The goal of Project Apollo, to place a man on the surface of the Moon and return him safely to Earth, was a task for engineering and technology. The resultant transportation system was so robust in its capability that a rich scientific harvest also was gathered in the process. The visibility and magnitude of the Apollo program left the impression, even within the scientific community, that the major lunar scientific questions had been answered. Since the Surveyor project, NASA's unmanned planetary program has ignored the Moon, preferring to concentrate its admitted limited resources on other bodies in the solar system.

In 1972, lunar scientists proposed launching a remote-sensing satellite into lunar polar orbit. Carrying a small number of geochemical and geophysical sensors, the Lunar Polar Orbiter (LPO) was designed to expand to global coverage the limited Apollo orbital science data set. Remote-sensing information from the orbiting Service Modules of Apollos 15, 16, and 17 had been invaluable in revealing the scale and extent of the planetary processes whose nature and timing were decoded in analyses of the returned samples. Low orbital inclination and limited time at the Moon resulted in tantalizingly incomplete results, often hinting at new geological insights just beyond the orbital coverage. Although the LPO had unquestioned scientific value, the mission concept fell victim to a scarcity of funds and a planning philosophy emphasizing complex exploration missions with great public appeal.

In the current planetary exploration program, a Venus Radar Mapper and a Mars Observer have been approved as new starts. A Comet Rendezvous and Asteroid Flyby has been proposed. The Soviets have announced an LPO mission to be launched before 1990, but lunar scientists in the United States are uncertain as to the availability and completeness of the future Soviet data. However, the announcement has caused some NASA program managers to suggest that a U.S. lunar mission should be put off for another ten years until the Soviet results have been evaluated.

Arguments for or against a near-term orbiting lunar survey satellite are couched in terms of purely scientific priorities within a fiscally restricted unmanned program. If an orbiter were seen as a precursor mission to a lunar base program, then one could argue...
from a different perspective that its entire cost would be a fraction of 1% of the manned program over a decade. It also becomes a long lead item because approximately eight years elapse from the declaration of a mission new start until a mature analysis of the results. Of course, hypothetical justifications by a lunar base program are irrelevant to real policy debates because no long range plan for manned lunar activities exists within NASA at the present time. In addition, some lunar base scenarios, such as a return to an Apollo site, require no precursor mission. However, new data from a low cost scientific satellite serves other purposes.

If we assume that NASA will continue historical behavior and propose a new major program only after the current one is complete or operational, then a lunar base will be planned no sooner than about 1995, after completion of the LEO space station. Scientists active in the Apollo data analysis will be at retirement; younger researchers will have no experience in lunar problems unless new lunar data sources are developed. A Lunar Observer mission, to use current nomenclature, is an inexpensive investment in expertise for the space activities of the next century.

The scientists who have contributed papers to this section are, for the most part, veterans of the Apollo scientific program and are well steeped in the critical scientific questions facing contemporary and future investigators. Taylor reviews the major scientific questions of planetary evolution and discusses the role of manned surface exploration in searching for the answers. Haskin et al. consider several field geological investigations in the vicinity of a base to address problems of geochemistry and petrology of the lunar surface. Vaniman et al. describe volcanism on the Moon and point out the resource potential of volcanic features. Cintala et al. present an extended geological traverse of 4000 km length around the Imbrium Basin. Although an engineering challenge, an advanced exploration of this type would yield invaluable scientific data on lunar stratigraphy. Friesen develops an observational strategy for detecting any volatile emissions from the lunar interior, while Wilhelms gives a thorough discussion of the scientific payoffs from a Lunar Observer orbital satellite. Hood et al. elaborate on the geophysical information to be gained from orbital studies, especially when combined with a surface network of geophysical stations. Strangway recalls the distinctive lunar geophysical properties and discusses key measurements needed to study them. Ander elaborates on the geophysical exploration techniques that are particularly suited for use in the lunar environment.

These manuscripts form an unusually complete survey of the state of lunar science and, by extension, our understanding of the terrestrial planets. The Moon, whose geological evolution ground to a halt so early in the history of the solar system, preserves an invaluable record of those times. In contrast, the Earth manifests a collection of dynamic geological processes seen only in part elsewhere among the planets. Studies of these two bodies in concert extend understanding of our environment both to the past and to the future.
THE NEED FOR A LUNAR BASE: ANSWERING BASIC QUESTIONS ABOUT PLANETARY SCIENCE

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Information derived from manned and unmanned exploration of the Moon has allowed us to develop an outline of lunar origin and evolution. Nevertheless, many questions await answers. These questions will be answered in part by data obtained from future unmanned missions such as the Lunar Geoscience Observer, but complete answers (and the new questions that will inevitably accompany them) will come only from additional manned missions. Although robot spacecraft can perform remarkable feats, they cannot match human ability to do field work, to react to unexpected discoveries, to do sophisticated preliminary analyses, and to deploy certain complicated equipment. One drawback to people living on the Moon is that they will affect the pristine lunar environment. Consequently, the first thing we must do when (and possibly before) the base is established is to obtain uncontaminated samples from around the Moon. This global contingency sample could be stored on the Moon for future study.

INTRODUCTION

The Moon has barely been explored, although there has been some impressive preliminary work. Six manned Apollo landings returned 382 kg of rock and soil. Three unmanned Luna spacecraft sent by the Soviet Union brought back 300 g of lunar soil from areas other than those sampled by Apollo. Geochemical and geophysical instruments onboard Apollo Command Modules and on subsatellites released from them made important measurements from orbit. Before Apollo, a series of unmanned Ranger and Lunar Orbiter spacecraft radioed back thousands of photographs. Several unmanned Surveyor spacecraft landed on the Moon, giving us a glimpse of the Moon's surface and an indication of its chemical composition and compositional variability. From this information we have been able to reconstruct an outline of lunar history. Nevertheless, gaping holes exist in our knowledge of the Moon's nature and evolution. The greatest accomplishment of lunar exploration so far is to show us how little we know.

This paper has five purposes: first, to point out that our ignorance about the Moon is all the more unfortunate because it is such an ideal place to study important planetary processes and to enlighten ourselves about early planetary history; second, to recount briefly what we have learned from the first phase of lunar exploration; third, to offer a list of unanswered questions about the Moon and its history and to explain why we must return to the Moon to answer them; fourth, to point out that people must return, not only unmanned machines; and fifth, to warn that pristine samples must be collected and preserved prior to or soon after a lunar base is established, because base activities could compromise the scientific integrity of the lunar environment.
THE MOON'S CENTRAL PLACE IN PLANETARY SCIENCE

In a sense, the Moon is the cornerstone of planetary science. The intensity and duration of its geologic activity have left behind a record of its earliest history, including clues to its origin; yet, at the same time, the rocks and surface features have recorded information about the processes operating in and on the Moon as it evolved. Consequently, the Moon contains information about planet formation (though admittedly cryptically inscribed), its early differentiation into core, mantle, and crust (written more clearly, but still far from translated), its subsequent chemical evolution (clearer), and its impact history (scrawled on its cratered surface, but not yet understood in detail). These are key events in solar system history whose traces have been annihilated on Earth by vigorous terrestrial geologic processes. To understand Earth's early history, we must study the Moon.

The Moon is a natural laboratory for studying significant processes such as impact cratering and volcanism. Vaniman et al. (1985) discuss the importance of understanding lunar volcanism. Cratering has shaped the surfaces of the terrestrial planets, the satellites of Jupiter and Saturn, and the bodies (presumably asteroids) from which meteorites come. Studies of terrestrial impact craters have led to some understanding of the process, but even the youngest impact craters on Earth have been substantially eroded, and none of the huge early basins remain. On the Moon, craters up to hundreds of kilometers across are preserved and could be studied in detail (e.g., Cintala et al., 1985).

The Moon also has the virtue of being accessible; it's close to us. No doubt many other bodies throughout the solar system contain information about planetary origin, evolution, and processes, but they are not as easily reached as is the Moon. We should continue to explore them with unmanned spacecraft, including sample returns and manned reconnaissance missions, but detailed manned exploration can start most easily on the Moon.

AN OUTLINE OF LUNAR HISTORY

To set the stage for the litany of unanswered questions posed in the next section, I first outline our current understanding of the Moon's history. Detailed reviews of lunar rocks and the Moon's origin and evolution can be found in S. R. Taylor (1982), Norman and Ryder (1979), Warren (1984), and Hartmann et al. (1985); recent non-technical sketches are given by Rubin (1984) and G. J. Taylor (1984, 1985a,b).

The Moon's origin has puzzled scientists for hundreds of years. The three traditional theories of lunar origin—fission from Earth, capture by Earth, and forming with Earth as a double planet system—all have serious flaws. The probability of capturing a fully formed Moon is so tiny that most dynamacists consider it impossible. The capture hypothesis cannot adequately explain why the Moon has a small iron core, in contrast to Earth and the other inner planets. The fission theory accounts for the difference in iron between Earth and Moon by requiring the Moon to spin off of the primitive Earth after core formation. However, there are problems explaining how the Earth was spinning fast enough (once every 2.5 hours) to fling off a blob of material from which the Moon formed. Studies
of the dynamics of planetary accretion indicate that it is unlikely that Earth was ever rotating that rapidly. In fact, it is hard to model accretion and account for the observed amount of angular momentum possessed by the Earth-Moon system, let alone substantially more of it. There are also problems with the double planet idea in accounting for the angular momentum of the Earth and Moon and in explaining why material around Earth stayed in orbit, rather than falling to Earth.

A new story for the Moon's origin has recently blossomed. Growing from seeds planted by Hartmann and Davis (1975), the new theory depicts a cataclysmic birth of the Moon: nearing the end of Earth's accretion, after its core had formed and while it was still molten, an object the size of Mars (one-tenth Earth's mass) smashed into it at an oblique angle. The resulting monumental explosion deposited large quantities of vaporized and molten impactor and Earth into orbit, and the primitive Moon formed from this material. This story seems capable of explaining the compositions of Earth and Moon and the total angular momentum of the system. Based on our knowledge of planetary accretion, the large impact is not dynamically far-fetched (Wetherill, 1985).

From analysis of lunar samples, we know that when the Moon formed 4.6 b.y. ago, it was substantially molten. The lunar highland crust contains exceptional quantities of plagioclase feldspar. Plagioclase constitutes more than 90% of many samples (called "anorthosites") and averages about 75% in the explored highlands. This large abundance of one mineral led to the suggestion (Wood et al., 1970) that when the Moon formed, it was enveloped by a huge magma system, commonly known as the lunar "magma ocean." Plagioclase, which has a relatively low density, floated to the top of the ocean as it crystallized, forming the original crust. The ocean had solidified by 4.4 b.y. ago.

Near the end of the magma-ocean epoch, magmas generated inside the Moon began to intrude into the crust and probably erupt onto its surface. These are represented by the "Mg-suite" rocks of the lunar highlands. They contain less feldspar and more olivine and pyroxene than do the anorthosites, and they constitute a diverse set of samples. This activity continued until about 4.1 b.y. ago, at which time basaltic magmas rich in elements such as potassium (chemical symbol K), the rare earth elements (REE), and phosphorus (P) rose to the surface and intruded into the crust. The characteristic enrichments in these elements has earned such basalts the nickname KREEP.

As this magmatism was constructing the lunar crust, the Moon continued to be bombarded by planetesimals (Fig. 1). The prominent circular basins now seen on the Moon, which are hundreds of kilometers across, formed around 3.9 b.y. ago, though numerous others had formed prior to 4 b.y. This bombardment transformed the upper 2–10 km of the lunar crust into a rubble pile. The nature of highland rocks reflects this: most are breccias, rocks composed of fragments of other rocks. Most of the fragments are themselves mixtures.

Beginning around 3.9 b.y. ago, lavas that formed by partial melting inside the Moon began to fill the basins with mare basalts, which contain less feldspar and more olivine, pyroxene, and ilmenite (an oxide of iron and titanium) than do highland rocks. Ages of lunar samples demonstrate that most of the mare volcanism ended around 3.0 b.y. ago, but photogeologic studies indicate continued activity to about 2.0 b.y. (Boyce et
Figure 1. A view of the farside of the Moon taken during the Apollo 16 mission. The abundance of craters attests to the fierce bombardment the Moon experienced. The dark-floored crater (upper center), Kohlschutter, is 60 km in diameter and appears to have been flooded by mare basalts, one of the rare occurrences of such lavas on the farside. The smooth horizon is interrupted by Mare Muscoviense, which also contains basalt flows. The pole protruding on the right is the boom for the gamma-ray spectrometer carried on the Apollo 16 Command Module. Apollo photo number AS16-0729(M).

al., 1974), or younger (Schultz and Spudis, 1983). Lavas with compositions like those of mare basalts had erupted prior to 4.0 b.y. ago, but repeated impacts as the Moon was bombarded during that time erased much of the evidence (see Vaniman et al., 1985).
UNANSWERED QUESTIONS AND MISSING INFORMATION

Detailed though it may seem, the above account of lunar history is little more than an outline. Many questions remain unanswered. What is the Moon's bulk composition? Does the Moon have a metallic core? How large is the core? Was there really a magma ocean? If so, how did it form? How deep was it? Was the Moon totally molten when it formed? How does the crust vary in thickness and composition laterally and vertically? How are the major lunar rock types related to one another? Have we identified all the major rock types? What were the effects of giant impacts on the Moon? Over what period of time did the large basins form? What does the presence of volatiles in lunar volcanic glasses imply about the inventory of such elements in the Moon? How old are the oldest rocks? What are the ages of the youngest rocks?

Studies of our present collection of lunar samples will continue to provide insight into these questions, as will improved understanding of how chemical processes operate inside planets. However, poor geographic sampling of the Moon limits what we can learn from the samples collected during the first round of lunar field work. The Apollo and Luna missions sampled rock and soil from the central nearside only, at a mere nine localities. The farside (Fig. 1) is completely unsampled. Furthermore, spectral observations of the Moon from Earth-based telescopes (Pieters, 1978) indicate that we have sampled less than half of the types of mare basalts present on the nearside. Such telescopic observations also show that the types of highland rocks that are rare among lunar samples, such as those rich in olivine and high-Ca pyroxene, occur on the floors and walls of large craters (Pieters, 1982, 1983). Obviously, we have not sampled all the types of rocks present on the Moon. This is the first priority when sampling begins again.

We have scant knowledge about the lunar interior. Three seismic stations set up by Apollo crews provided a glimpse inside the Moon, but they were located close together, on the nearside only, and in an area where the crust might be anomalously thin. The Apollo seismic network detected a change in seismic velocities 60 km beneath the surface, interpreted as the boundary between the crust and mantle, and another at a depth of about 1000 km, which seems to be a region that is partly molten. However, we do not know how the crust's thickness varies around the Moon or whether subtle contrasts exist in either the crust or the mantle. We have no direct evidence for an iron-nickel core like the Earth's. The presence and size of a metallic core has great bearing on theories for the Moon's origin and on the source of the unexplained magnetization of lunar rocks. Clearly, when we return to the Moon, an extensive network of seismometers must be set up and perhaps active seismic measurements carried out to probe the structure of the lunar interior.

We do not know enough about the composition of the Moon's crust or about how the composition varies laterally and vertically. The most compelling evidence for the lunar magma ocean and one of the best indicators of its depth is the exceptional abundance of plagioclase feldspar in the highlands crust (Warren, 1984), but we do not know how the abundance of this mineral (reflected chemically in the concentration of aluminum)
varies around the Moon or with depth in it. Spectral reflectance measurements (Pieters, 1982, 1983) show that rocks rich in olivine or high-Ca pyroxene occur in the central peaks of some craters, whereas other central peaks appear to be pure anorthosite. Because central peaks and crater floors represent deep materials brought up by impacts, it appears that there are complex variations with depth in the lunar crust. Sampling these areas is essential when lunar exploration begins in earnest from a lunar base.

How are the major types of lunar rocks related to one another? On Earth, we can directly observe the kinship among different lithologies. For example, we can study successive lava flows and know for a fact that they erupted from one volcano. In contrast, no lunar rocks were collected from discernible rock layers. Even the largest boulders were simply large rocks strewn on the lunar surface. However, photographs from orbit (Fig. 2) show that layers of rock exist in the walls of large craters; these could be sampled. Similarly, layers of rock in rilles, such as Hadley Rille where Apollo 15 landed, almost certainly represent successive lava flows. Furthermore, although the lunar crust has been devastated by impacts, careful field work might reveal huge chunks of igneous bodies that had differentiated into a series of related rocks. Such fragments of igneous intrusions might be found in the walls of large craters (Fig. 3). Tilted structural blocks may also provide access to layered crustal rocks (Haskin et al., 1985).

The huge impacts that excavated basins such as Imbrium, Serenitatis, and Orientale hurled material across the Moon and dredged up rocks from great depth. We do not understand the details of impact events of this magnitude. By studying some basins in detail we could assess how the formation of basins has obscured primary crustal compositional variations by lateral mixing and determine how deeply they excavated.

Figure 2. Layers of basalts adorn the wall of the crater Bessel (17 km diameter), which punctured south-central Mare Serenitatis. These layers of basalts could be sampled, as could layers visible in rilles. No mare basalts have been collected from an identified lava flow. Apollo photo number AS15-9328(P).
A traverse across the large lunar basin, Imbrium, is described vividly by Cintala et al. (1985). Because such basins have formed on numerous other planets and satellites, research on lunar craters has implications beyond the Moon itself.

The study of lunar basalts and pyroclastic deposits provides information about the Moon's interior and thermal history. Our present knowledge about lunar volcanism is as incomplete as the other topics discussed in this section. The gaps in our knowledge and suggestions for filling them are discussed by Vaniman et al. (1985) in this volume.

PEOPLE ARE NEEDED

There is no doubt that we have a tremendous amount to learn about the Moon and its history, but why send people? Why not return to the Moon with unmanned spacecraft? The answer: good idea! We should send unmanned spacecraft to study the Moon before we actually go back in person. A logical first step is a polar orbiter equipped with assorted remote-sensing devices to map the Moon's surface, as has been suggested for one of NASA's Observer missions (the Lunar Geoscience Observer). We ought also to have some unmanned sample returns before the lunar base is established to help define specific research programs at the permanent lunar facility. The returned samples will also help keep lunar science vital until the base is established. The current cadre of lunar scientists know much more than they could ever convey in publications. Their experience is an irreplaceable asset that must be preserved, and a new generation of lunar experts must be trained. Today's students will be the scientists who answer the questions—and ask the next ones.
Unmanned machines have performed remarkable feats, but they will never match a trained geologist in doing field work. As pointed out by Spudis (1984) in a talk at the Lunar Base Symposium and emphasized by Cintala et al. (1985) and Haskin et al. (1985), field work requires people. Field work is iterative because scientists need time to think about what they have seen before going further. Most importantly, creative minds can react to the inevitable unexpected discoveries; pre-programmed machines cannot, so we lose opportunities to sample the unexpected in detail. Also, it is not possible to program a machine with all the experience and perspective that a veteran geologist possesses. Machines cannot select samples as intelligently as can people.

Once samples are collected from outcrops or plucked from the lunar surface, people are required to do a reasonable preliminary analysis on the Moon. Unmanned probes do remarkable chemical analyses of soil or rock chips grabbed by a robot arm, and scanning electron microscopes with energy-dispersive detectors are being designed to fly on comet rendezvous missions. Nevertheless, these do not compare to the information gleaned by an experienced petrographer peering into a petrographic microscope or to the chemical data obtained by neutron activation or X-ray fluorescence analysis of carefully chosen subsamples. People are essential for good preliminary analysis of samples collected on the Moon.

In addition to their observational and decision-making abilities, people are needed to deploy and repair complex equipment. For example, can an automated spacecraft really plant a heat-flow probe or a seismograph properly? Lay out a set of seismic receivers to deduce local stratigraphy? Study the walls of a trench dug in the fragmental lunar regolith? Probably not.

Finally, a disclosure statement is in order. Although I am obsessed with anything related to finding out how the Moon formed and evolved, I am also enthralled by the concept of people going into space. I have been thrilled by the exploits of Yuri Gagarin and John Glenn, of Neil Armstrong and Sally Ride. They are our representatives in space. Machines give us information; people give us impressions and inspiration.

**PEOPLE CAN BE A PROBLEM**

Many of the scientific investigations described in this volume require the unique lunar environment, e.g., the amazingly low atmospheric pressure \(10^{-12}\) torr and the virtual absence of \(\text{H}_2\text{O}, \text{CO}_2\), and nitrogen compounds. For example, an important project will be to search for indigenous lunar volatiles (Friesen, 1985). Consequently, environmental changes must be monitored continuously after a lunar base is constructed. Most importantly, as noted by Duke et al. (1984), it seems that some environmental degradation will occur as a result of lunar base activities, so the lunar surface should be sampled thoroughly and characterized during (or even before) the initial lunar base operation. In short, we ought to obtain a global "contingency sample." Many samples could be stored in sealed containers on the Moon for future reference. This would ensure the preservation of pristine, uncontaminated, pre-base lunar samples.
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GEOCHEMICAL AND PETROLOGICAL SAMPLING
AND STUDIES AT THE FIRST MOON BASE

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Strategic sampling appropriate to the first lunar base can advance a variety of first-order lunar geochemical
and petrological problems. Field observation and collection of samples would be done on the lunar surface,
but detailed analysis would be done mainly in terrestrial laboratories. Among the most important areas of
investigation for which field observations can be made and samples can be collected at the initial base are
regolith studies, studies of mare and highlands stratigraphy, and a search for rare materials such as mantle
nODULES. Since the range of exploration may be limited to a radius of about 20 km from the first lunar base,
locating the base near a mare-highlands boundary would enable the greatest latitude in addressing these problems.

INTRODUCTION

The number of problems in lunar geoscience that can be studied from a base on
the Moon in conjunction with laboratory studies on Earth is nearly overwhelming to
contemplate (e.g., G. J. Taylor, 1984). Such problems range across studies of the petrological
products of the Moon's geochemical differentiation, of large-scale displacements of
segments of the Moon's crust, of processes of local regolith development, and of ancient
solar wind, just to name a few broad areas. Many studies are of the most detailed sort
and might at first seem to pertain to second-order problems. In fact, the understanding
of such apparently trivial phenomena as mixing and heterogeneity in local regolith can
have profound effects on interpretation of sampled materials in terms of all the areas
of study mentioned above. Without such information, interpretations of data on Apollo
samples must remain more speculative than desired, an especially serious situation when
the importance of the Moon as an analog for other cratered bodies in the solar system
is considered. This paper discusses briefly some projects for lunar geochemistry and
petrology that could be carried out at the first lunar base. Proper exploration of the Moon
will require extensive mobility and capability to sample material at depth (e.g., Cintala
et al., 1985) that are not considered in this relatively simple scenario. Rather, we assume
a multi-purpose base with mainly constructional equipment, relatively short tours of duty
(three to six months), and scientists whose tasks include general assistance in setting
up and operating the base. The emphasis is on field observation, sample collection, initial
characterization, and selection and preparation of samples for detailed study in laboratories
on Earth.
It does not seem realistic for the first base on the Moon to have sophisticated instrumentation for mineralogic and chemical characterization of collected materials. The hand lens and binocular microscope should suffice for most purposes, plus perhaps the ability to make some thin sections and examine them under a petrographic microscope. A small X-ray fluorescence spectrometer of the type based on radioisotope beta-ray excitation might prove useful for preliminary characterization of rock powders (see also the discussion by Lugmair, 1984). It does not seem plausible to provide more sophisticated apparatus for detailed laboratory study at a Moon base until tours of duty are extended to periods of years. It is difficult to imagine the rich variety of techniques available in terrestrial laboratories becoming available on the Moon for a very long time. The astronaut-petrologists and -geochemists will be busy enough designing and carrying out strategies for mapping and sample collection that they need not be burdened with more sophisticated study in situ. However, the scientist-astronauts will probably be confined to habitable quarters during the two-week lunar nights and will have time to do careful preliminary characterization of sampled materials. In fact, the scientists will probably be confined to working quarters underground during most days as well as nights because of the relatively high radiation levels on the lunar surface. Thus, outdoor activities may be mainly teleoperated with infrequent excursions to the surface, carefully planned for efficient scientific yield (see also the discussion by Spudis, 1984). The observational power of human geologists is not likely to be matched soon by robotic substitutes, however, and direct observation will be essential for many studies.

Here, we assume a base with dirt-moving equipment (expected to be necessary for emplacement of habitats, preparation of landing pads, assistance in providing feedstock for processing of lunar soil, etc.), rover capability over at least a 20-km range from the base headquarters, and adequate habitat and working area to enable preliminary characterization of collected samples as indicated above. We also assume the continuous presence of one or more geoscientists dedicated to careful observation and sampling of the local environment, working in partnership with other geoscientists in terrestrial laboratories. The analog is the field study and sampling followed by laboratory study of collected studies here on Earth.

Below, we describe some projects important to lunar science that could be done under the conditions outlined above. Some projects are tailored to Apollo sites. These are not meant to indicate that a return to any of those sites is essential, but to show specifically how individual projects could be designed. All projects mentioned are offered as examples in a generic sense, with selection and design dependent on the particular site chosen for the base.

REGOLITH CHARACTERIZATION

Most or all of the materials sampled at a lunar base will be regolith materials. Only in mare terrain do we know for certain that we can find bedrock in place. Thus, to some extent, most sampling strategies will contribute to regolith characterization, whether that is the main purpose of the study or not. What we refer to as “regolith characterization” in this section consists of observations and collection of samples to characterize the
shallow (1-2 m) regolith at the base site. It will be necessary to collect some of the samples for this characterization early, before activities associated with establishment of the base have disturbed the material.

The scientific problems to be studied are extensions of those approached in the shallow coring and trenching done at Apollo and Luna sites. What different igneous rock types contributed to the regolith? What fraction of the material is derived locally and what fraction is exotic? Can rays from distant craters be traced? What are the patterns of mixing and bedding? What marker horizons can be found and how far can they be traced? Can buried ancient soils be located, and what can we learn from them (McKay, 1984a)? Such questions are fundamental to understanding the Moon's surface history.

If mobility extends for a radius of 20 km from the base site, sampling strategy should be developed to understand the shallow regolith over the entire accessible area. This can be done mainly by sampling with drive tubes or coring devices similar to those used for Apollo missions, with collection of bulk samples from the upper few centimeters at each sampled location. Two or three regions, a few kilometers distant from each other, should be intensively sampled, with sufficient cores spaced 1-10 m apart to enable definition of small-scale structure and to determine dips of marker horizons over short distances. Cores at more widely spaced intervals can then be used to characterize the broader scale features of the regolith, showing changes in relative amounts of components over the entire area and enabling the tracing of crater ejecta. Such a study can provide directional indications for ejecta from distant craters; work of this type has led to tentative ages for the fresh craters Tycho (Arvidson et al., 1976) and Copernicus (e.g., Eberhardt et al., 1973), based on assumed sampling of ray material. Particularly interesting would be the discovery of abundant ray material 65 m.y. old, the age of the terrestrial Cretaceous-Tertiary boundary (recently suggested to have resulted from impact by a large meteoroid), perhaps as one manifestation of periodic bombardment of the Earth-Moon system (Hötz, 1984, 1985; McKay, 1984b). By combining petrographic and geochemical information (identification of rock types, mineral chemistry, major- and trace-element analysis, isotopic studies, nuclear particle track measurements, etc.) for well defined regolith strata, we can learn much about local and more distant regions.

These core samples would be studied only in terrestrial laboratories. At least one hundred cores would be necessary for initial characterization of the local regolith. More rapid means of core dissection than those used on Apollo cores would be required. Only obvious horizon boundaries in opened cores would need to be noted and only pebbles removed selectively during dissection. Continuous-strip thin sections could be provided for petrographic analysis. However, since petrographic analysis of lunar fines is difficult, primary characterization could be done geochemically, using methods such as X-ray fluorescence and instrumental neutron activation to show compositional discontinuities and using ferromagnetic resonance to show changes in soil maturity, as means of identifying horizon boundaries (e.g., Korotev et al., 1984). Following initial characterization, materials could be selected for more specific studies.

Shallow trenches were dug at Apollo sites, but they yielded little stratigraphic information. With dirt-moving equipment, a much more interesting set of experiments can be done. Trenches meters deep can be dug and visual and photometric studies of
texture and bedding made. Observed horizons can be sampled for comparison with the core samples. The cohesiveness of the soils should make it possible to produce relatively deep trenches for scientific study, 10–20 m, by stepping them in terraced intervals of 10–20 cm vertical dimension. Advantage should be taken continuously of excavations done for other purposes such as habitat construction, landing pad preparation, and acquisition of feedstock for materials processing.

CRUSTAL STRATIGRAPHY

Knowledge of crustal stratigraphy is crucial to understanding the fundamental geochemical and petrological nature and evolution of the Moon, once thought to be composed of average non-volatile solar system material that had not undergone chemical differentiation to form an internally zoned planet like Earth. The nature of the first lunar samples collected laid to rest any notions that the Moon was chemically undifferentiated. For a summary of the history of evolution of models for the development of the lunar crust, see the article by Walker (1983). Observation of the mineral plagioclase feldspar in materials from the lunar regolith led to the hypothesis that its outer regions were initially molten, forming a global magma ocean (e.g., Wood et al., 1970). On cooling, such a magma ocean would precipitate dense ferromagnesian minerals (olivine, pyroxene, ilmenite), which would sink, and less dense plagioclase, which would remain suspended. The plagioclase, it is speculated, would float to form a crust of anorthosite tens of kilometers thick. Anorthosite is a type of rock that consists of over 90% plagioclase feldspar. It is found as hand-specimen-sized samples among the materials collected from the Apollo 15 and 16 highlands and appears to be present as the central peaks in some lunar craters (C. Pieters, personal communication, 1984). However, it is not found among the large fragments of rocks collected from the Apollos 14 or 17 highlands, nor do most of the remotely sensed highlands surfaces have the composition of anorthosite. Different varieties of anorthosite are known, suggesting different origins (Hubbard et al., 1971; Dowty et al., 1974; Warren et al., 1983; Lindstrom et al., 1984).

To produce such a variety of rock types, crystallization of the hypothesized magma ocean would have to have been very complex. If it produced mainly anorthosites, how did the rest (e.g., Taylor, 1975) of the sampled and remotely sensed rock types form? A few may have been lavas extruded onto the surface, but most seem to be of intrusive origin (i.e., formed beneath the surface, as anorthosites themselves are formed on Earth). These intrusive rocks (troctolites, norites, dunes) contain ferromagnesian minerals. Plagioclase did not separate from the ferromagnesian minerals when the abundant, feldspar-bearing troctolites and norites formed. Since crystals of plagioclase have a density only slightly lower than that of the liquid suspending them, it might be expected that substantial quantities of the liquid would be entrapped among the suspended crystals as they floated to form the crust. This liquid would crystallize to produce ferromagnesian minerals along with the plagioclase. If so, then the lunar crust might have a composition characteristic of noritic anorthosite or anorthositic norite, more in line with the composition inferred from soil data and remote sensing data (e.g., Taylor, 1975; Korotev et al., 1980). Norites
are fairly common among the least altered Apollo highland samples, but noritic anorthosite is not; most sizable rocks collected of that composition are breccias, mixtures of precursor igneous rocks. If the anorthosite crust is as thick as has been suggested (20–60 km), why are intrusive rocks with ferromagnesian minerals so common among the collected highlands samples? Was an original anorthosite crust invaded by later magmas that crystallized to produce the norites and troctolites in analogy with the intrusive complexes found on Earth? Was the original crust mainly noritic anorthosite with only isolated “rockbergs” of anorthosite? Mapping and sampling of stratigraphically located highland materials would enormously improve our knowledge.

**Tilted Blocks**

It is not known whether any coherent blocks of crust that preserve original stratigraphy survived the heavy cratering of the lunar highlands. However, impact cratering and mixing processes were insufficient to homogenize the lunar highlands, and fragments of igneous rock at least as large as hand specimen size survived, so there is hope. Some blocks of original lunar crust may have become tilted, exposing to view a vertical cross section of their original horizontal layering. Perhaps the most promising example currently known is Silver Spur, about 20 km from the Apollo 15 landing site. Based on astronaut observations and photography, Silver Spur appears to be a tilted, coarsely layered block that exposes some 800 m of originally buried layers (Swann et al., 1972). The layering could be igneous, as desired for the study outlined here. It could also be a series of overlapping ejecta blankets, still of interest but for regolith studies. It does not appear to be an artifact of lighting conditions such that the layering is merely apparent, as observed in other regions of the Apennine front. Assuming that the layering is real, one argument in favor of its being igneous layering is that the breccias collected at the nearby Apennine front are relatively simple, consisting of one type of impact melt rock plus fragments of coarse-grained igneous rocks (Ryder, 1976; Ryder and Bower, 1977). This allows hope that impacts in this particular region did not destroy entirely the original igneous materials. To map and sample the steep face of Silver Spur would require at least two traverses down the face (assuming that the layering proves to be real) with local removal of obscuring regolith and sampling of the rocks in each stratum. Efficient transportation would be needed up the shallow slope of the top stratum to the summit, presumably by a rover. Then an astronaut in some sort of winch-driven sling would have to be lowered safely down the face, sweeping, mapping, and sampling as he went. An automated hammering or coring device might be needed for efficient sample collection. The project would require at least several days and perhaps weeks of sampling effort, depending on the coherence of the rocks and the depth of obscuring regolith. The rocks would undergo preliminary examination at the lunar base, then selected portions would be shipped to Earth for further characterization and study.

**Craters**

Impacts on the lunar surface excavate craters whose walls can reveal the strata into which the craters were punched. Whether that stratigraphy pertains mainly to layering
of highlands or mare igneous rocks or mainly to sheets of ejecta (including frozen melt pools) depends on the size of the crater and the material penetrated. The internal stratigraphy is of interest in either case and, for craters under a few kilometers in diameter, could be mapped and sampled with the aide of teleoperated dirt-moving equipment. Although there are craters at all sites, including the Apollo 15 site from which most of the examples in this discussion are drawn, to emphasize that these proposed studies are generic, we discuss as an example North Ray Crater at the Apollo 16 site. That crater is regarded as having penetrated into the highlands Descartes formation. Astronauts Duke and Young (Muehlberger, 1972) collected some 30 samples of light and dark breccias from its southern rim and described and photographed its northern wall. Initially, Ulrich (1973) attempted to match the breccias to light and dark materials seen in the crater wall and in the obscuring talus. He suggested that the crater penetrated through a blanket of Orientale ejecta into a blanket of Imbrium ejecta. Geochemical and petrographic studies (Lindstrom and Salpas, 1981, 1983), however, found many rock types among the breccias, so that the characterization as dark or light is misleadingly simple. Dark materials include three to five types of impact melt rocks; light materials include anorthosite, three types of granulite, and very KREEP-rich and KREEP-poor materials, indicating complex layering of the strata excavated. The Apollo 16 site was the site most nearly typical of lunar highlands; as determined from remote sensing data the significance of these rock types is Moon-wide. Other geological models for the Apollo 16 landing site have been developed (Spudis, 1984), but better knowledge of rock types and interrelationships is essential to understanding the nature and history of the region. The radius of North Ray Crater is about 1-km, and its depth is 230 m (Ulrich, 1981). The slope of its walls is only about 30°, shallow enough to be entered by dirt-moving equipment. Such a device of even modest capacity (10 m³/h) could cut a trench 10 m wide and 2 m deep from the rim to the center of the floor in a lunar day (about 328 hours). Of course, just how much dirt would have to be removed is speculative, but this estimate demonstrates the possibility for determining the stratigraphy of at least the upper two thirds or so of the rim. Most of the excavation could be done by remote control, with an astronaut visiting the site only periodically to map trench walls and collect samples. The information gained, in conjunction with that from samples taken from the rim and radially outward, would yield first-order insight into the petrologic character of the materials of the Descartes formation, into the mechanics of impact cratering, and into regolith mixing.

**Basalts**

Our understanding of lunar volcanism is far from adequate to answer key questions about the Moon's interior composition and melting processes (e.g., Vaniman *et al.*, 1984, 1985). Knowledge of stratigraphic relationships is vital to proper sampling of mare basalts as well as of materials from the lunar highlands. Several types of basalts and several different flows seem to have been sampled by the Apollo 11, 12, 15, and 17 missions (e.g., Taylor, 1975), and further types were collected during the Apollo 14 and Luna 16 and 24 missions. Moreover, each site yielded a perplexing variety of basalt compositions. Spectral data from ground-based remote sensing indicate the presence of yet other types,
some of which appear to be more prevalent than those already sampled (e.g., Pieters, 1978).

Without geological control over sampling, spatial relationships among the types at a given site and compositional variability within single flows cannot be established. Complete characterization of a mare basin may require traverses across the basin (Spudis et al., 1984; Cintala et al., 1985) to collect samples from all types of basalts that cover the surface and from craters that have penetrated beneath the uppermost flows to provide samples of earlier basalt types. All of the basalt samples collected by the Apollo and Luna missions, except perhaps one from the Apollo 15 mission, were collected from the regolith, and it is unknown from what flows or exact locations they derived. A lunar base near a rille offers the opportunity to sample at least several different flows along the rille wall.

Hadley Rille, visited by the Apollo 15 mission, is some 400 m deep and 1.5 km wide. Its original walls and floor are largely obscured by talus and debris from nearby impacts, but in situ bedrock was observed and photographed on the wall opposite the landing site. Layered strata were observed to outcrop discontinuously in the upper 60 m of the opposite rim. The more massive layers are only 1-3 m thick (Swann et al., 1972); some layers are observed to “weather out” differently from others, suggesting that the layers represent different flows or, in some cases, bands of intervening regolith. How many different flows might be represented is uncertain, however, as several layers could derive from a single flow. In addition to the flows possibly represented in the vertical face at one location, portions of the rille farther “downstream” could expose a different set of flows. Even the intervening regolith, if it exists, can provide information about the eruption sequence of different basalt types if there was substantial change in the types of material on the impacted surfaces from which the ejecta were produced. Sampling and more detailed study of the rille strata are required before we can know how many flows are represented and what the characteristics of flow tops and bottoms are.

Further study of mare basalts in situ is clearly important to understanding lunar volcanism. Detailed study of rille strata can provide observational information on the characteristics of flows, which presumably resemble the least viscous terrestrial pahoehoe flows of Earth's rift zones and oceanic island volcanoes such as those of Iceland and Hawaii. What is the typical thickness of lunar basalt flows? What are the characteristics of flow tops and flow bottoms; are they vesicular as on Earth? If so, what are the volatile components responsible for the vesicularity (a problem not yet solved from study of the samples of vesicular basalt acquired by the Apollo missions)? Are successive flows similar in character or do the different lava types known alternate in the eruption sequence? These and other questions can be answered by studying the walls of Hadley Rille and collecting samples. This requires equipment such as that discussed above for sampling the face of a raised, tilted fault block because sides of rilles are too steep, at least where seen by the Apollo 15 astronauts, to traverse on foot or by rover. The opposite wall of a rille, while an important source of supplementary information about the structure and stratigraphy of the rille, is too far away at 1.5 km for detailed observation. Thus, astronauts who study the stratigraphy will have to do so mainly on the face they cannot
see from the side they are on prior to descent. A power coring device or hammer is likely to be essential for proper sampling because lunar basalts, like their terrestrial counterparts, are coherent and tough. Several traverses down the face of the rille, each requiring one to a few days, would be needed for this study. It may be difficult to determine from field evidence and microscopic examination how many different varieties of basalt have been sampled, so for this study an X-ray fluorescence unit at the Moon base might be of particular value.

RARE MATERIALS

The presence of certain materials can be inferred from the nature of the known lunar rock types. These include possible lava lakes and mantle xenoliths in mare regions and concentrations of relatively volatile elements (e.g., sulfur, chlorine, arsenic, zinc) in mare pyroclastic deposits and in products of metamorphism in the highlands. It is to be expected that other, unanticipated rare materials will be discovered in the vicinity of the lunar base. These unanticipated materials will deserve sampling and study to understand their origins and natures, and they may also serve as horizon markers or as tracers of specific volcanic or regolith-modifying events. Lava lakes are important in demonstrating the nature of magmatic crystallization and as a potential source of ores. Their analogs on Earth have been studied, for example, on the Hawaiian volcano Kilauea. Magma becomes trapped in a pit crater or other depression, then forms an insulating crust by cooling against its container and against the convecting atmosphere (Wright et al., 1976). (On the Moon, radiation of heat into space would have to produce the upper crust.) Such events account for only a small percent of the exposed lavas on Kilauea and depend on the availability of depressions for their formation. They can thus be expected to be rare on the Moon as well, although flooded impact craters may offer added sites of a type not found on Hawaii.

Some varieties of lunar basalt are rich in ilmenite, a titanium mineral of possible interest for the manufacture of oxygen and of iron and titanium metals. Conceivably, that mineral or a chromium ore such as chromite (Taylor, 1984) might crystallize selectively in a lava lake to produce a useful as well as scientifically interesting ore. A lava lake might appear, dissected, on the wall of a crater or a rille. A lava lake might have been included in the target of an impact event so that coarse-grained products of mare volcanism might be found as rock chunks in the regolith. Such chunks would be relatively rare and might be discovered only by observation by an alert astronaut searching basaltic rubble.

The counterpart of the mare lava lake should also have occurred in the highlands. In addition to lava lakes born from magmas seeping from the Moon's deep interior, magma lakes may have formed in the lunar highlands within melt sheets from impact craters; some might have undergone analogous chemical differentiation by crystal settling.

One of the main sources of information about materials of Earth's mantle is mantle xenoliths, fragments of material broken from deep rocks and transported to the surface during volcanism. These are rare and tend to accompany more explosive types of volcanism,
perhaps because they have high enough velocities of flow to suspend them against the force of gravity. On the Moon the mare lavas have low viscosity, which works against the raising of mantle fragments, but there is also lower gravity, which makes it easier than on Earth. Xenoliths have not been observed among the lunar basalts collected so far, but, if they are as rare as on Earth, none would be expected in such a small sampling. On the lunar surface, where thousands of fragments of lunar basalt can be examined, there is a much better chance of finding them. If found, they would provide direct evidence of the nature of the Moon's interior and would be invaluable in constraining ideas about its mineralogy and composition. Perhaps mantle nodules are best sought in regions where the most explosive form of volcanism is believed to have occurred on the Moon. These may be near the so-called dark halo craters, from which lava fountains have been inferred to come and of which the orange glass found at the Apollo 17 site may be a product.

Most highlands rocks at the lunar surface are breccias, fragments of earlier rocks broken up and consolidated by impact processes. Within many of the breccias, however, are recognizable fragments of highlands igneous rocks. In many cases, these fragments show alteration from the impact and brecciation processes that made them. A few, however, show features characteristic of types of metamorphic processes found on Earth. For example, Apollo 16 breccia 67016 (Norman, 1981) contains fragments of igneous anorthositic norite, most of which are sulfide free but some of which are metamorphosed with veins of iron sulfide (troilite) and regions in which a ferromagnesian silicate mineral (pyroxene) has been partially altered to iron sulfide. It appears that a sulfur-bearing fluid had invaded that rock and begun to metamorphose it. Such a fluid could also extract rare elements from large quantities of rock, in analogy to the formation of hydrothermal ores on Earth. It is not evident whether the metamorphism accompanied or preceded the impact event that produced the breccia as sampled. Impact energy may have been the ultimate driving force for the metamorphism, but the style seems to be that of a percolating fluid.

Sulfur is also enriched in lunar pyroclastic glasses (e.g., Butler and Meyer, 1976); this sulfur is presumably of igneous origin. Sulfur is not the only apparent agent of metamorphic alteration. Some metamorphosed intrusive rocks, including anorthosites, are rich in phosphate and numerous trace elements. The origin of this material is unknown, but igneous processes as currently understood do not seem capable of producing it. The observed enrichment in trace elements is reminiscent of that found in the enigmatic lunar material called KREEP, but the concentrations of the major constituents are quite different, and the concentrations of the trace elements in the phosphate-rich regions are higher than those found in KREEP (e.g., Warren and Wasson, 1979). Additional evidence that the apparent metamorphism may not have been caused by the immediate impacts producing the breccia samples but may be a more regional event is the nature of the highlands breccias sampled at Apollo 15. Those breccias contain clasts of igneous rocks, some of which show signs of metamorphism, but most of which retain their igneous textures and do not appear to have undergone numerous impacts as the breccias from Apollos 14 and 16 seem to have done. A search for rocks with sulfide mineralization could be carried out in conjunction with other observing and sampling activities. The
pattern and frequency of occurrence of such rocks could indicate whether metamorphic processes are widespread, with the possibility of locating specific regions affected. A promising site for such observations would be the Silver Spur project outlined above.

CONCLUSIONS

The projects outlined above are but a few of many that would constitute important scientific research at a lunar base. They address restricted aspects of geochemistry and petrology, broad areas that are themselves only a subset of the geological sciences. They are designed to optimize the opportunities in the immediate vicinity of the base and to take advantage of the equipment that will be needed for construction and materials processing as well as for scientific study. Thus, they are suited to an initial, multipurpose base. They are also designed to take advantage of a very substantial terrestrial laboratory effort, with the astronaut-geologist or -geochemist mainly responsible for observation, details of experiment design, and sample collection during the tour of duty on the Moon. On returning from the Moon, the astronaut would then be an invaluable colleague to the numerous laboratories investigating a broad variety of lunar problems. The types of science outlined above are important for first-order understanding of the nature of the Moon and for constraining our ideas about its history.

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A CLOSER LOOK AT LUNAR VOLCANISM FROM A BASE ON THE MOON

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The American Apollo and Soviet Luna missions provided much information on lunar volcanism, but major questions remain. Field work associated with a manned lunar base will be indispensable for resolving the scientific questions about ages, compositions, and eruption processes of lunar volcanism. From a utilitarian standpoint, a better knowledge of lunar volcanism early in the lunar base program will yield profitable returns in improved lunar construction methods (e.g., exploitation of rille or lava-tube structures) and in access to materials such as volatile elements, pure glass, or ilmenite for lunar industry.

**INTRODUCTION**

Volcanism is a fundamental planetary process. Lavas probably flowed across Mercury's lunar-like surface, erupted to build huge shield volcanoes on Mars, and even oozed across the surfaces of some asteroids. Glowing lavas still make their way to the surfaces of Earth, Jupiter's satellite Io, and probably Venus, too. A major part of the Moon's landscape was formed by basaltic lava flows, which now constitute the dark areas called maria.

Volcanism is much more than a surface process, however. Lavas originate inside a planet when rocks undergo partial melting. Consequently, lavas serve as probes of the mineralogy and chemical composition of otherwise inaccessible planetary interiors. Much of the research done on samples of lunar volcanic rocks has been geared to understanding the varieties and origins of their source regions in the Moon's interior. Volcanic rocks also contain information about a planet's thermal history, which is intimately related to its origin and evolution. Did it form cold and heat up? Did it form hot and then cool? Did it heat up, cool, and then heat up again? Thus, although covering only 17% of the Moon's surface and constituting a tiny 1% of its crustal volume (Head, 1976), lunar volcanic rocks give us a broad picture of its geochemical processes.

Although a broad range of volcanic rock types probably occurs on the Moon (Head, 1976) the dark, low-silica rocks known as basalts constitute the only volcanic samples returned from lunar missions. Basalts of the lunar maria contrast with the light-colored highlands areas that are so strikingly visible when one looks at the Moon. Basalts of the lunar highlands do occur, but only a few small samples have been found within
impact-generated breccias. However, the concept of “highland volcanism” may stretch the limits of our previous conceptions of what lunar volcanism is.

The term “volcanism” implies eruption of a melt derived from solid material at depth. It has been suggested that some very old volcanic rocks on the Moon could have crystallized from liquid remnants of a very large magma system (“magma ocean”) that enveloped the Moon at some time prior to 4.4 b.y. ago (Wood, 1975). This is one explanation (Warren and Wasson, 1979) for some lunar magmatic compositions that are rich in the otherwise rare elements potassium, rare earths, and phosphorus (immortalized in the acronym “KREEP”). Such an origin as a result of crustal cooling is conceptually very different from volcanism caused by deep internal heating, though the actual extrusion may be very similar. There is also a possibility that some lavas could have been brought to the surface by impact excavation of crustal magma chambers (Schultz and Spudis, 1979). Although there is a slight semantic problem in calling such lavas “volcanic,” it is intriguing to consider the chances of finding these rocks on the Moon, since such lavas have not been preserved on Earth. Because of our very limited knowledge of these other magma types, this paper emphasizes speculations drawn from the larger data base on mare basalts.

Lunar mare basalts differ markedly from terrestrial basalts. Among major chemical constituents, titanium content is, in general, considerably higher, whereas aluminum, potassium, and sodium contents and magnesium-to-iron ratios are much lower. Potassium contents are in fact so low in mare basalts that this element is often listed as a trace constituent (less than one tenth of one percent). Conversely, chromium is often listed among the major constituents in mare basalts (about 0.5% Cr₂O₃), whereas it is strictly a trace element in terrestrial basalts. The higher chromium content of lunar mare basalts, along with their high to very high titanium content, suggests that useful concentrations of chromite and ilmenite may occur on the Moon. Metal oxides may well be concentrated by separation of heavy crystals from mare basalt magmas (Taylor, 1984). But the definition of an ore (i.e., a profitably mined geologic commodity) may lead to a classification as “ore” for some deposits that would be mundane on Earth. A key feature of the Moon is its depletion in volatile elements and compounds; in particular, mare basalts are depleted in water and carbon-oxygen compounds in comparison with terrestrial basalts. Sulfur, however, is as abundant or more abundant in mare basalts than it is in terrestrial basalts. Could accessible sulfur concentrations become an ore for lunar base exploitation? Mare basalt resources may also encompass the forms resulting from volcanic processes, such as lava tubes (Hörz, 1985; Khalili, 1984). Operations from a lunar base must be as aware of the resource potential of lunar volcanic rocks as of the outstanding scientific questions to be answered from studies of lunar volcanism.

**VOLCANIC ORIGINS, AGES, AND COMPOSITIONS**

Mare-flooding basalts that have been dated range from 3.8 to 3.1 b.y. old. Clasts of mare basalts within breccias extend the time of such volcanism back to 4.2 b.y. (Taylor et al., 1983). Volcanic rocks younger than 3.1 b.y. have not been found among the lunar samples but photogeologic and remote sensing studies suggest that there are high-titanium
basaltic lavas as young as 2.5 b.y. (Head, 1976) or younger (Boyce et al., 1974; Schultz and Spudis, 1983). The answers to several important questions of lunar history are tied to volcanic processes: when they began, when they ceased, and how much activity occurred.

The oldest lunar volcanism may be difficult to decipher because of the widespread impact disruption of samples older than 3.9 b.y. Model isotopic ages derived from lunar basalts indicate that the source regions for magma production were established at 4.4 b.y.; the Moon may eventually provide volcanic rocks as old as this, or we may even find “pseudovolcanic” residual liquids that predate these source regions. It is encouraging that, even with our limited sampling of the Moon, we have obtained volcanic rocks that are almost as old as the Moon’s initial differentiation. More detailed sampling might provide a map of chemical compositions and times of eruption that will record the ancient separation of lunar crust and mantle. From the experience we have had so far, it appears that the best place to look is within soils and breccias where small volcanic clasts occur. The oldest breccias exposed deep within the walls of large basins accessible from a lunar base should provide useful samples of these rocks.

The youngest lunar volcanism should be much easier to find, for these rocks will be the least impact-disrupted of lunar surface materials. Photogeologic and remote sensing studies have already pointed to volcanic flows in Mare Imbrium that may be as young as 2.5 b.y. (Schaber, 1973) or younger (Boyce et al., 1974; Schultz and Spudis, 1983). Spectral data indicate that these flows consist of high-titanium basalt (Pieters et al., 1974; Basaltic Volcanism Study Project, 1981), an interesting observation when it is considered that high-titanium basalts are also among the oldest (3.6–3.8 b.y.) radiometrically dated samples from lunar mare. The age-composition progression among mare basalts has already revealed a complex lunar mantle history that goes far beyond single-event melting of differing mantle source regions; closer study is required to evaluate what really went on. The history of lunar interior melting will also be an important parameter for determining lunar cooling history and the inventory of heat-producing radioactive elements in the lunar interior.

The volume of lunar volcanic rocks and variation of eruption rates through time are important parameters for determining a coupled history of lunar heat transfer and mantle evolution. A speculative summary of lunar eruption rates over time (Basaltic Volcanism Study Project, 1981) proposes two extreme scenarios: (1) very little volcanism prior to 3.9 b.y., or (2) abundant volcanism prior to 3.9 b.y. The total volumes of volcanic rocks estimated for these two scenarios differ by a factor of about two: around $10^7$ km$^3$ with minimal early volcanism and about $2 \times 10^7$ km$^3$ with abundant early volcanism. The difference in implications for lunar evolution, however, is greater. If there are large volumes of older basalt hidden beneath the lunar highlands, then large-scale melting of the lunar mantle may have followed fast on the heels of the “magma ocean” crystallization. The resolution of this question lies in the discovery of how much old volcanic material underlies the highlands. Dark-haloed craters in the highlands have been pointed out as promising sites for such an investigation because they expose low-albedo basaltic materials that apparently underlie the high-albedo (non-basaltic) highlands debris (Schultz and Spudis, 1979). The dark-haloed craters are excellent examples of a type of lunar deposit.
that has not yet been sampled, where a closer look is vital to our understanding of the Moon.

**Mare Basalt Compositions**

The presently available samples of lunar basalts have been studied in great detail, though not yet exhaustively. Data from these samples show that mare basalts fall into three main categories, based on their content of TiO$_2$: high-Ti (8.5-13.0 wt % TiO$_2$), low-Ti (2-5 wt %), and very low-Ti (<1 wt %). In addition, some low-Ti basalts are relatively enriched in Al$_2$O$_3$ and are called aluminous mare basalts. However, remote sensing data indicate that there are at least twenty different types of mare basalts (Basaltic Volcanism Study Project, 1981). Moreover, as discussed below, our present collection of lunar basalts may not represent the full variety of lava types present at a given site. For review of mare basalt chemical and mineralogical compositions, see Papke *et al.* (1976), chapter 1.2.9 in the Basaltic Volcanism Study Project (1981), and chapter 6 in S. R. Taylor (1982).

Sample analyses, geochemical calculations, and experiments at high temperatures and pressures suggest that most mare basalts formed by remelting of deep rocks (at least 100 km) that had originally formed from the "magma ocean." We do not know, however, how much assimilation of surrounding rock and how much fractional crystallization took place as the basaltic magmas migrated to the lunar surface and then flowed across it. Both these processes affect conclusions about the nature and origin of the mantle source rocks. Detailed sampling of mare lava flows accessible from a lunar base will help to test the effects of assimilation and fractional crystallization.

**Sampling a Larger Range of Basalt Types**

Based on analyses of lunar samples, mare basalts seem to form distinct groups with respect to a number of chemical discriminants. Extremes of TiO$_2$ content have been recognized, but remote sensing data obtained by telescopic observations of the Moon and by gamma ray and x-ray fluorescence experiments flown on the Apollo 15 and 16 command modules indicate that a full range of intermediate TiO$_2$ contents might be present among mare basalts. Moreover, a detailed analysis of spectral properties, summarized in chapter 4 of the Basaltic Volcanism Study Project (1981), suggest that the Apollo and Luna missions have sampled at most only one third of the basalt types exposed on the Earth-facing side of the Moon. A map of known, similar-to-known, and unknown basalt types based on this study is shown in Fig. 1. Figure 1 also summarizes some of the data from remote sensing using three of the critical signals used for this map: TiO$_2$ content, aluminum-to-silicon ratios, and K$_2$O content. An important feature is that the remote sensing data actually map the soils on top of the mare, and when we compare the soils with actual underlying basalt samples, the match is not good because of the mixing that goes along with lunar soil formation. Clearly we have much to learn about lunar basalts. Consequently, expeditions from a lunar base must sample all types of mare basalts that remote sensing data suggest are present beneath the veil of soil. A major prerequisite for doing this sampling intelligently is a more thorough photographic and spectral coverage of the Moon. This coverage can be obtained from unmanned polar-
orbiting lunar missions such as those tentatively planned by the United States, Japan, and the Soviet Union.

**Sampling Problems at a Given Site**

When working on Earth, geologists take great pains to collect samples from discernible rock units (e.g., from a single lava flow). No lunar basalt was collected in this manner. All were pieces of rock chipped loose by impacts and strewn about on the surface. As a result, we do not know how many individual lava flows were sampled at each landing site. We can make intelligent guesses from chemical and mineralogical data, but we have no definitive field data relating one basalt sample to another. Considering also that the chemical variability in mare basalt flows may be high (Haskin et al., 1977), we may have scarcely sampled the lunar maria at all.
Good sampling requires thorough field work, in which samples are taken from identifiable rock units such as those exposed in the walls of rilles and craters. At this time, we have visited only two sites where the volcanic deposits were relatively undisturbed: (1) the edge of Hadley Rille where a basalt flow was exposed (Apollo 15 site, Fig. 1) and (2) an overturned section of pyroclastic rocks within a crater rim in the Valley of Taurus Littrow (Apollo 17). Where such features are not exposed, samples can be obtained by drilling or by digging deep, wide trenches in the lunar surface (Korotev, 1984). Construction operations at a lunar base could also be integrated into the sampling of volcanic units, particularly where drilling or digging is involved.

Lateral Variations in Single Flows

Mare basalt lavas were much more fluid than terrestrial basalts (Murase and McBirney, 1970) and flowed easily across the Moon's surface. As they flowed, it is quite likely that they crystallized with heavier crystals concentrating near the flow bottoms. How much crystallization took place before a given flow reached an area sampled by an Apollo or Luna mission is anyone's guess. It is also possible that as lavas flowed across the Moon they reacted with the underlying regolith, assimilating a variety of chemical components. As a result, few if any of the basalts returned to us are likely to be “primary magmas” that maintained chemical integrity from their origins inside the Moon until sampled billions of years later. This is especially true if crystallization and assimilation took place inside the Moon before the lavas erupted.

It is difficult to obtain field data about processes operating inside a planet, but we can test the extent to which lavas crystallized or reacted as they flowed on the surface. Mapped flows could be sampled where they emerged (vents) and at intervals to their distal ends. It is possible that deposits of heavy minerals, including potentially valuable ones such as ilmenite (FeTiO₃), could be found by this type of exploration. Exploration on this scale will only be feasible where prolonged operations are supported from a lunar base.

VOLCANIC PROCESSES

Carefully documented stratigraphic studies of igneous rocks will provide information not only on the Moon's thermal history, but also on the processes involved in the filling of the mare basins. To understand lunar volcanic processes, it is important to find certain features of the mare basins and study the processes that formed them:

1. Dikes: Determine dike locations, orientations, and ages to study the migration of dike systems as the basins filled.

2. Products of explosive volcanism: Determine the extent and means of deposition of pyroclastic deposits; find source vents for these deposits and determine their shape, location, number, and size; find the lava flows that erupted contemporaneously with explosive activity.

3. Lunar lava flows: By mapping and sampling determine the eruption rates, sources, processes of crystal concentration and volatile loss during flow over
long distance, and mode of transport.

(4) Physiographic features interpreted as volcanoes: Determine if they are volcanoes; determine whether the variety of landforms, such as domes, shields (Fig. 2), cones, and fissure mounds imply a variety of magma types and eruption processes that we have not sampled. Studies of vent areas will test ideas concerning cold traps that may have concentrated volcanic volatile phases as sublimes in and near the fissures. Subsidence of ponded lavas may also provide information on degassing of these ponds or on backflow of lavas into vents during waning stages of the eruptions.

(5) Products of eruption processes that we have not studied on Earth: (a) rille formation is very important on the Moon (Fig. 3) but is still one of the great mysteries that challenge the volcanologist. Are the rilles a result of high eruption rates and temperatures, 1/6 g, or lack of an atmosphere? (b) Explosive eruptions into a vacuum have been modeled, and we have representative samples of their products, but we have not explored the extent and nature of these pyroclastic deposits.

This list of features is obviously not complete, for volcanism on the Moon is very different than that on Earth. Even on Earth we have found that generalizations about volcanoes are misleading. As we study more and more terrestrial volcanoes we find that each is different. The same might be said about the Moon's volcanoes as we move through the first phases of exploration from a lunar base.

Figure 2. Mare Veris, located at the base of the Rook Mountains scarp, eastern Mare Orientale. The rings of this large basin are only partly filled with lavas. Many of the basaltic volcanoes, the sources of these lava flows, are visible. In this Lunar Orbiter image, there are three lava shields (arrows); the topmost has a summit crater and the lower-right has a fissure vent crossing the shield.
VOLCANIC RESOURCES

Lunar volcanic features and volcanic rocks can be used to provide shielding, shelter, construction materials, and bedrock for anchoring structures. Specific uses of natural mare structures such as lava tubes or lava caves for shelter are considered in this volume (Hörz, 1985; Khalili, 1984). Soils of the mare basins provide materials of higher average atomic number than lunar highland soils. This property makes mare soils more attractive for shielding against solar and cosmic radiation. The iron-rich mare soils also melt at lower temperatures (~1200°C) than the highland soils (~1400°C), bringing them more readily within the range of construction processes that rely on fused brick or melted soil techniques. In addition to their lower melting temperatures, the mare soils also have a low melt viscosity (~10–100 poises) that makes them useful for thermal construction in which flowage is desired (Khalili, 1984).
Beyond the construction phase of lunar base operations, the profitable use of lunar resources must be explored for space-based industries and to support the development of space-based civilization. Lunar mare volcanic rocks are known to be sources of ilmenite (FeTiO₃) and chromite (FeCr₂O₄), minerals with metallic ore value on Earth that may likely be found as ores in mare regions of the Moon (Taylor, 1984). Such ores can be formed by gravitational separation of crystals from cooling magma of low viscosity, a process likely to be the most important one for forming metallic ores on the Moon. However, the volatile elements associated with some mare basalt deposits might also be considered as lunar ores.

Lunar basalts are known to be markedly depleted in water and carbon-oxygen compounds that are important volatile constituents in terrestrial volcanism. This fact is often construed to suggest that no volatile elements can be found on the Moon in abundances comparable to Earth. Such is not the case, for sulfur has an abundance (about 0.2 wt % in high-Ti basalts) that exceeds the sulfur abundance in most terrestrial basalts. Based upon samples from the Apollo 11 and 17 sites and on some good remote sensing studies, “dark mantle” deposits of the Moon’s nearside appear to be glasses of volcanic origin and may serve as unique resources for sulfur and sulfide–associated elements that are of great use for some manufacturing processes. Sublimates on surfaces of these glass particles, the residue of gases extruded during explosive volcanism, may provide the best source of volatiles on the Moon (Fig. 4). Furthermore, close study of these deposits may shed light on the source of volatile elements within the Moon, which has implications for theories of lunar origin (Delano, 1982). Volatile elements associated with lunar pyroclastic

![Figure 4. Constituents of lunar volcanic gas, based on Delano’s (1982) synthesis of volatile elements correlated with lunar volcanic glasses. In abundance, sulfur predominates and has an abundance (about 0.2 wt % in high-Ti basalts) that exceeds the sulfur abundance in most terrestrial basalts. Water and CO₂ are notably deficient in lunar basalts.](https://example.com)
Table 1. A Closer Look at Volcanological Processes on the Earth's Moon—Summary

<table>
<thead>
<tr>
<th>Processes to be Studied</th>
<th>Scientific Significance</th>
<th>Pragmatic Significance</th>
<th>Exploration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filling of the maria.</td>
<td>a. History of lunar volcanism.</td>
<td>a. Search for volatiles associated with vents.</td>
<td>a. Visit mare basins of different ages, levels of fill, and with a variety of volcanic landforms. At each location: determine the volcanic stratigraphy in crater and rille walls or by coring. Following field studies, obtain a complete complement of laboratory studies such as age dates, petrology, and chemistry.</td>
</tr>
<tr>
<td>Eruption rates and basin structure.</td>
<td>b. Vent locations and relation to basin structure.</td>
<td>b. Lava tubes and rilles for structures that must be buried.</td>
<td>b. Begin exploration with the rings of Mare Orientale (Fig. 2).</td>
</tr>
<tr>
<td></td>
<td>c. Variations in eruption processes in stages of mare filling and lava flowback.</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>d. Deformation of mare surfaces during filling.</td>
<td></td>
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</tr>
<tr>
<td>Explosive volcanic activity.</td>
<td>a. Evolution of lunar magmas through time with regard to volatile phases.</td>
<td>a. Locate concentrations of volatiles (sublimates in vent “cold traps”).</td>
<td>a. Visit vent areas identified.</td>
</tr>
<tr>
<td></td>
<td>c. Relations of lava flows and pyroclastic deposits.</td>
<td></td>
<td>c. Visit the variety of volcanic landforms seen on satellite photos of the Aristarchus Plateau and Marius Hills.</td>
</tr>
<tr>
<td></td>
<td>d. Dark mantle deposits—a few vents with widespread deposits or many vents with small deposits?</td>
<td></td>
<td>d. Gravity and active seismic surveys of suspected vents.</td>
</tr>
<tr>
<td>Magma migration within the Moon.</td>
<td>a. Rise of lunar magmas—dike formation.</td>
<td></td>
<td>a. Visit dike and vent localities.</td>
</tr>
<tr>
<td></td>
<td>b. Search for mantle and crustal xenoliths.</td>
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</table>
glasses are indicative of the combined fruits of a closer look at lunar volcanism in which both utility and science may be served.

CONCLUSIONS: A PROGRAM OF EXPLORATION

As part of geologic exploration from a lunar base (Table 1), the evolution of mare basins could be studied by visiting maria of different ages and with different levels of lava fill. A series of landings and traverses within the rings of the Orientale basin (Fig. 2) would provide an opportunity to visit shield volcanoes and fissure vents that may have erupted only enough lava (and ash?) to fill the bottoms of ring depressions. Visiting progressively older mare basins for field studies will eventually provide the observations and samples necessary for reconstruction of the history of lunar mare volcanism. Older highlands volcanism will be considerably more difficult to study because of intense cratering of those surfaces; reconstruction of this activity may be limited to breccia sample studies.

Another major phase of exploration will be to visit volcanic vents. Maps can be made of pyroclastic rocks, their associated sublimates, and the stratigraphy of those deposits along with the relation between clastic rocks and lavas. Deposits near vent areas may also contain xenoliths (foreign fragments of deep crustal or mantle rocks included in lavas). The search for lava tubes should begin near those vents identified by photogeologic mapping. The association of lava tubes and volatile-rich pyroclastic deposits makes locales such as these particularly enticing for the support of both science and utilization. Volcanic stratigraphy and the changes in basalt composition with time may be studied in rille walls, crater walls, and, if no outcrops are visible, by coring from the mare surface. Primary sites for these studies are along basin margins such as eastern Mare Serenitatis and Mare Imbrium and in what appear to be volcanic plateaus such as the Marius Hills and the Aristarchus Plateau. The possible terrains are many, and they provide a large range of sites accessible to a lunar base.

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REFERENCES


ADVANCED GEOLOGIC EXPLORATION SUPPORTED BY A LUNAR BASE: A TRAVERSE ACROSS THE IMBRIUM-PROCELLARUM REGION OF THE MOON

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Inherent with the existence of a permanent manned presence on the Moon should be the ability to conduct extended geological explorations. Not only would a wide variety of features become accessible to scientists, but the sophisticated investigations performed in the field would make the spectacular Apollo efforts pale in comparison. An example of such a traverse is presented here, with the Imbrium Basin and its environs the region selected to be studied. A field crew of six to eight members would travel a total distance of almost 4000 km as they visited 29 separate localities in an attempt to characterize the processes involved in the formation and evolution of a variety of major lunar features. Among the sites chosen in this expedition would be the Apennine Mountains, the Apennine Bench, Mare Imbrium, the Aristarchus Plateau, Oceanus Procellarum, the extreme western highlands, and Eratosthenes, Copernicus, and Aristarchus Craters.

INTRODUCTION

The Apollo missions to the Moon were able to acquire data that without question revolutionized the planetary sciences. A multitude of other disciplines, however, also reaped major gains. Among these other branches of science are those dealing with particles and fields, solar-planetary relationships, astronomy, astrophysics, isotopic studies, biology, and the interplanetary medium. This list is certainly not exhaustive, nor does it include topics in engineering or other disciplines affected by "spinoff," which would be much too extensive to address here. Although Apollo was inarguably undertaken as a politically motivated project, the sheer volume of the scientific return and analytical innovations was probably unsurpassed by that of any other single effort on record. Thus, if history can be taken as a suitable guide, it would require no gift of prophecy to foresee that the existence of a lunar base, however limited in initial extent, would provide the opportunity to expand our knowledge of the Moon—and of planets in general—by orders of magnitude.
The scientific importance of maintaining a permanent or semi-permanent manned presence on the Moon is perhaps best illustrated by considering the time spent on or in the vicinity of the Moon by Apollo astronauts. Apollo command/service modules spent a total of 716 hours and 2 minutes in closed lunar orbit, while the total stay-time on the surface was 299 hours and 44 minutes. Of the time on the surface, only 81 hours and 9 minutes saw the crews outside of their lunar modules (Baker, 1981). More correctly, at least one crew member was outside of the landing vehicle for that period of time. Generously assuming that both astronauts were performing science-related extravehicular activities (EVA) for the entire period of surface operations, a total of 162.3 man-hours are found to have been spent on surface science during the entire Apollo program. By way of comparison, this amounts to just under seven days for a two-person field team working 12 hours a day, which would comprise the beginnings of a reconnaissance effort in a terrestrial field-geology context. To contend that the Moon is a well-studied object from a geological standpoint would be severely optimistic.

Separate from these time limitations were others that were just as confining. The transportation capability on the surface during the final three missions, while outstanding in comparison with the walking EVAs of the first three flights, nevertheless left much to be desired. The lack of timely rescue capabilities levied the requirement that the astronauts could never be farther from the lunar module than their consumables (oxygen and cooling water) would permit them to walk, should the roving vehicle have failed; this cast an imposing shadow over the traverse planning teams (e.g., Muehlberger et al., 1980) and, of course, on the geological exploration itself. The quantity of scientific equipment that could be delivered to the surface of the Moon was relatively small, owing to the limited payload capacity of the lunar modules. (This is not to detract from the capabilities of the spacecraft or equipment itself, which were marvels of engineering. It is instead an indication that the variety of scientific experimentation was determined, for the most part, by engineering constraints that were in turn fixed by the available technology.) At the other end of the lunar visits, the quantity of lunar samples to be returned to Earth was likewise preordained by vehicle performance guidelines. All of these criteria were non-negotiable; the very success of the Apollo missions under these and other anticipated but unspecified contingencies serves as a testament to the ingenuity and dedication of all those involved in the construction of the flight plans and field activities.

The new generation of field geology made possible by the existence of a lunar base would suffer from few of the difficulties or limitations cited above. As an example, the quantity of samples available for study would be limited only by the ability of the scientists to find them, and the quality of those chosen would be enhanced by the time available to the field scientists in making their selections. The easy access to laboratory facilities would permit any number of investigations without, what would be in retrospect, the unreasonable restrictions caused by vehicle capabilities. The nature of the study—not time constraints, solar flares, or utter hopelessness of rescue—would dictate the duration of a stop at any particular locality. Should the time spent at a given locality be greater than that planned, the ability to rest, resupply, and repair malfunctioning equipment would minimize the impact on subsequent studies at different sites.
This contribution indulges in some speculation regarding a model traverse that might be undertaken by a field-geology team supported by a lunar base and its facilities. It is not intended to be a definitive study, but it might instead serve as an example of the sort of exploration made possible by the new capabilities, as well as to illustrate the requirements and rationale behind an extended scientific traverse across the lunar surface.

FIELD SUPPORT

It would be an exercise in futility to attempt to predict the equipment available to the next generation of lunar explorers, not only in terms of its sophistication, but also its quantity. Therefore, in the interest of a succinct contribution, a number of items and capabilities will be assumed. It is hoped that this list will not be unreasonable and that the reader will allow the unheralded appearance of these devices and instruments for the sake of the exercise. Without them or their counterparts, the traverse described herein would certainly be impossible; indeed, without the technology necessary to construct such hardware, the lunar base itself might be equally improbable.

Fundamental Requirements

In terms of both duration and distance, the expedition to be described here will be long by any standards. It could indeed be stressful to a single crew while presenting taxing demands on the technology used to develop vehicle-power and mobile life-support systems. A myriad of operational scenarios could be devised that would invoke unmanned, automated, and/or teleoperated segments of the traverse, such as those between scientific sites. Evaluation of the interaction between man and machine at that level, however, is well beyond the scope and intent of this contribution. A fully manned operation will be assumed for the duration of the exploration.

The team will consist of scientists and support technicians; should the geologic traverse vehicle (GTV) be manned during its movement between sites, the technicians would probably double as GTV operators and mechanics. The number of scientists is difficult to suggest, but some requirements help in refining the estimate. As discussed below, it would be extremely desirable to have relatively short-range excursion capability from the “base camp” (as defined by the location of the GTV). As envisioned here, these “rovers” would require a crew of two for reasons of efficiency and safety. Thus, should two rovers be allowable, and with two scientists left at the base camp, the number of scientists becomes six for the purposes of this exercise. Thus, including two technicians/transport crewmembers, the size of the field team is suggested to be six to eight, depending on the number of rovers.

Transportation and Logistical Support

The shape and details of the GTV are unknown and of little concern to this paper. Its mode of transportation is also problematic, although it will more likely be a wheeled or tracked vehicle than a rocket-powered one for reasons of economy. While the flying
version would be desirable in the sense that it would be faster and might double as a remote-sensing platform, lunar-orbiting spacecraft could provide such support. Therefore, the GTV assumed here will be a ground vehicle capable of negotiating steep (>30°) slopes of poorly consolidated material. It will be required to include or provide the following:

- Shelter and consumables
- First-order analytical equipment (described below)
- Navigational equipment and communications
- Sample-collecting equipment
- Reusable geophysical instrumentation (e.g., magnetometers, gravimeters, etc.)
- Multi-spectral cameras
- Pressure suits for all crewmembers, as well as spares

The two rover vehicles would be carried or towed by the GTV; each should have a nominal traverse distance of at least 50 km between recharging or refueling. As it would be extremely desirable for the scientists to study the surroundings as they moved between stops, the rovers should be ground vehicles in order to maximize the scientific return of the forays from the base camp. It would be very useful if they were also pressurized, offering sufficient room for sleeping and other activities while the independent excursions were taking place. Clearly, it would not be efficient to suffer untimely returns to the base camp when dictated by consumables or crew fatigue. Thus, each would be, in effect, a scaled-down, more agile version of the GTV in some respects, but without the extensive scientific support instrumentation. Multiple EVAs would be possible from each rover before they would return to the base camp for recharging.

Resupply of the consumables required by the team, as well as delivery of samples to the better equipped main complex would be accomplished by periodic ferry flights originating at the lunar base. The frequency of these flights would be set by a number of factors to be determined elsewhere.

**Analytical Instrumentation**

It should go without saying that the more instrumentation capable of being carried inside the GTV, the more “bits per buck” will be obtainable. On the other hand, it is unlikely that a complete geochemical/petrologic laboratory could be included in the vehicle. With this in mind, it would be highly desirable to have the following instrumentation:

- microscopes (binocular, petrographic) and thin-sectioning equipment
- equipment for first-order chemical analysis (primarily to obtain whole-rock compositional information)
- computer support

It would probably be more efficient for the rovers to have payload capacity relegated to samples than to analytical instrumentation. It would be useful, however, if they would include binocular microscopes and small X-ray fluorescence units with supporting hardware. This would provide the crews with enhanced sample characterization capabilities, thus permitting decisive sample selection in the field.
Field Equipment

Personal field equipment similar to that carried on Apollo would be used by all crewmembers, but a major advantage of this sort of exploration is the ability to perform investigations on a much larger scale than had been done previously. Thus, deep drill-coring operations (i.e., more than a few hundred meters) would be within the realm of possible field operations. Deep coring, however, is an extremely time-intensive proposition even on Earth with all of the requisite materials readily at hand. The Moon will present an environment that is much more inimical to such activities; lubricating fluids for the core tubes and bits, for instance, will present a severe challenge to geological engineers. A new drilling technology, the foundations of which might well have been laid already (Rowley and Neudecker, 1984), would be required in order to make such important studies possible. Given the deep-coring capability, a core-extrusion unit will be necessary for use in the field: 100 m of core-tubing, 10 cm in diameter and full of rock and regolith would possess a mass of roughly 2 metric tons. It is obvious that the field team would have to break down the core in the field, sampling it at strategic intervals. In this way, the bulk of the core could be left at the site for future retrieval, if desired, while representative samples could be returned to laboratories better equipped than that aboard the GTV.

The use of a backhoe or similar device would permit regolith studies on a scale that would minimize statistical extrapolations, setting stratigraphic studies on a firm basis. Comparatively deep trenches could be excavated with little effort, yielding a spatially extensive cross-section of regolith stratigraphy. Indeed, removal of regolith to the basal bedrock in some mare areas could become commonplace, a capability that cannot be overemphasized in terms of regolith science and studies of solar history.

These two devices will increase the scientific capabilities of the field team commensurate with the magnitude of the entire expedition. Indeed, they would provide a considerable incentive for the very concept of the extended traverse.

THE TRAVERSE

Before the traverse itself is described, a few points should be made. First and foremost, the route is presented only as an example and should be treated as such. The area covered, however, was chosen for a number of reasons.

The Imbrium Basin and its environs have been geological favorites for many years, not only for the basin's prominence on the lunar nearside, but also for the wide diversity of geologic formations and other features found in that lunar quadrant. A very important aspect of this region of the Moon, however, is the fact that it contains features that were crucial in the development of the lunar stratigraphic system (Shoemaker and Hackman, 1962). This classification scheme has been the vehicle for describing the geologic history of the Moon as it is presently understood (e.g., Mutch, 1970; Wilhelms and McCauley, 1971; Wilhelms, 1985); its only major drawback is the lack of established ages for a range of specific features, which would define an absolute chronology. One of the most important contributions of the proposed exploration thus would be the "calibration" of.
the lunar relative time-scale in terms of absolute ages, which would occur upon sampling the key formations to provide fodder for the various age-dating techniques. In addition to establishing an absolute time-scale for the lunar nearside, the traverse would provide the opportunities to examine a number of critical processes, which are described below.

Multi-Ring Basin Formation

Perhaps the most important process operating during the early histories of the terrestrial planets was the formation of the huge multi-ring basins characteristic of all large, solid bodies studied to date (Baldwin, 1949, 1963; Hartmann and Kuiper, 1962; Stuart-Alexander and Howard, 1970; Hartmann and Wood, 1971; Moore et al., 1974; Head et al., 1975; and many others). The impact events responsible for their formation on the Moon not only created major topographic features (i.e., gigantic crater-like structures that measure thousands of kilometers in diameter), but they also rearranged millions of cubic kilometers of lunar crust (see, for example, Moore et al., 1974; Head et al., 1975), created vast quantities of shock-melted material (Head, 1974a; Moore et al., 1974), generated sources of seismic energy that modified pre-existing terrain (Schultz and Gault, 1975a,b), and provided topographic “traps” for large volumes of subsequently erupted volcanic materials (see the review of Head, 1976). Thus it should come as no surprise that an understanding of these features and the mechanisms that were active during and after their formation is very high on the priority list for lunar geologists.

Large Crater Formation

Aside from some of the mare basalts, virtually every lunar sample that has been studied exhibits signs of shock damage (G. Ryder, personal communication, 1984), which is a consequence of crater formation by impact. Even a casual look at a telescopic photograph of the Moon is sufficient to demonstrate the importance of large craters in shaping the landscape and affecting the evolution of the lunar crust. By analogy, the same must be true of the other solar system bodies that possess high densities of craters. Thus, the mechanisms involved in the formation of large craters—indeed, craters of all sizes—are among the most important in the evolution of planetary surfaces. In this light, the study of craters, especially large ones (tens of kilometers across), will also receive considerable attention on the traverse.

Volcanism

Insofar as mare basalts cover more than one-sixth of the lunar surface (Head, 1975), volcanism played a highly visible role in the development of the surface and in the evolution of the interior of the Moon. These deposits are extremely diverse in composition, both on the basis of remote-sensing geochemistry (e.g., Pieters, 1978; Bell and Hawke, 1984) and analysis of returned samples (see the review of Papike et al., 1976), as well as in the ages of their emplacement (e.g., Boyce et al., 1974; Schultz and Spudis, 1983). These characteristics imply that the lunar interior (the source of the basalts) underwent a highly complex evolution during and after the period of early lunar bombardment. The origins of various lunar volcanic features are still problematical but have the potential of yielding...
important information on the factors governing the different styles of lunar volcanism. Among such structures are mare rilles and ridges, domes, dark mantles and dark halo craters, cones, individual flows, and the intricate volcanic complexes exemplified by the Marius Hills and Aristarchus Plateau (e.g., Whitford-Stark and Head, 1977). Since the Imbrium Basin is flooded with mare basalts, substantial emphasis will be placed on the study of volcanic deposits and related features.

The suggested route, which is approximately 4000 km in length, is illustrated in Fig. 1. In reality, the starting and ending points would be governed strongly by the location of the lunar base itself, although it is easily conceivable that another leg could be added.
to the trip from the base to a suitable starting site. The following paragraphs give an abbreviated description and rationale for the major stops, which are keyed to the numbers in the figure. At the end of each paragraph are the distance between that site and the previous site and letters indicating the principal purposes for studying that site. They are as follows:

A—Aristarchus Plateau, an impact-volcanic complex
B—Basin structure and stratigraphy, usually applied to the Imbrium Basin on this traverse
C—Large crater deposits and/or structure
V—Volcanic features and/or deposits.

**Murchison Crater Floor (Stop 1)**

An old, degraded crater, Murchison possesses a floor with an unusual morphology, being partially covered with either impact melt or volcanics. In addition, the walls and surroundings of the crater are mapped as Fra Mauro Formation, while parts of the floor are classified as Cayley Formation (Wilhelms, 1968). Both of these unit types were visited by Apollo missions, and their origins are still intensely debated. Finally, a ray from the young crater Triesnecker crosses the center of Murchison's floor, which provides an opportunity to establish a date for that crater's formation. (B, V; 0 km)

**Fra Mauro Formation/Bode Dark Mantle (Stop 2)**

The Fra Mauro Formation on the backslope of the Imbrium Basin will be sampled again on a line radial to the basin center (this technique will be employed throughout the traverse; since deeper materials should have been ejected to shorter overall distances, any radial variations in composition should, in theory, be related to vertical inhomogeneities in the target before the impact). A “dark mantle” of probable pyroclastic origin, associated with the sinuous rille Rima Bode and shown to be bluish in color by Earth-based spectral observations (Pieters et al., 1973), occurs in the “backwaters” of Sinus Aestuum. Early basalts to the east of these deposits are also bluish, indicating that they could be related (Head, 1974b). (B, V; 110 km. This single leg of the trip is more than 15% longer than all of the Apollo traverses combined.)

**Mare Vaporum (Stop 3)**

The Vaporum basalts were emplaced in a pre-Imbrian impact feature that was about 200 km in diameter. Work at this site will concentrate on the geophysical study of the Vaporum Basin's structure as well as on the Vaporum basalts themselves. (B, V; 150 km)

**Ina (Stop 4)**

First noticed on Apollo 15 panoramic photography, this feature has been interpreted to be a caldera (El-Baz, 1972; Strain and El-Baz, 1980). It is remarkable in that it has virtually no superposed impact craters, an observation that indicates a very young age for this feature and the probable volcanic process that created it. Nearby Imbrium Basin deposits will also be visited. (B, V; 150 km)
Conon Crater (Stop 5)

A crater 21 km in diameter and, more importantly, 3 km deep represents a substantial excavation into its target terrain. Insofar as Conon is located in the backslopes of the Apennine Mountains, which form a portion of a ring surrounding the Imbrium Basin, it represents an important "window" into the stratigraphy of Imbrium ejecta, as well as possible pre-Imbrian materials. Its ejecta should contain exciting clues regarding the crustal structure of the Moon before Imbrium was formed. (B, C; 110 km)

Apennine Scarp/Possible Imbrium Impact-Melt Pool (Stop 6)

The basin-facing side of the Apennine Mountains probably represents a major fault zone; if so, the stratigraphy sought at Conon Crater might also be exposed here. A multi-spectral survey of the scarp from the GTV should provide information on any such layering. A number of small "pools" of possible melt generated by the Imbrium Event are also in this region; study of these rocks would yield very useful data in deciphering the nature of the Imbrium-forming impact. (B; 115 km)

Apennine Bench Formation (Stop 7)

This region, just inside the Apennine Front south of Archimedes Crater, has been something of an enigma to geologists. While it has superficial resemblances to impact melt deposits such as those found inside the Orientale Basin (Head, 1974a; Moore et al., 1974), most recent interpretations give it a relatively old volcanic origin (Hackman, 1966; Hawke and Head, 1978; Spudis, 1978). If such were the case, it would represent the largest recognized deposit of non-mare volcanics on the Moon. (B, V; 90 km)

Montes Archimedes (Stop 8)

Orbital gamma ray detectors found abnormally high thorium concentrations in the rugged area just south of Archimedes Crater (e.g., Metzger et al., 1979). This area is also very red in a spectral sense (Malin, 1974; see, for example, McCord et al., 1976 for a description of lunar spectral types). The origins of these "red spots," which are scattered across the nearside, are uncertain (e.g., Malin, 1974). Sampling the rocks exposed at Archimedes would be a significant step in unraveling this mystery. [B, V(?); 80 km]

Wallace Crater (Stop 9)

Wallace is an old, flooded, unremarkable crater whose position in the Imbrium Basin brings it more attention than it deserves of its own accord. Rays and secondary-crater fields from Copernicus Crater occur in this area; thus, this site will mark the beginning of the radial sampling process for that classic crater. Relatively young basalts unsampled by Apollo are also abundant at this site, and a geophysical study will shed light on pre-mare basin stratigraphy. (B, C, V; 240 km)

Eratosthenes Crater Ejecta/Southwest Apennines (Stop 10)

Eratosthenes Crater is the type area for the definition of the Eratosthenian System of the relative lunar time-scale and, as such, will be studied in some detail. Examination of its ejecta will shed light not only on the emplacement dynamics of ejecta from large
craters, but also on the azimuthal variation of Imbrium Basin deposits—the projectile that formed Eratosthenes impacted the southwestern portion of the Apennine Mountains. Deposits from the pre-Imbrian Aestuum Basin appear to have been excavated by this impact, so there is a chance that these materials could also be collected at this stop. (B, C; 100 km)

**Eratosthenes Crater Interior (Stop 11)**

This site is important not only from a scientific standpoint, but it will also provide a good test for the terrain-handling capabilities of the GTV in that local slopes of up to 30° will be encountered. The interior of the crater will be sampled, with special emphasis on the impact melt on the floor; it will be used to establish the time of formation of the crater. A multi-spectral panorama of the crater interior will be very useful, as will a detailed study of the central peaks and the geophysical profiling of the crater subsurface. (C; 40 km)

**Copernicus Crater Rays and Secondaries (Stop 12)**

The radial sampling of Copernicus will continue with a stop closer to the crater but still in its discontinuous deposits. In addition to the crater's ejecta, the "background" basalts will be collected, since the two are undoubtedly well mixed at this distance from the crater. These samplings will aid in deciphering the dynamics of ejecta emplacement, which are only partially understood. (B, C, V; 80 km)

**Copernicus Crater Continuous Ejecta (Stop 13)**

This radial sampling stop is located in the "continuous ejecta deposit" of the crater, which is most likely a combination of crater ejecta and local material that intermixed as the ejecta impacted (Oberbeck, 1975). One of the major goals at this stop is to determine the relative proportions of actual crater ejecta and local material in the deposit. The mare basalts are very thin here, leading to the probability that much of the Copernicus ejecta will consist of Imbrium ejecta, which is much older; thus, azimuthal sampling of Imbrium material should also continue at this site.

**Copernicus Crater Rim Materials (Stop 14)**

The view into the 93-km crater at this site should help to mollify the rigors endured by the crew to this point in the trip. Ejecta from deep in the crust should be present at this location, as are large concentrations of impact melt (Howard and Wilshire, 1975; Hawke and Head, 1977). Samples of the ejecta will aid in the reconstruction of the effects of the Imbrium impact event, and the melt will be used in dating Copernicus, which will also define the beginning of Copernican time in the lunar stratigraphic system. This site is tailor-made for a panoramic multi-spectral survey. (B, C; 30 km)

**Copernicus Crater Central Peaks (Stop 15)**

Recent Earth-based observations suggest that the central peaks of Copernicus are composed largely of olivine (Pieters, 1982), suggesting the presence of uncommon lunar rock types. The material in the peaks probably came from a significant depth (on the
order of several kilometers), and a sampling effort here would be very informative. The thick impact-melt deposits on the floor will be sampled for compositional and textural variations to be compared with those examined at the rim. A geophysical survey of the crater is very high in priority. (C; 30 km, downhill)

**Montes Carpathus/Copernicus Crater Ejecta (Stop 16)**

The Apennines grade into the Carpathian Mountains on the extreme southern edge of Imbrium; a stop is planned here to continue the azimuthal study of Imbrium stratigraphy. The on-going examination of Copernicus ejecta will also profit from this locality, and possible pyroclastic deposits in the area will be sampled. (B, C; 140 km)

**Tobias Mayer Rilles/Copernicus Crater Ejecta (Stop 17)**

A muted volcanic complex exists to the northwest of Copernicus near the crater Tobias Mayer. Associated with this complex are a number of small rilles and potential calderas. This area will be studied in some detail, both geochemically and geophysically. The final opportunity to sample Copernicus ejecta in any significant concentration will probably occur at this stop. This will be the first of a series of mare sites located well into Mare Imbrium and Oceanus Procellarum. (B, C, V; 110 km)

**Euler Crater (Stop 18)**

This 28-km crater is surrounded by fairly young basalt flows (e.g., Schaber, 1973), which are the principal targets of this leg of the exploration. The continuous ejecta deposits of Euler, which probably contain pre-mare materials, will also be sampled. (B, C, V; 145 km)

**Mons La Hire (Stop 19)**

The Imbrium Basin is so thoroughly flooded that few remnants of its inner ring structure remain exposed. La Hire is one of those unburied massifs, and it, too, is spectrally red (Malin, 1974; Head and McCord, 1978). It will be studied both as a segment of an inner ring of Imbrium and as a spectrally distinct feature. (B; 180 km)

**Eratosthenian Flows West of Mons La Hire (Stop 20)**

In mid- to late-Eratosthenian time, a series of eruptive events covered a large portion of the Imbrium Basin from the southern border with Oceanus Procellarum to the northern reaches of Mare Imbrium (e.g., Schaber, 1973). Remote-sensing data suggest a composition for these lavas that is not represented in the samples returned by Apollo astronauts or Luna spacecraft (Whitaker, 1972; Etchegaray-Ramirez et al., 1983). These flows thus represent a significant, relatively late volcanic episode in the Moon's history. (B, V; 30 km)

**Gruithuisen Domes (Stop 21)**

Two separate groups of “red spots”—the Mairan and Gruithuisen Domes—are detectable with Earth-based instrumentation near the northwestern boundary of the Imbrium Basin. They are domical features, and have been interpreted to be the result
of a late stage of non-mare extrusive volcanism (Head and McCord, 1978). Whether they are indeed volcanic or simply represent more red ring massifs (such as Mons La Hire) is still debated. Sampling these distinctive features will help to settle the question and perhaps provide data on a potentially important process. A number of spectrally differentiable basalt types (Pieters, 1978) will also be sampled during the trip to the domes. (B, V; 410 km)

**Prinz Rilles/Aristarchus Crater Ray (Stop 22)**

The Aristarchus Plateau and its immediate surroundings represent an area of remarkable diversity, in terms of both geology and the processes that were involved in its evolution (e.g., Zisk *et al*., 1977). Five full sites will therefore be dedicated to the exploration of this region of the Moon. This stop will be utilized to investigate the Prinz Rilles, which comprise a series of valley-like depressions in obviously volcanic terrain. A ray from Aristarchus Crater extends across this location; collection of material in that area will begin the radial sampling of this 40-km crater. Highland samples in this area will also be collected as the opportunities arise. (A, B, C, V; 300 km)

**Aristarchus Crater Rim (Stop 23)**

If it could be possible, the view here should be even more impressive than its equivalent was at Copernicus, since Aristarchus is less than half the diameter of the former, but almost as deep. The crater's continuous ejecta blanket will be examined at this site, while the rim structure and stratigraphy will be probed. The abundant impact-melt flows and ponds in this area will also be sampled for comparison with that on the crater's floor. (A, C, V; 75 km)

**Aristarchus Crater Floor (Stop 24)**

The melt sheet and central peaks will be high-priority sampling objectives here. In addition, a multi-spectral panorama will be acquired, and a geophysical profile will also be made. Special emphasis will be placed on an attempt to establish the stratigraphy of the crater's northwestern wall, which cuts through the volcanic plateau. The GTV will receive another workout during these investigations. (A, C, V; 25 km)

**Vallis Schröteri/Aristarchus Plateau Dark Mantle and Basalts (Stop 25)**

An effort as intensive as any on the traverse will be made at this site. The dark mantle materials, which probably represent pyroclastic eruptives, will be on an equal sampling priority with the flow basalts in the area, and a number of geophysical profiles will be taken across the Plateau. It is anticipated that the GTV-defined base camp will be rather mobile during this leg of the exploration, because the largest sinuous rille on the Moon, Schröter's Valley, will also be an object of extensive scrutiny. It is likely that Aristarchus ejecta is fairly common across much of the Plateau, so the radial sampling effort might well continue. [A, C(?), V; 60 km]
Schiaparelli Basalts (Stop 26)
Remote-sensing data show the basalts to the northeast of Schiaparelli Crater to be titanium-rich, but they appear to be very young on the basis of superposed-crater abundances. Since the vast majority of high-titanium basalts returned by the Apollo missions are very old (e.g., Taylor, 1982), samples of these flows will be very interesting for modelers of the evolution of the lunar interior. (V; 180 km)

Lichtenberg Crater and Basalts (Stop 27)
Not only is Lichtenberg Crater interesting because it excavated pre-mare material in northern Oceanus Procellarum, but the basalt flows that embay its ejecta deposits appear to be the youngest recognized lava flows on the Moon (Schultz and Spudis, 1983). (C, V; 300 km)

Struve L Crater (Stop 28)
Struve L is about 14 km in diameter and is a very good candidate for an Orientale Basin secondary crater. It also possesses a floor that is unusual in the sense that it might be comprised predominantly of impact melt from the Orientale Basin (Schultz, 1976a). If not, it would still offer a very good chance at obtaining Orientale ejecta. This stop is in a region of the Moon (the western “hores” of Oceanus Procellarum) that is teeming with diverse features and formations, many of which will be sampled between sites. (B, C; 370 km)

Balboa Crater (Stop 29)
Large craters with fractured floors are not uncommon on the Moon. While their origins are not certain, the leading hypothesis to account for their morphology is the intrusion of magma below the crater into the material that was disaggregated by the impact (Schultz, 1976b). Balboa represents one such crater, and a geophysical survey of its interior should provide some answers to the questions regarding the responsible processes. (C; 190 km)

CONCLUSIONS

This traverse would be an ambitious undertaking, but the scientific dividends it would yield are equal in magnitude to the challenge. Many variations of the route can be proposed, especially in the Oceanus Procellarum region. In fact, much difficult debate was involved in planning the path that is presented above. Some might view this as a sign of uncertainty or the lack of a clear goal for the exploration. On the contrary, the prospects opened by such capabilities are overwhelming, particularly in light of the pressures and limitations under which all similar planning had occurred in the past. When suddenly confronted with the profoundly exciting ability to travel over such great distances with highly sophisticated support equipment, it is almost unfair to ask that one’s composure be maintained. The prospects are magnificent, and much remains to be done. . .
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SEARCH FOR VOLATILES AND GEOLOGIC ACTIVITY FROM A LUNAR BASE

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A lunar base can be used as a central point from which to monitor lunar seismic activity and to search for lunar volatile emissions. This project could be carried out in a twofold effort with (1) a network of instrument packages placed over the lunar surface by manned rover vehicles, and (2) a polar-orbiting satellite. Each instrument package would include a seismometer plus mass spectrometers capable of detecting and analyzing gas species. The polar satellite would carry spectrometers and photometers operating at ultraviolet, visible, and infrared wavelengths, a mass spectrometer, and an alpha spectrometer to look for surface radon enhancements. The primary purposes for this project are to obtain a detailed analysis of lunar seismic activity and internal structure, to determine whether lunar gas venting occurs and, if so, with what intensity, and to locate the sources of any volatiles found.

INTRODUCTION

A lunar base can be used as a central point from which to monitor lunar geologic activity and to search for lunar volatile emissions. There are two primary purposes for such an investigation. The first purpose is to determine whether gas venting does in fact take place on the Moon, and to learn whether there are reservoirs of volatiles anywhere on or within the Moon. This interest is in part scientific curiosity and in part economic. If the Moon contains any substantial volatile reservoirs, and if these contain any substances of value such as water or carbon dioxide, the logistical problems of supporting a base on the Moon might be considerably eased. The second purpose is to monitor lunar seismic activity to determine its temporal and spatial patterns and to study the internal structure of the Moon. This sort of investigation was done during the Apollo program (Lammlein et al., 1974; Latham et al., 1978), but with a larger number of detectors placed more widely over the lunar surface, and by observing for a longer period of time, we can expect to gain a more precise and detailed picture of the lunar structure and seismic activity patterns.

Existing evidence suggesting that gas venting occurs on the Moon takes three primary forms:

1. Unusual and unexplained brightenings or obscurations have been observed by astronomers from Earth and are often referred to as lunar transient events (LTE). Middlehurst (1967, 1977) and Cameron (1977) have provided extensive and detailed summaries of locations, times, and activity patterns for reported LTE.
2. Apparent venting was observed instrumentally during the Apollo program, both at the surface (including the water vapor reported by the Apollo 14 Suprathermal Ion Detector Experiment (SIDE) (Freeman et al., 1972)) and from lunar orbit (Hodges et al., 1973).

3. Greatly enhanced concentrations of $^{222}\text{Rn}$ and its decay daughter $^{210}\text{Po}$ were indicated by alpha spectrometers carried on board the Apollo 15 and 16 service modules at certain locations on the lunar surface, as compared with the surrounding regions (Gorenstein et al., 1973, 1974). In many of these locations, the decay rates of $^{222}\text{Rn}$ and $^{210}\text{Po}$ were not in equilibrium with each other, indicating a change of emission rate for radon at these locations that was rapid compared to the half-life of $^{210}\text{Pb}$ (21 years) for $^{210}\text{Po}$ excesses or $^{222}\text{Rn}$ excesses.

**METHOD OF INVESTIGATION**

The search and monitoring effort proposed would be carried out in a twofold effort: with a network of instrument packages placed over the lunar surface and with a polar-orbiting lunar satellite monitored from the base.

It is very probable that scientific work conducted from a lunar base will involve geologic exploration and field work (Spudis, 1984) including traverses to considerable distances from the base, such as the one proposed by Spudis et al. (1984) for the Imbrium basin. It should not require much additional effort to carry along instrument packages on such traverses and to deploy the packages at appropriate locations on the lunar surface. This paper assumes that the first lunar base will be on the Earth-facing hemisphere of the Moon, as will the early geologic traverses. Since LTE reports and $^{210}\text{Po}$ enhancements appear to favor edges of maria (Middlehurst, 1967; Bjorkholm et al., 1973), it would be worthwhile to place instrument packages in several of the major basins. Additional instrument packages would very likely be placed at other locations where there is cause to suspect, from LTE reports or Apollo alpha spectrometer observations, that gas venting may occur; for example, at the craters Aristarchus (Bjorkholm et al., 1973; Middlehurst, 1977) and Alphonsus (Kozyrev, 1963). In order to follow up on the suggestion of Arnold (1979) that volatiles may be frozen in shadowed regions at the lunar poles, at least one instrument package should be placed as far north or south as feasible.

A set of proposed instrument locations is shown in Table 1. The proposed locations are subject to change; they will depend, for example, on what geological traverses are selected. The entire network would probably not be put in place at once; rather it would be placed station by station, as traverse opportunities permit. The most important factors in site selection are that ultimately one wants a network of many stations and even more important, these stations should be widely separated. Three or four instrument stations separated by thousands of kilometers would be worth more than ten or fifteen separated by only tens or hundreds. Indeed, one would eventually like to extend this network to the farside of the Moon.
A few words about the vehicles needed to conduct geologic traverses and emplace the instrument packages: these would be pressurized vehicles, probably the size of a camper or large van, with a normal crew of two. For safety's sake, the vehicles should set out in pairs, and each should be capable of providing life support for all four people in the event of a mishap to the other vehicle. Also for safety's sake, the vehicles should be furnished with digging equipment, not only for geological sampling, but also so that they can bury themselves rapidly in the event a solar flare occurs while they are far from the base.

The most promising power source for such vehicles appears at present to be hydrogen-oxygen fuel cells. Nuclear power was considered, but for man-rated vehicles it appears to require an unacceptably large shielding mass (French, 1984). Preliminary calculations based on information in McCormick and Huff (1984) and in Fuel Cells for Transportation Applications (Huff, 1981) indicate that fuel cell powered vehicles could have very good range. For excursions of more than one or two thousand kilometers from the lunar base, the vehicles might need to tow special fuel trailers or borrow the technique from mountain climbers and early polar explorers of setting up caches of consumables along the route.

The base would maintain communication with the vehicles (and the instrument packages, once emplaced) via a communication satellite that could be emplaced at the L1 Lagrange point between the Earth and the Moon.

Each instrument package should include seismometers to monitor for moonquakes and impacts, plus mass spectrometers capable of detecting and characterizing any gas species that may be present. The information needed from the mass spectrometers will be the chemical species and incoming energy of any gas atoms, molecules, or ions detected. If the mass spectrometers can be designed to distinguish the direction of arrival of the incoming gas, that information will also be useful. To gain the maximum scientific return from this program, it would be useful to monitor the sun as well as the Moon. A long-term monitoring of the solar wind would be a valuable tracer of solar activity. For this purpose, the mass spectrometers should be designed to be able to measure the composition and energy of solar wind ions, as well as to monitor any native lunar gas that may
be present. Other instruments that might be included in the packages, for still other investigations, would be cosmic ray detectors and radio receiver elements for long baseline interferometry.

In addition to the instrument packages, a number of small gas reservoirs should be placed on the Moon. Once the instrument network was in place, these reservoirs would calibrate the network by providing gas releases of known location, time, duration, quantity, and composition.

Just as a lunar base program is likely to include geological traverses, it is also likely to include polar-orbiting lunar satellites for various types of mapping. In fact, a polar satellite such as the proposed Lunar Geoscience Orbiter is likely to go into operation before a lunar base is constructed, and data from it may well influence base site selection. I suggest that one or more lunar polar satellites continue operating into the manned phase of lunar base operation, and that the instruments for a polar satellite include some capable of detecting lunar activity, if any occurs. Such instruments would include spectrometers and photometers operating in the ultraviolet, visible, and infrared (useful for mapping as well as for monitoring activity) wavelengths. There should also be a mass spectrometer to look for lunar gases and an alpha spectrometer to look for surface concentrations of radon and polonium. In addition to providing an additional data point and being able to monitor surface radioactivity, a lunar polar orbiter's optical instruments may be able to detect one type of lunar activity that the surface stations cannot: large-scale dust motion. This will be significant if, as Geake and Mills (1977) have suggested, some LTE involve dust clouds.

A polar-orbiting satellite has the limitation that it can only pass directly over any given lunar location once every two weeks. To alleviate this, the satellite could be placed in as high an orbit as is consistent with its other scientific objectives, and could be given a capability to look a significant angle away from vertical. It might be necessary for the satellite's instruments to scan from one side of its ground track to the other as it passed over the Moon.

To summarize, the equipment required for this study includes: (1) a lunar base, (2) rover vehicles, (3) instrument packages, (4) a lunar polar-orbiting satellite, (5) a communication satellite at the L1 orbit, and (6) gas reservoirs to calibrate the instruments.

If any events are detected by this network of surface instruments and polar satellite, how will they be interpreted? For seismic events, each seismic station should record the time, duration, and intensity of any observation. From this information, geophysicists will attempt to determine the spatial and temporal patterns of lunar seismic activity and to deduce as much as possible about the internal structure of the Moon, in a manner very similar to what was done during the Apollo program.

If any gas venting is observed, each surface station will record for each observation the start time, the duration, the intensity as a function of time, and the composition as a function of time. The polar-orbiting satellite will obtain information similar to that provided by the ground stations. In addition, the polar satellite will make note of its orbital position throughout any observation, the surface locations being observed at the time, and any associated surface phenomena observed, for example: radon enhancements,
optical brightenings, or obscurations. From the times and intensities for each venting observed at each ground station and by the satellite, the personnel at the base will try to deduce the time and location at which that event originated. Researchers will also look for coincidences between the times and places of venting events and those of seismic events.

It would greatly aid this investigation if professional and amateur astronomers on Earth can be enlisted. A network of astronomers who are prepared to observe the Moon on short notice is needed. There might be an existing astronomical organization enlisted, or one may be especially set up for this purpose as was done to look for LTE in the 1960s in Operation Moon Blink (Cameron and Gilheany, 1967). Some means of rapid notification would be established—perhaps a telephone tree. Whenever the lunar surface mass spectrometers or the polar-orbiting satellite report a strong burst of activity, the Moon base personnel would immediately relay the information to the Earth-based astronomers, who would observe the Moon and report any unusual phenomena they detect.

**CONCLUSIONS: WHAT CAN BE LEARNED FROM A STUDY OF LUNAR VOLATILE AND GEOLOGIC ACTIVITY?**

For seismic activity, we wish to determine in as much detail as possible its patterns in location and time. We also wish to determine the internal structure of the Moon in as much detail as possible. This would follow the seismic work done during the Apollo program in greater precision and detail.

For gas venting, we seek answers to four primary questions:

1. Does gas venting actually take place on the Moon? If so, does it involve sufficient amounts of material and energy to account for LTE observed from Earth? Also, does gas venting coincide in location or time with any seismic activity?

2. Do significant reservoirs of volatiles exist anywhere within the Moon, or is the entire Moon as depleted in volatiles as the surface locations we have examined so far? If reservoirs exist, where are they, how deep, and how great are the quantities of volatiles they contain? Do venting locations tell us where the volatiles are, or only where channels to the surface are?

3. What information or constraints does the presence (or absence) of volatiles provide regarding the origin, history, and present state of the Moon? Does this provide any clues about conditions elsewhere in the early solar system, especially in the region of the terrestrial planets and asteroids?

4. Do volatiles exist in sufficient quantity, and in locations accessible at low enough cost, to constitute a resource usable by a lunar base?

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UNMANNED SPACEFLIGHTS NEEDED AS SCIENTIFIC PREPARATION FOR A MANNED LUNAR BASE

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Additional knowledge of the Moon's geology, geophysics, and geochemistry is required to maximize the scientific return from a future program of manned lunar exploration. Relatively simple and inexpensive unmanned missions could provide the necessary new data if they are targeted on the basis of knowledge obtained from the first round of lunar exploration. Polar orbiters, sample returners, and seismic probes are required.

INTRODUCTION

Much has been learned about the Moon since the Soviet Union's Lunas 2 and 3 began the era of spacecraft exploration in 1959. The origin of the maria (volcanic basalt) and of most craters (impact) is settled. The approximate compositions of the Moon's crust and mantle and of many geologic units are far better known than before the space age. Representative deposits exposed at the surface have been dated on both the relative and absolute time scales, and the antiquity of the Moon's face has been established. Any comparison of pre-1960 and current lunar literature quickly shows how far our knowledge has advanced (see reviews by Taylor, 1975, 1982; Basaltic Volcanism Study Project, 1981; Wilhelms, 1984, 1985).

Nevertheless, many important scientific questions remain unanswered. The Moon's mode and place of origin are still unknown. Its subsurface structure is poorly known even in relatively well explored areas. The pre-mare impact record is too poorly calibrated to establish such fundamental issues as the time of crustal solidification and the origin and lifetime of large solar system projectiles. The timing and volume of volcanism before 3.8 and after 3.2 aeons ago are uncertain (1 aeon = 10⁹ years). The relation among composition, age, source depth, and extrusion site of the mare basalt flows is hypothetical. The compositions and ages of most farside maria are unknown. Terra (highland, upland) compositions are known only approximately from a few spot samples and from low resolution orbital measurements that covered a small percentage of the surface. The ages of most of the rayed craters are uncertain within broad limits. The origin of central peaks and shallow floors of complex craters is uncertain. The origin of basin rings and even the position of the boundary of basin excavation—central questions in studies of impact mechanics, lunar petrology, and stratigraphy—are frustratingly elusive. Lunar remote studies and direct exploration, now almost quiescent, have not completed their task.

Some of these matters can probably be settled by continued experimental and field study on Earth. The origin of complex craters and basin rings might yield to further study of terrestrial craters, laboratory and large-scale explosive experiments, and physical theory.
Other gaps in our knowledge, such as the distribution of mare basalt compositions, can be partly filled by continued geologic mapping, crater-frequency counts, telescopic spectral studies, and petrologic theory. Still other pieces of the lunar puzzle may be found by examining or reexamining the large and still incompletely exploited Apollo sample collection (Ryder, 1982).

Investigation of most of the remaining geologic questions, however, requires resumption of lunar spaceflights. This volume concerns a proposed manned lunar base. Such a base can be neither effectively sited nor productively exploited scientifically without additional preparatory exploration by unmanned spacecraft. This paper explains how three types of unmanned missions can address the questions that remain to be answered by the second round of lunar exploration. Two classes of missions, orbital surveys and sample returners, have already proved their value. Seismometers, which were not successfully included on the unmanned precursors to Apollo, will also be needed.

POLAR ORBITER

Lunar Orbiters 4 and 5 provided indispensable photographic coverage of most of the Moon from their near-polar (85°) orbits. Our current knowledge of the Moon would be appallingly incomplete without these missions, which were originally intended for detailed landing-site studies in the equatorial belt and not for reconnaissance purposes. Lunar Orbiter, however, carried no geochemical or geophysical instruments. Except for gravity data obtained by doppler tracking, the only geochemical and geophysical data obtained by any orbiting mission were those obtained at relatively low spatial resolutions by Lunas 10 and 11 (flown by the Soviet Union in 1966) and by Apollos 15-17 (1971-1972) from parts of the belt between 30° N and S latitudes. A new lunar global orbiter could gather important data concerning at least six major topics.

Mare Compositions

At present, remote sensing data useful for extrapolating to large areas the compositional data obtained from returned samples are available only for the small area overflown by Apollos 15-17 and, for the nearside, from telescopic remote sensing (Pieters, 1978). A polar orbiter could readily obtain data in several wavelengths that could be used to determine the compositional variability of all the lunar maria. The estimated compositions of the basalts could then be correlated with their ages and with the sizes and inferred depths of the containing basins. The volumes, depths, and thermal histories of the mantle source zones of the basalts could be partially inferred from these correlations.

Terra Compositions

Terrae cover 83% of the Moon and terra materials constitute almost all of the lunar crust. Ignorance of terra compositions is thus even more serious than ignorance about the volumetrically minor mare basalts. The terrae have been directly sampled at only five spots (Apollos 14-17 and Luna 20), and, because most terra materials are mixtures of the original igneous rock types, the remote sensing data so far available have not...
closely specified the compositions of the unsampled remainder. This ignorance severely limits the petrologist, geochemist, and cosmogonist attempting to learn the origin of the Moon and the solar system.

**Gravity**

Except for a few small areas overflown at low altitudes, regional and local lunar gravity fields are poorly known. Two major problems are the mass balance of basins and the nature of the offset of the Moon's center of mass from its center of figure. Modeling has indicated, probably correctly, that mascons (positive gravity anomalies) are due mostly to mare basalt (Solomon and Head, 1980); however, whether the gravity field following basin formation and before filling by the basalt was positive, negative, or neutral is not known. Another unanswered but even more fundamental question is whether the mass offset results from a first-order heterogeneity in the Moon's crust, mantle, or core, or from the gravity anomaly created by a giant nearside basin.

**Topography**

Gravity modeling, geodesy, estimates of geologic units' thicknesses, spaceflight engineering and operations, and other important scientific and technical tasks depend on knowledge of a planet's topography. For the Moon, the heights of basin rims and other rings and the elevations of the contained maria are particularly significant. Yet the topography of none of the basins has been completely determined. That of the Orientale basin, which is the model for others because it is relatively young and large, is known only within wide limits. Accurate photogrammetry can be performed only for the illuminated parts of the Apollo groundtracks. Refinements of the rest of the nearside's topography still depend on telescopic selenodesy and radar modeling. The topography of the non-overflown parts of the farside and polar regions is almost completely unknown. The need for these basic data is obvious.

**Magnetism**

Another problem only partly approachable with the limited existing data is the origin of the remanent magnetism found in lunar samples and from orbit. Several alternative hypotheses for the origin of the fields and the way the magnetism was acquired are still viable; different alternatives may apply at different stages of lunar history. Global measurements of the remanent magnetism from orbit will help determine whether the Moon possesses a core, a central question in considerations of lunar composition, thermal history, and origin.

**Stratigraphy**

Determining the post-accretional history of a planet and extrapolating geochemical and geophysical data depend on knowledge of the stratigraphy of its near-surface rocks. The lunar stratigraphy has been worked out to a good approximation on the nearside and central farside. However, the photographs necessary for stratigraphic analysis have not been obtained at adequate resolution for the poles, most of the limb regions on
both hemispheres, the farside at latitudes greater than about 40° N and S, or a zone between 100 and 120° W. The latter gap is particularly severe because it includes part of the Orientale basin. The east limb includes the large and puzzling Crisium basin, and the other poorly photographed zones also include basins whose stratigraphic sequence and ring structure should be examined. Thus, any future polar orbiter should include an imaging system.

UNMANNED SAMPLE RETURN

Solution of other problems requires additional samples from the Moon itself. Lunas 16, 20, and 24 proved the value of unmanned samples returned from targets that, apparently, were not selected in advance except within broad selenographic limits. Despite the small sample size, they provided two absolute ages in the maria and one in the terra, added two types to the list of mare basalt compositions, and sampled typical terra material at an outlying point not reached by Apollo. A relatively inexpensive program of unmanned sample-returning spacecraft could yield significant advances if our current knowledge of lunar geology is applied to the selection of landing point sites. The following five categories of geologic questions are most important. Table 1 lists 19 sites or groups of sites, in approximate order of descending priority, where sampling missions could address these objectives. Data from each site could be extrapolated to larger areas by means of currently available or future orbital sensing. Each probe is considered capable of returning a single sample of regolith randomly selected from within the designated area. Other geoscientists could augment and amend the list.

Absolute Ages

Several more ages are needed to calibrate the lunar stratigraphic column, particularly for basins (items 1, 6, 10, 15–17), young maria (items 2, 13, 14), and young craters* (items 7, 8). Only the age of the Imbrium basin (about 3.85 aeons) and a questionable age of the Nectaris basin (3.92 aeons; James, 1981) are available to date the old part of lunar history. The highest priority is given here to dating the Nectaris basin, whose relative age is well known, and which, if securely dated, would therefore provide the needed calibration for the pre-mare cratering rate (Wilhelms, 1985). Dating of events in the last 3 aeons of lunar history is similarly imprecise. Maria younger than 3.16 aeons (Apollo 12) have been dated relatively (Boye, 1976; Schultz and Spudis, 1983) but not radiometrically, and the Apollo 12 unit is hard to date on the relative time scale.

Compositions and Rock Textures

Although the emplacement mechanism of most lunar geologic units is now known to a good approximation, that of many plains and domelike hills is still questionable. These units should be sampled to decide once and for all whether non-mare volcanism has occurred on the Moon (items 3, 4, 17). Also, some impact phenomena need to be further explored, notably the relative volumes of impact-melt rock and clastic ejecta (items 15–17, 19).
Table 1. Potential Landing Sites for Future Unmanned Lunar Sampling Missions

<table>
<thead>
<tr>
<th>Item</th>
<th>Stratigraphic Unit (Orientale-basin impact melt)</th>
<th>Landing Area</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nectaris basin</td>
<td>(a) Ejecta near 35° S, 42° E (b) Plains (impact melt?) near 22° S, 41° E</td>
<td>(a) Absolute age (b) Composition</td>
</tr>
<tr>
<td>2</td>
<td>Copernican mare</td>
<td>Southeast of Lichtenberg, near 31° N, 67° W</td>
<td>(a) Absolute age (b) Composition of source</td>
</tr>
<tr>
<td>3</td>
<td>Terra plains</td>
<td>(a) Albategnius (b) Ptolemaeus</td>
<td>Nonmare volcanism or buried mare basalt flows?</td>
</tr>
<tr>
<td>4</td>
<td>Terra domelike landforms</td>
<td>(a) Gruíthuisen delta or gamma (b) Hansteen alpha</td>
<td>Nonmare volcanism?</td>
</tr>
<tr>
<td>5</td>
<td>Farside mare</td>
<td>(a) Floor of Tsiolkovski (b) Mare Ingenii</td>
<td>Composition of source</td>
</tr>
<tr>
<td>6</td>
<td>Maunder Formation</td>
<td>South of Mare Orientale</td>
<td>(a) Age of Orientale basin (b) Composition of crust</td>
</tr>
<tr>
<td>7</td>
<td>Crater Copernicus</td>
<td>Impact melt on floor</td>
<td>(a) Absolute age (b) Composition of crust</td>
</tr>
<tr>
<td>8</td>
<td>Crater King</td>
<td>Impact melt on rim or floor</td>
<td>(a) Composition of farside crust (b) Absolute age (a) Composition</td>
</tr>
<tr>
<td>9</td>
<td>Ancient crust</td>
<td>Near 30° N, 160° E</td>
<td>(a) Composition (b) Absolute age</td>
</tr>
<tr>
<td>10</td>
<td>South Pole–Aitken basin massifs</td>
<td>South of Korolev, 21.5° S, 160° W</td>
<td>(a) Composition of farside crust (b) Absolute age</td>
</tr>
<tr>
<td>11</td>
<td>Pre–Late Imbrian mare (?) massifs</td>
<td>(a) Center of Schickard (b) North of Balmer</td>
<td>(a) Absolute age (b) Composition</td>
</tr>
<tr>
<td>12</td>
<td>Early Late Imbrian mare</td>
<td>Mare Marginis, in Ibn Yunis</td>
<td>(a) Absolute age (b) Composition (KREEP-rich?)</td>
</tr>
<tr>
<td>13</td>
<td>Eratosthenian mare</td>
<td>(a) Southwestern Mare Imbrium (b) Surveyor 1 region, near 2.5° S, 43.5° W</td>
<td>(a) Absolute age (b) Calibration of color spectra</td>
</tr>
<tr>
<td>14</td>
<td>Central Mare Serenitatis</td>
<td>Between Bessel and Dawes</td>
<td>(a) Calibration of color spectra (standard spectrum) (b) Absolute age (near Imbrian–Eratosthenian boundary)</td>
</tr>
<tr>
<td>15</td>
<td>Orientale-basin lobate ejecta</td>
<td>Near 53° S, 79° W</td>
<td>Impact melt or other ejecta?</td>
</tr>
<tr>
<td>16</td>
<td>Alpes Formation (knobby Imbrium basin ejecta)</td>
<td>Southeast of Vallis Alpes, near 45° N, 5° E</td>
<td>(a) Impact-melt/debris content (b) Composition of deep ejecta</td>
</tr>
<tr>
<td>17</td>
<td>Apennine Bench Formation (planar deposit in Imbrium basin)</td>
<td>Near 27° N, 8° W</td>
<td>(a) Impact melt or KREEP-rich volcanic materials? (b) Absolute age (c) Calibrate orbital geochemical data</td>
</tr>
<tr>
<td>18</td>
<td>Reiner Gamma Formation (irregular bright patch on mare)</td>
<td>Near 7.5° N, 59° W</td>
<td>(a) Absolute age (b) Magnetism involved in origin?</td>
</tr>
<tr>
<td>19</td>
<td>Fissured crater floor deposits</td>
<td>Floor of Murchison, 1° W, 5° N</td>
<td>Ejected Imbrium basin impact melt?</td>
</tr>
</tbody>
</table>
Terra-crust Composition

The remote sensing data discussed above need to be calibrated by "ground truth" at points of known stratigraphic context (items 1, 6–10, 16). Such extrapolation from small to large areas has proved to be the most efficient use of lunar sample data.

Mantle Compositions

Similar remarks apply to the mare basalts; extrapolations from samples of currently unsampled color and age units could readily calibrate the existing and future remotely sensed properties (items 2, 5, 12–14).

Compositions and Ages of Premare Volcanic Basalt

Basalts appear to have formed in abundance before and near the end of the disruption by the early impact barrage (Schultz and Spudis, 1983), but their extent, compositional variability, and age spread are not known. This is a problem for directed sampling of certain breccias and thin plains units (items 3?, 11, 17?).

SEISMIC PROBES

Knowing the average and local thickness of the lunar crust is a prerequisite to assessing gravity models, the composition of the Moon, the depths of basin excavation, the elevation of the source regions of mare basalt and KREEP, and many other important facets of lunar geoscience. Yet the crustal thickness is known only in the limited area reached by the Apollo ALSEP's; in other areas it must be determined by extrapolation and modeling that are highly model-dependent (Basaltic Volcanism Study Project, 1981, section 4.5.2). The important problem of the core could also be resolved by good seismic data. Additional seismic data are therefore among the most urgently needed returns from renewed lunar exploration. Passive seismometers like those of the Apollo ALSEP's could record large meteorite impacts and greatly improve knowledge of the Moon's third dimension. Because the ALSEP's were shut down in 1977, new instruments are required. Also, a much greater spatial spread than that of the ALSEP's, including the farside, is needed.

CONCLUSION

If geoscience is to play a major role in mankind's return to the Moon, more scientific data are needed as preparation for that venture. The most severe gap is in knowledge of the subsurface structure and of surface composition and stratigraphy outside the near-equatorial nearside. Near-polar unmanned orbiters, unmanned samplers, and geophysical instruments emplaced on the surface can substantially improve on the present data base. These relatively simple and inexpensive instruments can be targeted intelligently on the basis of our current understanding of the Moon, incomplete as it is. Even if no manned missions will take place, these unmanned missions would add enormously to our dawning understanding of the Moon's makeup and history.
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THE NEXT GENERATION GEOPHYSICAL INVESTIGATION OF THE MOON

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Primary deficiencies of current lunar geophysical data sets include: (1) uncertainties in the seismic velocity structure of the mantle, especially at depths > 500 km; (2) inadequate global coverage of high-resolution gravity field, topography and, to a greater extent, magnetic field data; (3) sparsity of surface heat-flow measurements; (4) lack of definitive constraints from either seismic or magnetic field data on the existence and radius of a metallic core; and (5) lack of ground-truth samples over most of the accessible surface. This paper discusses how these deficiencies may be removed in the course of preparing for and conducting the next set of manned lunar missions. A polar orbiting geoscience survey could complete lunar potential field and topographic mapping and obtain indirect global heat-flow measurements, while simultaneously providing basic geochemical and geophysical data for long-term manned site selection and resource evaluation. Later deployment of autonomous surface geophysical stations at widely spaced locations during manned exploration and utilization activities would provide the improved seismic and electromagnetic sounding and direct surface heat-flow data needed for a more accurate characterization of the deep interior. The result would be a significantly improved understanding of lunar origin and internal evolution.

INTRODUCTION

The primary aim of planetary geophysics is to determine the structure, composition, and state of a given body and the relationship between internal processes and surface tectonic features. The proximity of the Moon, and its small size implying relatively low internal pressures and temperatures, make it an obvious initial case for application of geophysical techniques to bodies other than the earth. The major goals are to distinguish among lunar origin models and to test theories of lunar (and hence planetary) evolution. The purpose of this paper is to outline some of the lunar geophysical studies that are incomplete, how they can be completed in our future exploration strategy, and what they might tell us.

Some initial progress toward geophysical exploration of the Moon was made as a result of the Apollo manned landing series and associated scientific investigations. For example, it was established that a plagioclase-rich crust with a thickness of 50–60 km beneath Oceanus Procellarum is present, implying differentiation of at least the outer few hundred kilometers of the early Moon. Based on analyses of gravity and topography data, it was shown that the farside crust is either less dense or thicker than the nearside crust; the latter asymmetry is sufficient to explain the observed center-of-figure to center-
of-mass offset of about 2 km and may also account for the predominance of the nearside maria (see, for example, Taylor, 1982). Both seismic velocity measurements and analyses of mare basalt samples have been used to infer approximate limits on the composition of the lunar upper mantle (depths < 400-500 km). The lunar mean density and moment-of-inertia have been determined with excellent and fair accuracy, respectively. However, many fundamental issues remain unresolved, and their lack of resolution at present handicaps attempts to geophysically distinguish among either lunar origin models or models of lunar internal evolution.

Major unresolved issues include: (1) the depth of initial melting and differentiation; (2) the structure, thermal state, and bulk composition below the upper mantle; (3) the existence and radius of a possible metallic core; (4) the origin(s) of lunar paleomagnetism; (5) the value of the globally averaged surface heat flow; and (6) the importance of subsolidus convection in the present-day Moon.

Numerous additional aspects of the structure, composition, and history of the crust and uppermost mantle are also not well constrained. Included are the depths of mare fill in circular and irregular maria, the thickness of basin and crater ejecta deposits, the geometry and vertical extent of fault surfaces at depth, the existence and geometry of subsurface igneous intrusive bodies, and the state of stress in subsurface bedrock. The latter question is of particular importance for understanding the support of lunar mass concentrations (mascons) and for estimating the extent of global contraction. Further, near-surface geophysical studies of diverse phenomena including impact cratering physics, near-Earth meteoroid flux history, and the history of solar wind and cosmic ray ion bombardment are generally incomplete. After a brief burst of investigation during the Apollo program these investigations ceased, leaving much undone.

It is reasonable to expect that the next major throughput of geophysical data pertinent to the questions noted above will occur in the process of preparing for and carrying out more extensive manned exploration and utilization of the Moon, possibly involving establishment of a permanent base. Independent of any future manned lunar activity, an orbiting Lunar Geoscience Observer (LGO) mission may obtain expanded orbital geochemical and geophysical data sets during the 1990s as part of the planned Planetary Observer series (Randolph, 1984). Resulting measurements may then play a basic role in allowing a more knowledgeable manned site selection process and assessment of lunar resource potential prior to future landings. Thus both orbital geophysical and manned mission planning objectives may be simultaneously realized. However, several of the most basic geophysical issues such as the composition, structure, and thermal state of the deep interior can be adequately addressed only with the acquisition of long-term surface seismic and electromagnetic sounding and direct surface heat-flow measurements. While unmanned landers may provide some useful new measurements, manned emplacement of sensitive geophysical stations followed by periodic calibration checks and maintenance over at least a decade may be necessary to accurately resolve properties of the deep interior. In the following, we briefly discuss the present status of major lunar geophysical data sets, their relationship to the issues cited above, and the extent to which future orbital surveys and surface measurements may resolve these issues. Emphasis is
intentionally placed on measurements pertaining to global scale properties that are of most interest in evaluating lunar origin and evolution models.

SEISMIC DATA

Analyses of lunar seismic signals afford a primary means of probing the structure, composition, and thermal state of the interior. Derived inferences concerning the composition of the middle and lower mantle and the radius of a possible metallic core are of basic interest in distinguishing among lunar origin models (e.g., Newsom, 1984). Because of the small lunar seismic energy release and the occurrence of intense scattering in a near-surface brecciated zone, a long-term data base is required for accurately deducing the velocity structure of the lunar mantle and deep interior. Unfortunately, the reception of transmitted data from the four stations of the Apollo seismic network was terminated on September 30, 1977, as a cost-saving measure. The resulting marginal quantity of measurements and the limited selenographic separation of the seismometers has made interpretations difficult. A general summary of final conclusions based on the available data has been given by Nakamura et al. (1982).

Sources of lunar seismic signals include artificial and natural impacts, weak repetitive deep-focus moonquakes triggered by tidal stresses (Toksoz et al., 1977), and more energetic but sparse, shallow moonquakes that are most probably entirely tectonic in origin (Nakamura et al., 1979). The generally low signal-to-noise ratio reduces the accuracy of identified wave arrival times despite the application of various signal processing techniques. This factor combined with the poor areal distribution of the Apollo array and the temporally limited data base has resulted in large uncertainties in the seismic velocity structure of the middle and lower mantle. In the upper mantle (depths < 400-500 km), P- and S-wave velocities are relatively well determined and imply a Mg/(Mg+Fe) ratio for mantle olivines and pyroxenes in the range 0.70-0.85 (Nakamura et al., 1974). Such a range is in agreement with independent estimates for mare basalt source regions at comparable depths based on petrologic analyses of surface samples (Ringwood and Essene, 1970; Morgan et al., 1978). In the middle mantle (500-1000 km depth), the most recent analysis of the complete arrival time data set (Nakamura, 1983) has yielded only one-standard deviation limits on the mean P- and S-wave velocities i.e., the probability that actual velocities are within the derived range is only about 68%. The derived velocity limits would be consistent with an increase in the Mg/(Mg+Fe) ratio of middle mantle olivines and pyroxenes if the garnet abundance is not too large. Such an increase would in turn suggest that initial melting and differentiation extended down to at least 1000 km depth (Nakamura, 1983). In the lower mantle (> 1000 km depth) essentially no seismic velocity limits or compositional constraints are available.

Although an early interpretation of a P-wave arrival from a single farside meteoroid impact suggested the presence of a small low-velocity core (Nakamura et al., 1974), this interpretation was never confirmed with additional data during the active operation period of the seismic network, and it is now regarded as undefined (e.g., Goins et al., 1981). In principle, mantle density models consistent with seismic velocity limits and
other constraints such as moment-of-inertia \((I/MR^2 = 0.3905 \pm 0.0023; \) Ferrari et al., 1980) provide an alternate means of evaluating the likelihood of the existence of a metallic core. In particular, a more magnesium-rich (lower-density) middle and lower lunar mantle as suggested by Nakamura's (1983) seismic velocity model would require a substantial iron core with radius > 360 km in order to match the mean density and moment-of-inertia values (Hood and Jones, 1985). However, current uncertainties in mantle seismic velocities and their interpretation preclude deduction of the existence and radius of a metallic core on this basis alone. Additional independent constraints on the core radius such as may be provided by magnetic field data (see below) or by interpretations of laser-ranging data (Yoder, 1981) are needed.

In general, analyses of existing lunar seismic data have established the existence of a crust, an elastic upper mantle, and an attenuating lower mantle indicating temperatures much cooler than the solidus for depths less than about 500 km and suggesting a close approach of the selenotherm to the solidus at depths > 1100 km. However, compositional inferences based on seismic velocity structure needed for resolving fundamental issues such as depth of initial differentiation, bulk composition of the middle and lower mantle, and the existence of a metallic core are much more uncertain. Additionally, other questions of lunar seismicity including the nature of lateral heterogeneities and the focal depths, source mechanisms, and precise epicenters of the tectonically important shallow moonquakes remain largely unanswered. A significant change in this situation is likely to occur only with the acquisition of an improved data set involving emplacement of more widely separated surface seismometers and compilation of continuous measurements over a decade or more. Incorporation of a stored-mode operating system with relatively brief downlink transmission at regular intervals rather than continuous (24-hr) transmission, as was the case for the Apollo seismometers, would minimize the cost of long-term data acquisition. Finally, it should be noted that an effort to record the moon's free oscillations using improved seismic sensor design and emplacement (e.g., in deep boreholes below much of the scattering layer) may lead to significantly improved constraints on the density and velocity profile of the deep interior.

**ELECTROMAGNETIC SOUNDING DATA**

An alternate but equally difficult approach toward investigating the existence of a metallic core and the thermal state of the interior involves determining limits on the electrical conductivity as a function of depth via measurements of induced magnetic fields. Two primary techniques were developed in the Apollo era. The first used a single orbiting satellite, such as one of the Apollo 15 and 16 subsatellites, during periods when the Moon was in the quasi-vacuum conditions of the geomagnetic tail. After a period of five to ten hours, the geomagnetic tail magnetic field can diffuse through the poorly conducting lunar mantle so that any residual distortion of the field is due to a more highly conducting core. This distortion is marginally measurable by a spacecraft magnetometer and results in an estimate for the residual induced dipole moment. Measurements of the latter were obtained indicating the probable existence of a core
with radius $> 400$ km and conductivity $\geq 10$ S m$^{-1}$ (Goldstein et al., 1976; Russell et al., 1981). However, the core conductivity limit is consistent with either a partially molten silicate core (conductivity $\sim 10$ S m$^{-1}$) or a metallic core (conductivity $\sim 10^2$ S m$^{-1}$). Thus definitive evidence for a metallic core was not obtained. Also, the available Apollo data base was limited because of the finite lengths of the subsatellite missions and the need to eliminate periods when measurable ambient plasma densities were present. Confirmation of these measurements via future orbiters such as LGO would provide improved evidence for a highly conducting lunar core.

A second electromagnetic sounding technique employed both orbital (Explorer 35) and surface (Apollo 12) magnetometers to measure the external forcing field and the output field (forcing field plus induced field), respectively, as a function of frequency. These measurements together with a suitable theoretical model allowed limits to be established on the mantle electrical conductivity profile. The technique was applied both for times when the Moon was in the geomagnetic tail (Dyal et al., 1976), and for times when the moon was in the supermagnetosonic solar wind (Sonett et al., 1972; Hood et al., 1982a; see the review by Sonett, 1982). Results are in reasonable (order-of-magnitude) agreement and show that the conductivity rises from $10^{-4}$ to $10^{-3}$ S m$^{-1}$ at depths of a few hundred kilometers to $10^{-2}$--$10^{-1}$ S m$^{-1}$ at depths of 1000--1200 km. The same technique can be applied to put bounds on the radius of a highly conducting (partially molten silicate or metallic) core. For example, solar wind response measurements have been found to imply an upper bound of 435 km on the radius of such a core (Hobbs et al., 1983). However, uncertainties resulting from accuracy of the theoretical model used to interpret the data and possible intercalibration errors between the surface and orbiting magnetometers suggest that a more conservative upper limit on the core radius from time-dependent induction studies is near 500 km. When an array of surface magnetometers is again deployed on the lunar surface, steps must be taken to eliminate the possibility of instrument drift and intercalibration differences in order to ensure that maximally accurate limits on the core radius are obtained.

A further application of derived lunar mantle conductivity profiles is to empirically limit the range of allowed radial temperature profiles using laboratory measurements of conductivity versus temperature for relevant minerals. Results show reasonable consistency with thermal history model calculations and experimental solidus curves but are sensitive to compositional assumptions (Hood et al., 1982b). Nevertheless, the results are encouraging, and significant experimental constraints on the form of the selenotherm may be possible when mantle composition models are more refined as a result of improved seismic data.

**HEAT-FLOW DATA**

Heat-flow probe measurements were successfully obtained at only two of the Apollo landing sites, Apollo 15 and 17, yielding final estimates of 21 and 16 mW/m$^2$, respectively (Langseth et al., 1976). Derivation of globally representative averages from these isolated values is necessarily difficult, and values ranging from 11 mW/m$^2$ (Warren and Rasmussen,
1984) to 18 mW/m² (Langseth et al., 1976) have been suggested. Assuming nominal radioactive element ratios and a steady-state balance between heat production and loss, the latter rates would imply bulk Moon uranium abundances of 29 and 46 ppb, respectively, compared to 14 ppb for CI chondrites and 18 ppb for the bulk Earth. However, a steady-state balance may be inappropriate if the interior heat production is declining with time (Schubert et al., 1979; Hsu, 1979), so that the above average heat flow values may be consistent with as little as 20 and 35 ppb, respectively. The larger of these two bulk Moon uranium abundances is significantly larger than terrestrial and chondritic values, supporting the view that the Moon is generally enriched in refractory elements (Kaula, 1977; Taylor, 1982, 1984). However, the lower of these abundances would not imply a significant lunar enrichment. Thus establishment of the true globally averaged heat-flow value would be a useful step toward the construction of more accurate lunar bulk composition models, which may ultimately distinguish the mode of lunar origin. Lateral heat-flow variations are also of interest in the context of a number of geological problems including the energy partitioning during impact cratering; measurements within and near comparatively recent impact craters would be useful in this regard. In addition it should be self-evident that the observed heat flow and inferred radioactive element abundances impose primary constraints on lunar thermal evolution models (e.g., Tókóz et al., 1978).

In the absence of new surface measurements, the best near-term method for determining the actual globally averaged heat flux involves orbital measurements of subsurface radio brightness temperature at a series of wavelengths near 10 cm (Minear et al., 1977). Such a remote heat-flow instrument is being proposed for inclusion on the planned LGO mission (D. Muhleman, personal communication, 1985) and may result in a much improved assessment of lateral heat-flow variations and their dependence on physiography. Later surface measurements in different (non-mare) locales than were sampled during Apollo would provide ground-truth controls on the orbital data, thereby further increasing the accuracy of the global heat-flow determination.

**GRAVITY/TOPOGRAPHY DATA**

A primary application of combined gravity and topography data is the estimation of lateral crustal thickness and/or density variations, thereby allowing extrapolations from sparse seismic measurements. Resulting estimates for the volume and mass of the crust are important for constraining lunar bulk composition, depth of differentiation, and overall radial density models.

Precise measurements of the lunar gravitational field using observed accelerations of artificial satellites have thus far been limited by lack of direct line-of-sight Doppler tracking data on the farside and by an incomplete set of satellite orbital parameters (e.g., Michael and Blackshear, 1972). Although harmonic analysis techniques have been developed to deduce approximate long-wavelength gravity fields over the entire Moon from nearside tracking data (Ferrari and Ananda, 1977; Bills and Ferrari, 1980), the available high-resolution coverage needed for detailed geophysical modeling studies of individual crustal structures is limited to low-latitude portions of the nearside. Similarly, lunar
topographic data are absent for large regions of the farside and polar zones, so that global spherical harmonic models are of reduced accuracy and are limited to wavelengths representative of features of basin-scale or larger (Bills and Ferrari, 1977a).

The observed crustal gravity field is generally mild and is dominated by the mascon anomalies associated with major basins (Muller and Sjogren, 1968). Analyses of combined topographic and gravity data indicate that isostatic compensation is nearly complete for pre-Imbrium highland topography but is incomplete for post-Imbrium structures such as the Apennine Mountains (Ferrari et al., 1978), indicating global cooling and thickening of the elastic lithosphere since about 4 Ae. From detailed studies of several nearside basins, including Grimaldi and Mare Serenitatis, over which high resolution measurements were obtained, it has been provisionally concluded that the mascons are most probably due mainly to rapid mantle rebound at the times of basin-forming impacts combined with a small additional mass excess due to later mare basalt filling (e.g., Taylor, 1982). Assuming that lateral density variations are entirely the result of thickness variations of a nearly constant-density crust (Airy isostatic compensation), available gravity and topography data have been applied to show that (1) the average farside crustal thickness would be greater than that of the nearside and (2) crustal thickness would range from 30–35 km beneath the mascons to 90–110 km beneath the highlands (Bills and Ferrari, 1977b). However, it is also possible that a significant Pratt compensation component (lateral density variations in a constant thickness crust) is present, implying a somewhat different mean crustal thickness and density (Solomon, 1978). Either model would in principle explain the observed center-of-figure to center-of-mass offset. In order to establish the degree of Airy versus Pratt compensation, seismic crustal thickness determinations at a greater variety of surface locations are needed. Existing seismic data obtained near the Apollo 12 and 14 landing sites on Oceanus Procellarum indicate a thickness of 50–60 km (Nakamura et al., 1974; Toksöz et al., 1974) with possible evidence for a somewhat greater thickness beneath the Apollo 16 Descartes highlands site (Goins et al., 1977). More than these three control points are needed. In addition, more complete high-resolution gravity and topography coverage would allow firmer conclusions about the completeness of isostatic compensation in different physiographic regions. More accurate estimates of crustal mean density, thickness, and lateral variations needed for bulk composition modeling would follow, as well as an improved understanding of the evolution of the early lunar lithosphere.

PALEOMAGNETIC DATA

Prior to the Apollo missions, the Moon was regarded as magnetically inert because previous flybys and orbiters had detected no global magnetic field and the low mean density required a small or non-existent core. Unexpectedly, both surface traverses and orbital surveys detected widespread crustal magnetic fields with scale sizes up to about 100 km, demonstrating a pervasive magnetization of lunar surface materials. If this magnetization is ascribable in whole or in part to the existence of a former core dynamo, by analogy with the terrestrial case, then the presence of a substantial metallic core
would be required. Such an inference would be a valuable supplement to direct geophysical measurements, which are currently not definitive.

The dominant ferromagnetic carriers in lunar materials are metallic iron grains typically produced in impacts by reduction of pre-existing iron silicates. Repeated heating of returned samples necessary for Thellier-Thellier paleointensity determinations resulted in alteration of the magnetic properties of these grains, so that accurate paleointensities have been difficult to obtain. The few available Thellier-Thellier determinations, together with measurements by other more approximate paleointensity methods, indicate maximum lunar surface paleofields of the order of 1 Gauss during the 3.6–3.9 Ae period with much lower fields outside of this period (Cisowski et al., 1983). The latter authors conclude that the inferred high-field epoch is most directly interpreted in terms of a temporary core dynamo. On the other hand, significant paleointensities exist for some young samples; in particular, 70019, an Apollo 17 impact glass sample dated as < 100 m.y. old, has yielded a Thellier-Thellier paleointensity of 0.025 G, considerably larger than present-day surface magnetic fields (Sugiura et al., 1979). This fact, combined with the observation that many orbital anomalies are correlated with basin ejecta units and swirl-like albedo markings that may have impact-related origins (Hood et al., 1979), has led to suggestions that impacts themselves may generate transient fields that could have contributed substantially to the paleomagnetism (e.g., Hood and Vickery, 1984). However, other observations, including the correlation of one anomaly with Rima Sirsalis, an extensional graben-like feature south of Grimaldi (Anderson et al., 1977; Srnka et al., 1979), and evidence that surface field amplitudes on the nearside maria correlate with surface age (Lin, 1979) are supportive of the core dynamo hypothesis.

One means of evaluating the evidence for a former core dynamo involves the determination of approximate bulk directions of magnetization for major anomaly sources using orbital magnetometer data. Sources of comparable age should ideally be magnetized along field lines oriented in the shape of a dipole centered in the moon if a steady core dynamo was responsible for their magnetization. Unfortunately, the coverage of orbital magnetometer data is presently limited to narrow equatorial bands on the nearside plus a few farside areas (Hood et al., 1981) so that a total of only 28 sources with widely varying probable ages can be studied in this manner. Consequently, the directional evidence from these sources for a core dynamo is currently extremely difficult to evaluate, with different analysts drawing very different conclusions (Hood, 1981; Runcorn, 1983).

Two major steps can be taken to further understand the paleomagnetism and evaluate its implications for lunar internal evolution and history. First, a global vector magnetic anomaly map with sufficiently high resolution would lead to much more definitive evidence for or against the former existence of a large-scale lunar magnetic field. Determination of both anomaly correlations with surface geology and directional properties of the magnetization as described above would be possible in much greater detail than was the case using Apollo data. Such an anomaly map can be obtained by the planned LGO spacecraft if periapsis altitudes of < 50 km are achieved and are distributed reasonably well around the Moon. Second, the return of samples from at least some major anomaly sources, including oriented "bedrock" samples, preferably from dated mare basalt flows,
would greatly facilitate the interpretation of both the orbital data and sample paleointensity determinations. Although automated landers may be capable of returning surface regolith samples, it is unlikely that the return of oriented specimens undisturbed by meteoroid impact and comminution will be achieved without manned landings. Thus a complete resolution of the paleomagnetism enigma may come only in the course of future manned exploration and utilization missions.

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GEOPHYSICS AND LUNAR RESOURCES

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The Apollo program provided a wealth of information about the nature of the Moon's upper 1-2 km. As a result, our knowledge of the physical properties of this material gives a sound basis for planning the geophysical aspects of a resource mapping and exploration program when a lunar base is established. Possible approaches to exploration include gravity, magnetic, electromagnetic, and seismic methods.

INTRODUCTION

The Apollo program taught us a great deal about the physical properties of the lunar surface. This information is of importance when considering the question of the role that geophysical methods will play in connection with the establishment of a lunar base and the resulting opportunity for exploration. This paper will not consider the question of establishing the global properties of the Moon and the nature of the deep interior, although that is an important topic in its own right. This paper considers only the question of more local and regional exploration, either for the purpose of geophysical mapping or for the assessment of resources. During the Apollo program we learned a great deal about gravity fields on the Moon and about magnetic fields and their ancient past. Seismic exploration methods were also employed at several sites and gave information on the nature of the regolith. The Moon is especially suited to the use of electromagnetic methods since, with the lack of any fluid, the Moon is quite transparent to most electromagnetic signals in a manner quite different from most terrestrial environments.

Arnold and Duke (1978) reviewed and laid out the types of resources that are expected to be of significance. The first of these was quite simply large quantities of material suitable to be used as collected for shielding materials, either on the lunar surface or for long duration missions for protection from the radiation environment. The second was rather more sophisticated and related to the use of large volumes of material for the extraction of specific materials such as titanium, aluminum, magnesium, silicon, or iron. The third was to consider the possibility of first detecting and then exploiting specific concentrations of unusual minerals or materials such as chromite, or ice in the polar region.

GEOPHYSICAL METHODS APPLIED TO LUNAR RESOURCE STUDIES

Magnetic

The magnetic method for mapping geophysical information and for the detection of magnetic ores of the various iron oxides or of the various sulphides is commonly used on Earth. It is now common to use airborne magnetic methods for mapping of
very large areas. This is often the first step, for example, in establishing a reference for exploration programs in third-world countries. In general, the distribution of iron oxide in the form of magnetite ($\text{Fe}_3\text{O}_4$) and its solid solution series with titanium is mappable due to the magnetization induced by the Earth's magnetic field.

The Moon, on the other hand, has no modern-day magnetic field; furthermore, essentially no magnetite has been detected. This means that lunar magnetic mapping and exploration is entirely different in concept than terrestrial mapping. The lunar soils contain small particles of metallic iron or iron-nickel resulting largely from the reduction that takes place upon impact melting in the lunar vacuum (Strangway et al., 1977). Most soils have about 0.5% metallic iron. The source rocks, either basalts or anorthosites from which the soils were derived, also contain metallic iron but in much lower quantities (typically 0.1% for basalts). Since there is no ambient field, no magnetic anomalies arise from this source. The particles are, however, very small, and many of them are in particle sizes that are close to the superparamagnetic single-domain threshold (approximately 150 $\text{Å}$). This means that the phenomenon of magnetic relaxation that is a function of both grain size and iron content (Carnes et al., 1975) is very strong. Magnetic relaxation or viscosity refers to the property by which a magnetic material exposed to a magnetic field does not lose the magnetization as soon as the field is turned off; rather, it decays away over a period of time. It would be quite straightforward to develop an active magnetic mapping system on a traversing vehicle that could measure iron content and give some information on the grain-size distribution of metallic iron in the regolith. This information could be of use in selecting high-Fe soils or for the design of magnetic separation techniques.

Many observations have shown that the lunar samples carry some permanent magnetization. The source of the field that caused this magnetization is not well understood, but it could be due to an early lunar field with a value of a few thousand nanoTesla. Anomalous lunar magnetic fields have been detected from orbital magnetometers, from surface magnetometers (fixed stations and portable), and from an orbital electron reflection experiment. Significant volumes of the lunar outer layers carry this remanence and indicate that bombardment has not completely broken up and randomized the source layers. There is strong evidence that the greater anomalies are associated with breccias that are enriched in fine-grained iron just as the soils are (Strangway et al., 1975; Hood et al., 1978). Uniformly layered units do not give magnetic anomalies, but lateral variations do give rise to anomalies. Thus, magnetic mapping is particularly useful for detecting lateral changes and boundaries. It would be of extreme interest to obtain a complete satellite map of magnetic anomalies as part of a map of magnetic fields over large areas of the lunar surface. A lunar base, supported by a roving vehicle, could also provide much information on lunar magnetic history and be used to select sites for detailed study.

**Electromagnetic Sounding**

Electromagnetic sounding has been extensively used on the Earth for mapping near-surface properties as well as for sounding to considerable depth. Both ground and airborne systems have been useful in the search for conducting minerals—in particular for massive sulphide deposits. The Moon is known to be extremely dry and the electrical resistivities
of lunar rocks and soils are extremely high, often as resistive as some of our best commercial insulators (Strangway et al., 1977; Strangway and Olhoeft, 1977). As a result, electromagnetic energy propagates very readily into the Moon; it is possible to consider the concepts of reflection and refraction rather than the diffusion process usually considered on the Earth. Electromagnetic depth penetration can be considerable and can be accompanied by high resolution. The extreme resistivity of the surface layer means that the Moon is not amenable to the more conventional electrical resistivity methods that require current to be driven into the ground (see for example, Linlor, 1970).

A surface experiment confirmed the electrical properties of the surface at the Apollo 17 site (Strangway et al., 1977). Frequencies from 1-32 Mhz were used to penetrate the surface and were recorded on the rover as it traversed away from a fixed transmitter. The results encountered were very similar to those found over ice sheets. Penetration was great at frequencies of 1, 2, and 4 Mhz, and reflections from depths of over 1 km could be detected. In addition, it was possible to measure the dielectric constant of the surface layers and its increase with depth. At the higher frequencies, the regolith proved to be a strongly scattering medium in which the contrast of dielectric constant between soil (approximately 3) and rock (approximately 7-8) caused many reflections. This experiment specifically confirmed that high-resolution mapping of the subsurface was possible with electromagnetic methods. A radar-like experiment used in a manner completely analogous to radar sounding of ice sheets would give much information on stratigraphy in the regolith. Such methods could be set up to function on a traversing vehicle. This would yield information on layering in the regolith, on the soil-rock interface, and on regolith thickness. It could also locate regions of high conductivity (radar-reflective) materials. In addition, the electrical losses are sensitive to the amount of ilmenite present. This approach would be useful in many aspects of assessing the character of the regolith, the distribution of ilmenite, or the presence of massive concentrations of metallic conducting phases such as chromite or other magmatic segregations.

**Seismic**

This paper does not review the need for a lunar-wide seismic observatory but does consider the use of seismic methods for assessing the character of the regolith. In the dry lunar vacuum, seismic propagation is very different than it is in normal terrestrial materials. The regolith is comprised of finely ground powder and pieces of breccia, basalt, and other igneous or metamorphic boulders with a wide range of sizes. At depths of a few meters to tens of meters there may be bedrock, as inferred, for example, from the walls of Hadley Rille at the Apollo 15 landing site. Nevertheless, these units are also heavily fractured. Since there is no fluid, the lithostatic load is supported entirely by particle-to-particle compression, and there is very little loss of seismic energy as it propagates through the rock. The net result is that the Moon has very high Q, and seismic energy is heavily scattered (Cooper et al., 1974). This has meant that the active seismic experiments carried on several of the Apollo missions showed a straightforward velocity increase with depth following a fairly simple law (Johnson et al., 1982). There is some argument about the precise nature of the relationship, but it is nevertheless consistent with a soil in which
seismic velocity increases uniformly with depth. The large array used at the Apollo 17 site shows a sharp increase in velocity at a depth of 1.4 km that gives velocities typical of solid rock. There is a suggestion of a discontinuity at a depth of 32 m, perhaps corresponding to a stratigraphic horizon (ejecta blanket or lava flow) in the regolith.

It is clear that the application of the shallow seismic method on the lunar surface will be very different than on Earth. Nevertheless, mapping of the stratigraphy may be possible using a combination of shallow reflection and refraction techniques. Very small energy sources can give useful results, and one could imagine a rover-mounted impulse transmitter and receiving device.

Gravity

There has been only a small amount of gravity work done on the lunar surface, although orbital tracking has revealed the presence of large gravitational anomalies in the form of mascons (Muller and Sjogren, 1968). Because of the strength of the lunar crust, even very old features such as craters filled by dense mare basalts have not relaxed since they were formed nearly 4 billion years ago. Apollo 17 landed in a mare basalt-filled valley in the highlands of the Moon, and enough stations were measured to give a profile across the valley (Talwani et al., 1973). The gravity values were high in the middle of the valley over the basalts and dropped by as much as 50 mGal as the highland massifs were approached. The massifs are rich in anorthositic highland materials of lower density. A simple model of basalts with a density contrast of 0.8 g/cm³ and a thickness of 1 km explains these results adequately.

Thus, gravity methods could be used to assess the character of basaltic rocks and would of course be quite useful in exploration for local concentrations of heavy minerals that might be expected as products of magmatic segregation.

Discussion

The experience of the Apollo program has given information on the physical properties of regolith, basalt, and breccia in the lunar vacuum condition. In this environment, many physical properties are very different than those on Earth. The Apollo experiments using electromagnetic, magnetic, seismic, and gravity measurements give a clear idea of how these measurements can be carried out at a lunar base. These geophysical methods can and should play a role in the mapping that will be done in association with a lunar base as expeditions are mounted from this base. Geophysical methods can also play a role in assessing the character of the regolith materials for exploitation, especially if these methods are combined with geochemical techniques such as γ-ray and x-ray studies. Drilling also will be of considerable use for outlining stratigraphy between the holes and for confirming the geophysical interpretations. If there is a concentrated effort to search for ore deposits, many of these methods will be even more effective than they are on the Earth because of the Moon's more uniform background signals and the fact that electromagnetic energy can penetrate the dry surface much more readily than on Earth. The use of these methods for long traverses or for more local surveys seems clear, both
for stratigraphic mapping and to search for and understand lateral changes. If sites are selected for deeper drilling, the use of geophysical methods in preliminary site surveys is essential.

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SURFACE ELECTROMAGNETIC EXPLORATION
GEOPHYSICS APPLIED TO THE MOON

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With the advent of a permanent lunar base, the desire to explore the lunar near-surface for both scientific and economic purposes will arise. Applications of surface exploration geophysical methods to the Earth's subsurface are highly developed. This paper briefly addresses some aspects of applying this technology to near-surface lunar exploration. It is noted that both the manner of application of some techniques, as well as their traditional hierarchy as assigned on Earth, should be altered for lunar exploration. In particular, electromagnetic techniques may replace seismic techniques as the primary tool for evaluating near-surface structure.

INTRODUCTION

Application of geophysical techniques to the Moon will provide information in two areas: scientific and economic. Scientific data will provide a more detailed understanding of the lunar interior, which, when coupled with geologic data, will give us better insight into the creation and evolution of the Moon. It can also aid in mapping of structure and lithology and provide information on the physical properties of rocks.

Exploration data will assist in prospecting for mineral concentrations and for water, an even more precious commodity. We are primarily interested in emphasizing surface exploration geophysics as applied to the upper few kilometers of the Moon's crust.

There are several important lunar characteristics that differ from terrestrial conditions and, therefore, alter the manner of application of geophysical methods, as well as their traditional hierarchy as assigned on the Earth. The absence of water precludes secondary alteration, mineral concentration, erosion, and deposition by hydrologic means. It also causes lunar materials to have an extremely high electrical resistivity. The only active geologic processes known to be occurring on the Moon at present are crater formation and subsequent regolith deposition via meteorite impacts.

Although some thin layering has been observed associated with ejecta blankets, continuous sedimentary beds as they occur on the Earth are unknown on the Moon. Other features affecting geophysical studies include the extensive impact structures, with attendant lithologies and shock metamorphism, and also lack of a core-generated magnetic field.

Standard geophysical exploration techniques employed on the surface of the Earth include gravity, magnetics, seismics, electrical, and electromagnetics. Although these techniques will be discussed separately, our experience on Earth has repeatedly proven the necessity for integrating data from as many geophysical and geological sources as possible to derive reasonable models and interpretations.
There are several other surface exploration geophysical techniques that will not be discussed in this paper because they are not widely used but have specific terrestrial applications, e.g., radiometrics used in uranium exploration, and radon and other gas detectors used in geothermal exploration. Also, there are a wide variety of below-surface (well logging) and above-surface (remote sensing, potential field mapping, etc.) techniques that can be used either in planning or in conjunction with a surface exploration program, but these are not within the scope of this paper and will not be discussed here. Furthermore, electromagnetic techniques will be emphasized because of their expected importance in lunar near-surface exploration relative to other geophysical exploration techniques.

**GRAVITY**

Gravity is typically the first technique applied in terrestrial prospecting because it is relatively inexpensive and often provides important constraints on possible exploration targets. Gravity exploration could easily be undertaken on the surface of the Moon with little change in application other than that expected because the gravitational field of the Moon is approximately one sixth that of the Earth’s field. Gravity exploration will probably play an important role in mapping gross structure in the subsurface, and it might be useful in the search for large buried fragments of meteoritic material.

Density information is needed for constraints on modeling or inversion of gravity data. This information is usually obtained from measuring specific gravity of rock samples obtained from the surface or from cores or cuttings obtained from drill holes. Density may also be inferred from gamma-gamma or seismic velocity drilling logs once these logs have been calibrated for lunar materials. Gravity data reduction to obtain residual Bouguer anomalies will be similar in principle to the procedure used on Earth. It will differ in practice only in that a lunar reference equipotential surface must be used rather than an Earth reference spheroid and that a “standard” density must be agreed upon for regolith material in order to perform a Bouguer correction. It will be necessary to obtain the lunar reference equipotential surface to as high a precision as possible using satellite data. Initial models of global lunar gravity have been obtained by fitting sixteenth-degree harmonic series to data collected from the Lunar Orbiter and Apollo missions (Wong et al., 1971; Ferrari and Ananda, 1977; Bills and Ferrari, 1980). Lunar gravity modeling and inversion techniques will be identical to those applied on Earth.

**MAGNETICS**

Magnetics has traditionally been used as a major tool for detection of ore bodies on the Earth. Magnetic exploration on the Moon will be primarily affected by the lack of a large ambient lunar magnetic field such as that occurring on Earth. The small remanent field on the Moon generated by metallic iron disseminated in the lunar regolith would only represent noise to magnetic exploration. Strangway (1976) has already pointed out that, in order to use magnetics for exploration, an artificial magnetic source in the form of a large coil must be placed on the surface to induce magnetization in the rocks.
The addition of such an artificial magnetic source modifies the magnetic technique to such an extent that it essentially becomes a special case of the active inductive technique, which will be discussed later.

**SEISMICS**

Seismics has traditionally played the prominent role in terrestrial prospecting because of its extensive application in hydrocarbon exploration. Since it is not likely that petroleum fields exist on the Moon and because seismics is not typically useful for minerals exploration, it will probably not be very useful as a lunar minerals prospecting tool. Data from the Apollo Seismic Net (Toksöz et al., 1974) indicates that lunar seismograms are not at all like Earth seismograms. In particular, lunar seismograms have a small first arrival, the amplitude builds up slowly, the signal reverberates for an extremely long time, and the amplitude envelope has a very long rise time. The long reverberating seismic wave train is explained by strong scattering and very low velocity attenuation in the near-surface regolith. Seismic energy appears to propagate through the lunar regolith by anisotropic diffusion. Thus, lunar seismic waves are very hard to interpret. They have been used during the Apollo Project to glean information about gross lunar structure. In particular, they may be used (with difficulty) to estimate the combined thickness of the regolith plus megaregolith. Unfortunately, from an exploration standpoint, the very high rate of seismic energy dispersion that occurs in the regolith will very sharply decrease the resolution and hence the usefulness of seismic waves in discerning shallow, subsurface structure. Toksöz et al. (1974) studied the structure of lunar seismograms by comparing them to synthetic seismograms. The application of both synthetic seismograms and seismic three-dimensional physical model scaling is developing very rapidly and may help to unravel the very complex structure of future lunar exploration seismic data.

**ELECTROMAGNETICS**

Electromagnetics, of which electrical methods are a subset, will probably replace seismics as the dominant technique for exploring the lunar near-surface. Application of electromagnetic techniques will be quite different from that on the Earth because of the very high resistivity, which may vary from $10^6$ to $10^{18}$ ohm/m (Strangway et al., 1972; Olhoeft and Strangway, 1975; Strangway and Olhoeft, 1977) for lunar material, as opposed to $10^1$ to $10^5$ ohm/m for terrestrial rocks. These exceptionally high lunar resistivity values greatly increase the usefulness of electromagnetic methods on the Moon. In terrestrial applications these techniques are mainly used to detect differences in salinity and amounts of water in the host rock; whereas, for lunar rocks, electromagnetics can be used to derive values for actual physical properties and also to detect lateral and vertical variations in these properties that would be most useful from the standpoint of prospecting.

Because externally generated electromagnetic fields diffuse into the ground, their skin depth of penetration ($S$) and hence their depth of investigation is a function of frequency ($\omega$) and subsurface electrical resistivity ($\rho$). For a homogeneous Earth half-space, $S =$
where \( \mu \) is the relative magnetic permeability. A given electromagnetic frequency will penetrate much deeper on the Moon relative to the Earth because the Moon's near-surface resistivity is much higher. Therefore, techniques with much higher frequency responses (possibly as high as \( 10^7 \) Hz) will be needed to obtain data to within a few meters of the lunar surface. With an increase in frequency comes an increase in resolution. This will be another major advantage of applying electromagnetic techniques to lunar exploration, relative to terrestrial exploration.

Unfortunately, with an increase in resistivity comes a decrease in frequency at which displacement currents become dominant. The presence of displacement currents substantially complicates electromagnetic exploration theory. Above about \( 10^4 \) Hz, they become important in the Earth. Consequently, other electromagnetic techniques with frequency responses above \( 10^4 \) Hz are seldom used in exploration because they are harder to quantify. In addition, on the Earth non-displacement current techniques exist that can sample to within a few meters of the Earth's surface, making the use of higher frequencies unnecessary in most cases.

Electromagnetic techniques can be subdivided into two categories: active and passive. Active techniques involve artificially generated and induced fields, whereas passive techniques utilize naturally induced fields. The active techniques include direct current (DC) resistivity, induced polarization (IP), conductive source electromagnetic (EM) depth sounding, inductive source EM depth sounding, and displacement current techniques such as ground penetrating radar (GPR) and very low frequency (VLF) soundings. The passive techniques include the self-potential (SP) technique, telluric current technique, geomagnetic depth sounding (GDS), magnetotellurics (MT), and audio-magnetotellurics (AMT). Currently, there are no passive techniques used on the Earth that operate in the frequency range dominated by displacement currents. Such techniques will have to be developed for lunar operation. For a discussion of each technique and their Earth applications, see Telford et al. (1976).

The IP and SP techniques are directly tied to the presence of ground water and therefore will have no lunar application. The separation of the various passive techniques is somewhat artificial, primarily involving the frequency response of the various types of magnetometers used to measure the magnetic fields, and, hence, each technique has a different depth range of investigation, given a particular subsurface electrical resistivity structure: \(< 10^4 \) Hz for GDS, \( 10^4 - 10^5 \) Hz for MT, and \( 10^5 - 10^6 \) Hz for AMT. Telluric profiling is a subset technique of magnetotellurics in which only natural electric fields are measured. On the Moon, displacement current techniques will become very important. In order to properly interpret resulting data, sophisticated modeling schemes will have to be developed.

The sources and nature of passively induced electromagnetic fields located at the surface of the Earth and Moon are quite different. The Earth-atmosphere-ionosphere establishes a spherical wave guide where the ionosphere forms a conductor, the atmosphere is the dielectric, and the Earth is a "leaky" conductor. The motion of charged particles in the ionosphere, due to their interaction with the solar wind, induces EM fields into the waveguide that then propagate around the Earth. When these EM fields impinge upon the Earth, a small fraction of their energy diffuses or "leaks" into the Earth. This
An ionospheric source decreases in energy with increasing frequency and is overpowered by a second EM source above about 10–100Hz. The second EM source is due to worldwide lightning strikes (called spherics) that feed energy into the waveguide and drive that part of the natural spectrum that is above about 10Hz.

On the Moon there is no atmosphere, no ionosphere, and hence no lightning. There is also no large main magnetic field. Therefore, there is no shield, buffer, or modifier between the surface and extralunar fields. Extralunar fields, which consist mainly of solar wind and the terrestrial magnetic field, are free to directly induce EM fields beneath the surface. Extensive modification of passive EM exploration theory is required in order to take advantage of the passive exploration techniques on the Moon. So far, theoretical studies have been aimed at the response of the Moon to long wavelength, time-dependent external fields with the intent of investigating the gross electrical resistivity structure of the Moon. These studies are quite complex and a great deal of theoretical work must be performed before natural EM fields at sufficiently high enough frequencies can be utilized for near-surface exploration. For discussion of this work see Dyal et al. (1974), Sonett (1982), and Hood et al. (1982).

Active electromagnetics can be divided into conductive, inductive, and displacement current techniques. Active inductive techniques use a closed wire loop to generate a time-varying magnetic dipole that induces an electric current in the subsurface. Induction methods are highly sensitive to the presence of conductors, which leads to the supposition that such techniques could play a dominant role in exploring for metallic mineral concentrations beneath the lunar surface. Active conductive techniques use current passing through a grounded wire to generate an electromagnetic field. The DC resistivity technique is a special case of the conductive EM method. The high sensitivity of conductive methods to resistive targets implies that these techniques may be very important in mapping near-surface structure because of the highly resistive lunar surface. The contact resistance of the electrodes with the surface will be extraordinarily high and may pose a severe problem. Extremely high voltages, possibly as high as a megavolt, will probably be required to overcome the problem. Traditional equipment used for conductive electromagnetic exploration must be redesigned. Realistic sources for the increased power might be Cockcroft–Walton or Van De Graaff generators that are presently used in particle physics applications.

Although active displacement current techniques have not been important for terrestrial exploration, they will be very important for lunar exploration. The primary active displacement current surface exploration techniques are the VLF prospecting technique and GPR. The VLF technique uses as a source radio transmission for communications with submerged submarines and long-range radio positioning at frequencies of 3–40 kHz. Such a system does not seem practical for lunar exploration. GPR is a relatively new exploration technique that provides high resolution but poor terrestrial depth of penetration. This technique operates by transmitting an electromagnetic pulse with a 100-MHz center frequency into the ground and receiving energy reflected by any changes in dielectric permittivity (Olhoeft, 1979; 1984). GPR will most probably be a very useful near-surface lunar exploration tool.
CONCLUSION

Although gravity and seismics may provide a great deal of information on the gross structure of the Moon and, in addition to magnetics, may provide some limited data on the lunar near-surface, the expected efficiency of electromagnetic techniques suggests that substantial efforts should be directed toward extending our abilities in applying electromagnetics to lunar exploration.

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