasonably well understood, but there are clear gaps in our understanding of the mare volcanic episodes at this site. For example, the two chemically distinct groups of mare basalts have the same age and radiogenic isotopic systematics, and similar trace element patterns. The proper interpretation of this puzzling feature, which has never been adequately addressed, might tell us about the composition and evolution of the lunar mantle beneath the Imbrium basin and about the petrogenesis of mare basalts in general. Several geochemists have suggested on the basis of small chemical differences that the two main mare basalt groups have sub-groups, but more analyses are required for verification. If the sub-groups do exist, we need to address how they originated, and whether mantle processes or crustal assimilations influenced their chemistry. The formation of Hadley Rille might have included assimilation if it incorporated downcutting of some type. The inventory of basaltic types at Apollo 15 has not necessarily been completed, because some small samples have not been adequately characterized. Precisely what mechanism is responsible for the formation of Hadley Rille and other lunar sinuous rilles? Can the features seen in the walls of Hadley Rille be adequately correlated with the known characteristics of the mare basalts, for instance, the thickness of flows as determined from samples? What magma type created Hadley Rille? What is the significance of the supposed "high lava mark" around the base of the massifs at the site? Is an episode of lava ponding recorded within the mare basalt samples? What is the significance of the topographic ridge upon which the LM site lies; is it somehow related to the high KREEP abundance at the LM site?

Post-mare (~3 b.y. old) regolith development is particularly appropriate for examination at the Apollo 15 landing site. Regolith at the lip of Hadley Rille is very thin, and this is the only site on the Moon where bedrock blocks have been sampled almost *in situ*. The Apollo 15 site is an ideal location to assess regolith development at mare/highland contacts and the relative importance of vertical versus lateral mixing of regolith materials.

Finally, a number of "recent" lunar events (upper Eratosthenian/Copernican) may be studied at the Apollo 15 site. Specific ray materials can possibly be identified among samples, if adequate criteria can be developed. Do exotic rocks (e.g., 15405) record major impact events, perhaps related to Aristillus or Autolycus? If ray deposits within core and drill sections are identifiable, perhaps we can use this information to decipher the mechanisms of ray deposition. The geology of the South Cluster has the potential to tell us about the formation of large secondary craters.

Apollo 15 is an important lunar site where a remarkably complete lunar stratigraphic section may be studied. Aspects of all major lunar processes may be profitably studied from this single location. A workshop on the geology of the Apollo 15 site will be held in November, 1985 and should stimulate the kind of high-quality work that the Apollo 16 Workshop induced in the past. With it, an improved understanding of lunar geologic processes and history will be achieved.

Workshop (or Conference?) on the Planetary Magma Ocean Controversy

The concept of a primordial lunar magma ocean was first proposed at the Apollo 11 Lunar Science Conference in 1969. Since then, our knowledge of lunar petrology and geophysics has increased enormously. Indeed, the petrologic complexities of the impact-battered highlands crust are still being assessed through active sample research. Although doubts continue to be voiced, the magma ocean hypothesis remains the most popular interpretation of the primary lunar differentiation. Many researchers have suggested that the Earth must have experienced a similar episode of massive primordial melting. Most geophysicists agree that any heat source capable of producing a magma ocean on a small body such as the Moon would have a similar effect on a larger body such as the Earth.

If the magma ocean hypothesis is even approximately correct, it would have major geoscientific implications, and a workshop where effective "brainstorming" and synthesis can occur is appropriate. Some of the questions the workshop will address are the following:

What were the sources of primordial heat? What were their relative strengths on the Moon and the Earth (and other planets)? What are the phase-equilibria constraints that pertain to the magma ocean controversy? For example, many researchers have recently argued that at pressures corresponding to about 300 km depth in the Earth, silicate partial melts have negative buoyancy relative to residual solids; does this (relative) density inversion occur at a depth shallow enough to be a factor in the evolution of a terrestrial magma ocean?

What was the origin of the Moon's crust? What was the nature of the early differentiation of the Moon's mantle? How can the magma ocean be reconciled with the plethora of compositions of highland materials? How did primordial differentiation affect the origin of mare and/or KREEP basalts? Was primordial differentiation ever a partial influence on the Moon's volatile element depletion?

Was there a terrestrial magma ocean and, if so, what was its role in Earth's history? Did primordial heating influence core formation? Did primordial differentiation produce layering in the mantle? When and how did the first buoyant, "continental" lithosphere form? Did primordial differentiation have long-term aftereffects (roughly analogous to the Moon's mare volcanism)? Did primordial differentiation lead to transient and/or permanent depletions of volatile elements from the mantle? What was the first atmosphere like and how did it originate?

The workshop participants will include geochemists, petrologists, and geophysicists, and will encompass both researchers concerned primarily with the

Earth and specialists in lunar science. This multidisciplinary meeting, which will coordinate well with the goals of the Early Crustal Genesis project, will engender new collaborations and many important new ideas about the primordial heating of terrestrial planets.

Workshop on the Origin and Evolution of Mare Basalts

Mare basalts provide vital information about the lunar interior, the Moon's thermal history, and its initial differentiation. Mare basalts received considerable attention in a mission-oriented mode during the first several years of the lunar program. Since then, however, measurement techniques have been dramatically refined, but studies on mare basalts have been given lower priority during the past several years. Nonetheless, spurred by research on lunar volcanic glasses and ancient mare basalts in Apollo 14 breccias, and by improved understanding of terrestrial basalt generation, interest in lunar volcanic rocks is increasing considerably. To help focus this rekindled interest, LAPST will organize a workshop that will concentrate on problems of mare basalt origin. The workshop will probably be held before the end of 1986. Some of the questions this workshop will address are the following:

What were the mare basalt source regions in the lunar mantle like? When and how did they form? Were any undifferentiated? How deep were they? How do they vary laterally and vertically?

What happened to basalt magmas after they left their source rocks in the mantle? Did they react with surrounding rocks as they oozed toward the surface or flowed across it? Did they begin to crystallize on the way to the surface? Did magmas mix before erupting? After erupting?

When did mare-type volcanism begin? When did it end? How much took place before 3.9 b.y. ago and is mostly detectable only as a chemical component in highland breccias and soils? Can we constrain the youngest recognizable volcanism? What does the duration of mare volcanism imply about the Moon's thermal history?

Are lunar "volcanic" glasses all really volcanic, or are some of them impact melts? Are there any crystalline equivalents? How do basalt compositional types relate to glass compositional types? What is the source of volatiles on their surfaces? How do the volatile components of crystalline basalt samples compare with those of glasses? Why did the pyroclastic glasses erupt in a manner different from the basalts?

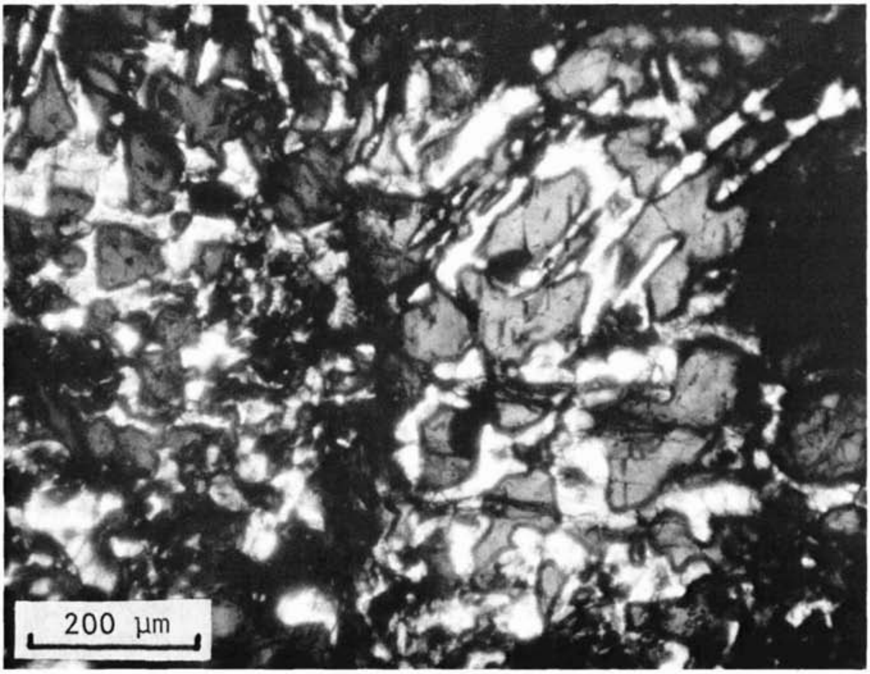
What can we learn about unsampled types of mare basalts from remote-sensing or from additional sample studies (e.g., breccias, coarse fines)? How did basalts and pyroclastics erupt? Where are the vents? How do rilles form? Why are there so few calderas? What volcanic landforms are there?

The workshop participants will include experts in petrology, geochemistry, chronology, remote-sensing, photogeology, and geophysics. LAPST expects the workshop and preparations for it to generate new sample requests.

Workshop on Apollo 14 and KREEP

The crust in the area of the Apollo 14 landing site is extraordinarily "evolved" by lunar standards. Concentrations of thorium and uranium in Apollo 14 soil samples are roughly 15 times greater than the average crustal concentrations (estimated from orbital spectrometry data). Most Apollo 14 samples are greatly enriched in all incompatible elements, with incompatible element ratios generally conforming to the distinctive pattern of KREEP. Other evolved rock types such as granite, very high potassium (VHK) basalt, and alkali anorthosite are also common among the few "pristine" lithic fragments (those not affected by impact-mixing) for Apollo 14. In many respects the record of lunar igneous activity is more extensive among the diverse clasts found in Apollo 14 breccias than among samples from any other mission. Many important unanswered questions about the Apollo 14 crust can be addressed by further sample studies, and by up-to-date interpretative syntheses of sample-studies results. The purpose of this workshop will be to stimulate both these endeavors.

The Apollo 14 landing site was chosen primarily to sample the Fra Mauro Formation, which was believed to be a deposit of ejecta from the Imbrium basin. Most Apollo 14 rocks are polymict impact breccias, and their ages have often been assumed to date the Imbrium impact. But many workers argue that although the Fra Mauro Formation was certainly sculpted by Imbrium ejecta, most of its material is of local provenance. What proportion of the Fra Mauro Formation is Imbrium ejecta? In particular, did the abundant KREEP at the Apollo 14 site come from Imbrium? Orbital spectrometry data indicate that the global distribution of KREEP is highly asymmetrical (concentrated in the central-western near-side; mare basalts follow a roughly similar distribution). Is this pattern significant? If so, what caused



Thin-section view of one of several "pristine" lunar granites; notice the distinctive graphic texture comprising intergrowths of two coarse-grained, optically-continuous, single crystals (quartz = white; K feldspar = grey).

it? What is the relationship (if any) between KREEP and the magma ocean? Pristine KREEP is rare or absent among the Apollo 14 lithic fragments. What was the Apollo 14 KREEP component like in pristine form, before it was mixed into the polymict breccias? Why is pristine KREEP now so rare?

The Apollo 14 lithic fragments comprise many high-Al mare basalts, including the distinctive VHK basalts, and the oldest (4.2 b.y.) basalt known from the Moon. High-Al basalts are also abundant among the soil particles from Luna 16, and small pieces are occasionally found among Apollo 12 and Apollo 16 samples. What is the origin of high-Al basalt in general, and VHK basalt in particular? What is the volumetric abundance of pre-4.0 b.y. mare basalt in the Moon's crust? What other mare basalt types may be found among the Apollo 14 lithic fragments?

A suite of plutonic lithologies from Apollo 14 is distinctive and has not yet been thoroughly studied. Small lunar granite fragments are relatively abundant among Apollo 14 and some Apollo 17 samples. How did these highly evolved rocks form? Are they related to KREEP? Was liquid immiscibility involved? Apollo 14 troctolites tend to have higher incompatible element contents than their counterparts from elsewhere on the Moon. Are these magnesian cumulates somehow related to KREEP? How old are they? Alkali anorthosites seem to far outnumber ferroan anorthosites among Apollo 14 lithic fragments. How and when did alkali anorthosites form? Why are ferroan anorthosites and plutonic norites rare from Apollo 14? Are any of the Apollo 14 lithologies direct products of the magma ocean?

If even a few of the above questions can be answered as a result of this workshop, models for the origin and evolution of the Moon's crust will have to be substantially revised.

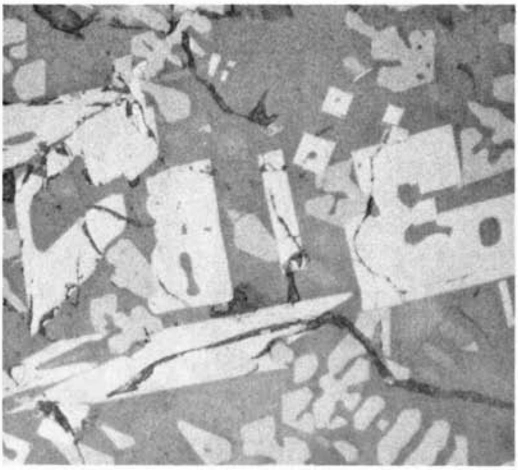
2
LUNAR MATERIALS APPLICATIONS

Eventually, the U.S. will return to the Moon, not just to visit but to stay. There has been speculation and conceptualization on lunar habitations, colonies, and industries, but little has actually been tested. The applications encompass many applied sciences practiced on Earth, with the extra problems and opportunities provided by working in a low-gravity, volatile-poor, thermally dynamic vacuum exposed to powerful solar and galactic energies.

The breadth of testing required for adequate materials utilization is tremendous. Bulk materials must be used for construction and for shielding. Life-support products, such as water, must either be produced locally or imported and managed with supreme conservation. Environmental management must use lunar materials for processes such as waste processing, and must control lunar problem materials such as dust. Power generation may ultimately require the fabrication of large solar lenses, solar cells, rocket fuel, and other products from lunar materials. Ultimately, lunar feedstocks for industry will be sought for the production of materials such as metals and oxygen, and eventually for products.

APPLICATIONS RESEARCH

As planning progresses for a return to the Moon and for a lunar base, increasing attention will be given to lunar samples in regard to their resource potential. Unfortunately, our data on chemical composition, mineralogy, and soil and rock physical properties are limited. Some compilations of these data can be supplemented by measurements from corresponding terrestrial materials, particularly for minerals



Reflected-light view (0.8 mm wide) of a polished section of fine-grained ilmenite (white), titanomagnetite (grey), and silicate glass (dark matrix) produced by melting of an ilmenite-rich rock powder by 2.45 GHz microwave energy. Microwave melting of rock powder is being explored as a rapid and energy-efficient method for producing either fused bricks or fused material in situ *on the Moon.*

where the differences between terrestrial and lunar samples are small. For lunar rocks and soils, there are some data on mechanical, electrical, magnetic, optical, and thermal properties, as well as gas-solid interactions and surface exposure features (e.g., cosmic and solar particle bombardment). However, this data base is incomplete, primarily because the characterization of these features was not pursued as actively for samples from later Apollo missions as for those from the earlier missions.

An up-to-date consideration of the data needed for lunar materials utilization must be made. Some books and monographs on lunar materials are available and at least one book is now in progress; from these publications, some deficiencies are evident. For example, in order to have a reducing agent for oxygen production, the desorption of implanted hydrogen from mineral grains is a topic of great interest. However, little is known about the nature of hydrogen retention on lunar particles or the influence of mineralogy, shock features, and surface track damage on hydrogen retention. For the preparation of fused materials one needs to understand the behavior of heated lunar soil, but there are few phase diagrams for lunar soils. Compressive and tensile strength data are available for some rock types, but many of the rock types in which mining could occur (e.g., impact melt sheets of variable texture) are not well studied. A full list of "unknowns" is not possible without active dialogue between planners, engineers, and scientists.

Much experimentation will be required to develop a wide range of processes and products from lunar resources. Most of our present concepts of processing are scaled to large amounts of material, but only a small amount of our lunar sample reserves can be used for destructive testing. Simulated lunar materials are important, not only to conserve the real lunar samples, but also to provide enough sample for large scale experiments. Moreover, any requests for lunar samples to be used in utilization experiments will have to be justified by tests using simulated materials. These simulated lunar materials will have to be tailored to individual needs. For example, some igneous rocks might be replicated by crystallization of melts formed by appropriate mixtures of chemical reagents, although some textures may be difficult, or even impossible, to reproduce. It will be difficult, if not impossible, to replicate regolith samples that contain agglutinates, shock-damaged particles, and surface-correlated volatiles. How much expense and effort are justified in simulation remains to be determined.

Although some lunar samples will have to be sacrificed for utilization experiments, this sample loss must be minimized. Experience gained from the last sixteen years of lunar sample research will contribute considerably in this effort. For example, consortium studies have been exceptionally productive in bringing diverse disciplines together for studying complex lunar samples; in utilization experiments, a benefit of consortium studies would be the extended life of the sample collection. Sample life may be prolonged by sequential experimentation; for example, experiments on delicate features such as surface-correlated volatiles might precede melting of the same sample for experiments on metal and oxygen production. Innovative research programs must be developed, and will require close liaison between experimenters with different goals. Improved techniques are necessary to obtain critical information from samples much smaller than those normally used in terrestrial studies.

APPLICATIONS WORKSHOP

Communication and cooperation between researchers is vital. An Applications Workshop is being planned, probably to be convened in 1986, that will help to explore research opportunities, to develop an understanding of what can and should be simulated, and to open communications between research groups. Major goals of this workshop would be to (1) encourage experimenters to form consortia, (2) expose utilization experimenters to the available scientific data base on lunar samples, and (3) expose the present lunar sample research community to the data needs of utilization experimenters.

This workshop will probably include a general session on the data available for lunar rocks, minerals, soils, and volatile elements and will cover the prospects for producing useful simulants. Topical sessions will discuss fuel extraction (oxygen, hydrogen, aluminum, and calcium), metal extraction methods (chemical, electrical, thermal, and mechanical), and metal fabrication and the formation of structural materials (concrete, glasses, ceramics, and sintered products). A session on mining and bulk materials processing will encompass regional geology, strip and subsurface techniques, ore processing, and the estimation of probable ores. A session on lunar environmental control and protection will cover the topics of dust, waste, and atmosphere control. A special session must be reserved for fresh ideas about other innovative products and materials for the space environment.

3

RELATIONSHIP TO MISSIONS

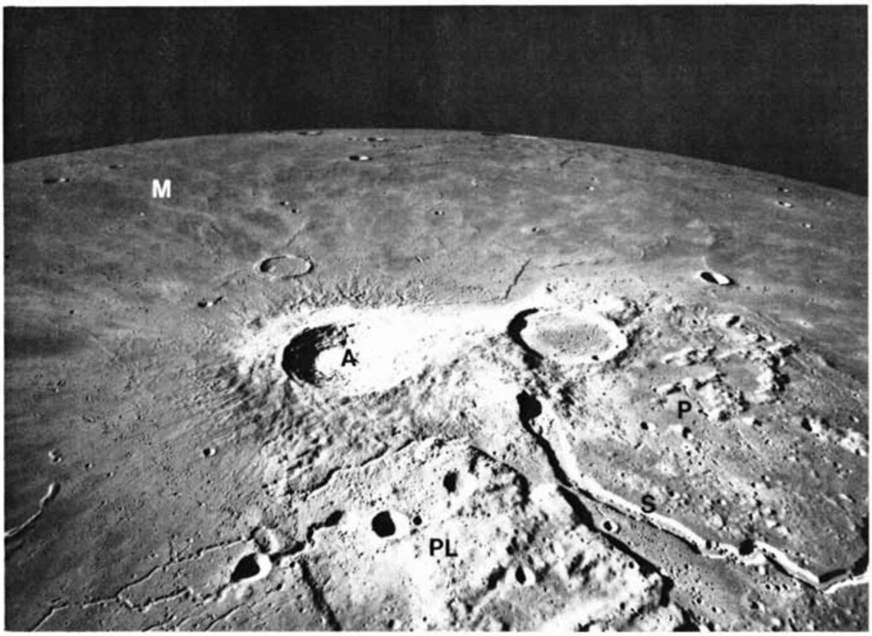
Lunar sample studies support all NASA planetary missions in a general way by elucidating planetary processes such as volcanism, impact cratering, and planetary differentiation. Sample studies relate *directly* to the Lunar Geoscience Observer, and possibly to other planned missions as well.

LUNAR GEOSCIENCE OBSERVER (LGO)

The Lunar Geoscience Observer might follow the Mars Observer in the Planetary Observer series. Lunar research has provided well-defined scientific goals for this mission, i.e., to resolve the problems outlined here in the section entitled Outstanding Lunar Science Problems. Scientists familiar with lunar samples are actively involved in planning the mission. LAPST intends this involvement to continue into flight teams. Lunar sample results are and will continue to be the primary source of "ground truth" data that will ensure the fullest use of the geochemical and mineralogical global maps to be provided by the LGO mission. Because the upper lunar crust is extensively mixed by impacts, continued sample study will refine and extend the spectrum of lunar primary igneous rock types and is critical to our understanding of regional geochemical compositions, which will undoubtedly be interpreted as mixtures of pristine rock types. The discovery of pristine rock types could greatly alter our perception of the geologic and petrologic significance of geochemical variations that will be mapped by LGO. New laboratory work is needed on the spectral characteristics of a variety of lunar rock types in order to interpret the global maps of lunar spectral reflectance that LGO will obtain. Earth-based telescopic spectra have shown us which lunar rock types are potentially relevant to the understanding of lunar spectral data. The larger the spectral data base on lunar samples that is available prior to the LGO mission, the better we will be able to comprehend the abundant and rapidly-returning spectral data from the spacecraft during mission operations. The result: a new understanding of and perspective toward the Moon's composition and evolution that will most likely feed back to more specific sample studies.

SAMPLE RETURN FROM THE MOON AND OTHER BODIES

Sample return missions to various large bodies in the solar system are highly desirable because some fundamental questions can only be answered by making measurements on samples. These bodies include Mars, the Moon, and Venus. However, the rationale for sample returns needs to be addressed. Below are some of the key points that demonstrate the advantages of sample return over *in situ* measurements.



Oblique view of the Aristarchus Plateau (PL) and environs. The fresh, Copernican-age crater Aristarchus (A) is about 42 km in diameter; remote-sensing data indicated the presence of clinopyroxene-bearing, high Th (~18 ppm) rocks —possibly KREEP-rich, plutonic evolved rocks such as granite or quartz monzodiorite. The Plateau itself displays varied geological units including the Imbrium Basin Alpes Formation (an ejecta facies), light plains (P) for which Th contents suggest KREEP lava flows, and extremely red, KREEP-rich pyroclastic dark mantle deposits. Schroter's Valley (S) is a complex, nested sinuous rille, with a morphology that implies a protracted volcanic eruption history. Mare basalts (M) on the horizon span an age from about 3.0 b.y. to possibly less than 2.0 b.y. A future sample return from this area of the Moon has the potential to collect a wide variety of rock types within a relatively limited geographic region.

Sample Return Rationale

Laboratory Equipment Will Always Have Better Resolution and Precision Than Flight Instruments. Over the past ten years, laboratory instruments have undergone major improvements in their ability to analyze increasingly smaller samples and to provide significantly greater resolution of physical and chemical differences and improved precision for isotopic analysis. Because of weight and power limitations, no proposed flight instrument can ever be as good as the best laboratory instrument in its ability to analyze small samples or to detect small differences. This ability is critical to understanding the samples, so laboratory instruments will always provide better data and better understanding of planetary samples. For many types of planetary samples this superior resolution and sensitivity is not only desirable but is absolutely vital to understanding the material. For instance, only by using instruments of very high resolution that can discriminate among individual mineral and glass phases is it possible to understand a planetary regolith. Very precise data are needed for reliable isotope age determinations and isotopic ratios. It is not likely that some kinds of analyses will ever be accomplished to the required precision by remote instruments. Such age and isotopic ratio determinations are critical to the understanding of the geological evolution of a planet and can be used to calibrate other time scales such as those based on crater densities.

Returned Samples Become Resources That are Accessible in the Future for Rapidly Improving Analytical Technology. Over a period of years, analytical instruments undergo considerable improvements and entirely new instruments are developed. If planetary samples are brought back to terrestrial laboratories, improved or new instruments can be applied to them as they become available. The samples can then be periodically mined for new data. In contrast, flight instruments "freeze" the state of the technology some time before launch and cannot be improved. Only an entirely new mission can take advantage of improvements in instrument technology that may occur from year to year. The technology of mass spectrometry could not support Nd-Sm dating at the time of the Apollo missions, but several years later this technique provided key data on returned lunar samples. Third-generation ion probes and PIXIE analyses now allow trace element determinations on individual mineral and glass grains; such techniques were not available during the Apollo missions.

Unforeseen Key Discoveries Can Lead to New Experimental Design. A package of flight instruments must be chosen and designed well before the mission begins. The choice of the instrument mix and the design of each instrument is entirely dependent on the best guess of what the targeted samples may be like. If the samples are not entirely as expected, the instruments may not work at all, may give the wrong kind of data, or may miss the critical data. An example is an instrument package designed to sample fine particulate material that instead encountered coarse-grained material. If the chemistry of the samples is not as expected, the proper analyzing system may not be included in the package. Flight instruments inevitably lack flexibility and can only do what they are designed to do based on a model for the characteristics of the samples to be analyzed. If the sample characteristics were known perfectly before the flight, the analyses would not be necessary. Hence, the supposed characteristics are likely to be wrong in some respects and, therefore, the package will not be entirely suitable. Sample return and laboratory instruments allow complete flexibility of instrument types and sample preparation, and even have the ability to handle totally unexpected situations.

There are No Weight/Power Considerations on Laboratory Instruments. Many laboratory techniques require massive or power-hungry devices. Examples include high-resolution mass spectrometers, ion probes, ferromagnetic and nuclear magnetic resonance devices, and synchrotron radiation. A recent example is the Brookhaven synchrotron XRF probe for lunar and meteorite samples. None of these techniques are easily adaptable to flight instruments because of the power and weight limitations.

The Variety and Complexity of Laboratory Instrumentation for Sample Studies are Unlimited. Laboratories contain a variety of very complex instruments. Literally hundreds of different types of instruments and techniques have been applied to lunar samples and have provided a complex variety of data types, all of which have contributed toward understanding the samples. In contrast, only a few different instruments will ever be practical for a flight package. Even if these instruments are equal to their laboratory equivalents, the limited number of instruments will limit the kinds of data that can be acquired. If we had been limited to only five or ten instruments in our analyses of lunar samples, it is doubtful that we would have made much progress in understanding these complex samples. In addition, sterilization requirements can limit the quality and complexity of flight instruments.

OTHER POSSIBILITIES

A central part of NASA's program is the construction of the Space Station. It is difficult to predict how the Space Station will affect lunar science, but we envision several possibilities. One is improved telescopic observations of the Moon from an observatory installed on or near the Space Station. The absence of atmosphere would allow observations of the Moon in a wider range of wavelengths than is possible from Earth's surface, thus providing more chemical and mineralogical information. Such an observatory would supplement the LGO.

Experiments in microgravity and high vacuum could have significance for understanding lunar rock evolution. Such experiments have not yet been designed, but we expect them to be proposed when material research laboratories are in place on the Space Station. The Space Station will be the best place to conduct many lunar-sample utilization studies, for many lunar materials will ultimately be used in orbit for space manufacturing and construction. Again, there is interaction progression between sample studies and sample utilization.

4

OUTLOOK FOR CURATORIAL OPERATIONS

It is vital that the curatorial operations continue to support the Planetary Materials and Geochemistry Program (PMGP), at least at the present level of activity. In 1981, the curatorial effort was significantly reduced and has since remained at a constant level of effort, with budget growth sufficient to cover inflationary costs only. The present activity is efficiently supplying the needs of the community and preserving the integrity of the samples.

The active approach of exposing more surfaces and samples for study by the planetary materials community should be continued. Cutting of breccias is stimulating significant research activities. Several research groups have also taken advantage of the chance to pick significant samples from the supplies of 1-4 mm soil fragments. However, detailed cataloging would permit more effective use of these valuable samples. Systematic thin-sectioning and descriptions of regolith breccias have focused the research of several groups on these samples. LAPST will continue to encourage the Curator to actively process the collection.

LAPST will evaluate the need to open specific lunar cores for investigation. The dissection of lunar cores was discontinued in 1981 with approximately one-third of the cores unexamined. Several lunar investigation teams have expressed interest in studying new cores. LAPST will evaluate both the significance of the potential science and the impact on curatorial operations.

LAPST will continue to review the status of the cataloging and documentation of the lunar sample collection. The present set of documentation is uneven in thoroughness and quality. Excellent, thorough reviews in the form of catalogs are available for the Apollo 15 and 16 collections. LAPST will systematically review the other sample documentation (guidebooks, catalogs, core descriptions, etc.) and identify significant shortcomings. A prioritized plan will be proposed to direct such future curatorial efforts.

LAPST and the Curator will remain ready to take advantage of opportunities to develop new sources of extraterrestrial materials. For example, recently returned Solar Max spacecraft parts have provided samples of captured cosmic dust. The Long Duration Exposure Facility (LDEF) will soon be available as another source. In the new era of replaceable, repairable spacecraft, LAPST expects new opportunities and will encourage use of the curatorial facilities to recover cosmic dust samples.

A significant challenge to the Curator and LAPST is the increasing interest in studies of potential utilization of lunar samples and other extraterrestrial materials. The Planetary Materials Branch is the sole source of lunar materials, and the curatorial staff will identify samples that are suitable for use in such engineering and applied studies. The curatorial staff will be a source of information on suitable simulants for engineering and applied studies. Use of simulants can reduce the demand for lunar material and should be used to pre-test experiments in order to optimize return from studies of actual lunar materials. LAPST recognizes the significant costs of producing simulants but also recognizes the need to have studies done on realistic lunar simulants. Whether major stocks of simulated lunar material should be produced by the Curator is a question that cannot be answered until more is known about the nature, volume, and cost of responding to requests for such materials.