

GEOSCIENCE INVESTIGATIONS
CONDUCTED FROM A LUNAR BASE

B. Ray Hawke
Planetary Geosciences Division
Hawaii Institute of Geophysics
University of Hawaii
Honolulu, HI 96822 U.S.A.

Paul D. Spudis
Branch of Astrogeology
U. S. Geological Survey
Flagstaff, AZ 86001 U.S.A.

ABSTRACT

A lunar base will probably be established by some nation or group of nations during the first decade of the 21st century. Geoscience investigations will be one of the major activities conducted at this base. The results of various missions as well as the continued analysis of the Apollo data sets have provided the necessary information to allow the development of a comprehensive lunar exploration strategy which involves precursor missions, reconnaissance sampling, and field studies. A phased approach is critical to the success of the exploration effort from the lunar base. In order to meet geoscience objectives, increasingly more sophisticated equipment for chemical analysis on the Moon will be required.

1. INTRODUCTION

It seems likely that a permanent base will be established on the surface of the Moon by some nation or group of nations during the early years of the next century. While the long term settlement of the Moon will be for economic reasons, the initial return will be for a variety of scientific reasons. These include astronomical observations, basic physical science studies, and geoscience investigations as well as support of both manned and unmanned missions for the exploration of the Solar System. At all stages of lunar settlement, geoscience will be an important activity. The purposes of this paper are as follows: 1) To present the rationale and objectives of lunar geoscience investigations; 2) To describe a phased approach to meeting science and exploration goals; and 3) To detail the research needs and the instrumentation and analytical requirements for performing chemical analysis-supported research at a manned lunar base.

2. LUNAR GEOSCIENCE INVESTIGATIONS

There are a number of compelling reasons for lunar geologic investigations. The Moon is a baseline for understanding planetary surface processes as well as the early history and evolution of the terrestrial planets and many satellites of the outer planets. The Moon possesses a differentiated crust as well as an ancient surface that has been well preserved since very early in Solar System history. These characteristics as well as the Moon's relative accessibility make it an advantageous laboratory for investigating the early history of the inner Solar System. The Apollo missions acquired data that without question revolutionized lunar and planetary science. Although considerable understanding of planetary surface processes

has been achieved using the Apollo database, a number of fundamental problems remain, including: 1) lunar origin and accretion; 2) lunar crustal structure, composition, and petrogenesis, 3) Earth - Moon bombardment history; and 4) mantle composition and heterogeneity.

A number of unmanned lunar missions have been proposed as precursors to a manned lunar base. The Lunar Observer mission will almost certainly be flown prior to the establishment of a lunar base. Other missions may be conducted in support of the specific goals and objectives of the lunar base. Still, while the results of these missions would undoubtedly produce a major advance in lunar science, it is unlikely that the majority of the critical questions can be answered in a satisfactory manner. In this paper, we identify and discuss the problems which will be solved by geologic studies supported by a Lunar-based Chemical Analysis Laboratory.

Impact cratering is a fundamental planetary process of great importance. The manned lunar landings and returned samples generated major interest in impact cratering processes. Subsequently, important advances were made in our understanding of cratering mechanics and processes by theoretical and experimental cratering studies, detailed investigations of terrestrial impact structures, and analysis of the lunar samples. Still, many questions remain unanswered. While studies of terrestrial impact craters will continue to be useful, the highly eroded state of large terrestrial craters and the fact that they formed in a terrestrial environment limits their utility towards understanding planetary impact craters. The proposed lunar base will allow field studies and sampling of impact structures which range in size over several orders of magnitude. Small, fresh impact craters will be present in the immediate vicinity of the lunar base. Expeditions supported by the lunar base will be necessary to investigate a variety of large craters. The major problems to be addressed include: 1) the modes of ejecta emplacement (i.e., ballistic transport, base surge, surface flow, etc.), 2) the distribution and compositional homogeneity of impact melt in and around craters as a function of size, 3) the depth of origin of the various ejecta units, 4) the nature of the crater modification processes, and 5) the composition of the lunar crust at the target site.

Special attention will be paid to the lunar multi-ringed basins because these large impact structures have played such a dominant role in controlling lunar surface morphology and composition. Absolute ages for these basins can be determined by radiometric dating of their melt deposits. This information is critical for deciphering the early cratering history of the Moon. Volcanism has also played a major role in the geologic evolution of the lunar surface. While much has been learned by intensive geochemical and petrologic studies of the returned mare basalt samples as well as recent photogeologic and remote sensing investigations, many key questions regarding lunar volcanism remain unanswered. These include the duration and extent of mare volcanism, the role of early mare volcanism in controlling crustal composition, and the composition of mare basalt source regions in the lunar mantle. The nature and relative importance of highlands volcanism is also poorly understood.

Finally, investigations conducted from a lunar base will be necessary to determine the origin and stratigraphy of the lunar crust. The petrogenesis of the crustal rocks and the structure of the highlands crust are of critical importance to an understanding of the nature of early planetary differentiation.

3. A LUNAR EXPLORATION STRATEGY

Continued planetary missions as well as analysis of the various Apollo data sets have provided the necessary information to allow the development of a logical and comprehensive plan to continue the exploration of the Moon (Spudis and Taylor, 1990). The plan described in this paper is a synthesis of the recommendations of a number of Working Groups, workshops, and individual lunar scientists (e.g., Taylor and Spudis, 1989; Spudis and Taylor, 1990; Cintala

et al., 1985; LGO Science Workshop, 1986; Lunar Geoscience Working Group, 1986).

All lunar scientists agree that a polar orbiting spacecraft is the next logical step in any program for the future exploration, utilization, and settlement of the Moon. It is absolutely essential that geochemical, mineralogical, lithologic, geophysical, and photographic maps be obtained for the entire lunar surface. These data sets will provide critical information concerning sites for reconnaissance missions, the placement of geophysical network stations, regions containing potential resources, and potential locations for the lunar base. As noted above, the large amount of new remote sensing data will allow major advances in our understanding of the evolution of the Moon. Still, it is clear that other missions will be required to answer the remaining questions.

After analysis and interpretation of the global maps, other orbital missions could be planned. Several possibilities for follow-on orbital missions were described by Spudis and Taylor (1990). For example, high-resolution geophysical data might be valuable for understanding regional structures or in evaluating the resource potential of selected areas. Very high-resolution orbital geochemistry and spectral data will be needed to understand the composition, evolution, and resource potential of small, complex geologic structures such as late-stage plutons which have been exposed by impact cratering events. The spacecraft utilized for these follow-on missions might be placed in relatively low lunar orbits designed to provide adequate spatial resolution for selected features. Alternately, tethers could be utilized to lower instrument packages close to the lunar surface. While these follow-on orbital missions need not precede the establishment of a lunar base, a number of extremely-high resolution (<1-m) images of potential base sites may be needed prior to the construction of the lunar base. Binder(1988) detailed numerous advantages in having remote sensing spacecraft in orbit after the establishment of the lunar base.

Lunar scientists agree that a thorough understanding of the bulk composition, structure, origin, and evolution of the Moon will be impossible without knowledge of its interior. In order to obtain the necessary information, the installation of a geophysical network of at least eight stations will be required (Spudis and Taylor, 1990). At a minimum, each station must include a seismometer and a heat-flow probe. Other instruments such as magnetometers, gravimeters, and atmospheric sensors will be included in some packages.

A number of options exist for the deployment of this global geophysical network. These include penetrators, soft landers, surface rovers, and astronauts. The advantages and disadvantages of each method have been presented by Taylor and Spudis (1989). While the final emplacement of the geophysical network need not take place before the lunar base is constructed, it is certainly desirable to begin installation as soon as possible and to continue station deployment during the lunar base era.

Reconnaissance sampling missions conducted by both astronauts and automated spacecraft are important components in the proposed lunar exploration strategy. Reconnaissance missions are of limited duration and are designed to answer specific questions concerning limited areas on the lunar surface. As described by Ryder et al. (1989), many significant scientific questions can be answered through the detailed studies of lunar samples returned by relatively unsophisticated, automated spacecraft similar to the Soviet Luna landers. These spacecraft could be sent to numerous sites over a period of many years, starting before outpost construction and continuing indefinitely afterwards. Such automated sample-return missions have an important role in the general scientific exploration of the Moon and may or may not be related to the lunar base program.

Astronauts could also conduct reconnaissance missions prior to, as well as after, the establishment of a lunar outpost. For example, human missions would be useful to investigate potential base sites and might be required for site certification.

Geologic field study is a complex, work-intensive activity that requires the presence of human intelligence. It involves the study of rocks and rock units in their natural environment and it entails detailed observations, mapping the relative distribution of rock types, and collection of samples from a known geologic context (Taylor and Spudis, 1990). Field study has ambitious goals and requires the intimate involvement of human geologists. The goals are to understand lunar surface processes, geologic formations, and lunar evolution at all levels of detail. Hence, field study is a time intensive and complex operation that requires the time and ability to think about observations made in the field. It is an iterative process that often requires the capability of return visits to a field area interspersed with laboratory analysis and revision of working hypotheses and conceptual models. (Taylor and Spudis, 1990).

Field studies require long-duration missions, so they clearly need the capabilities that accompany a lunar base. Initial human field work will almost certainly be restricted to within 50 km of the lunar outpost. This range would be expanded to several hundred kilometers by the development of a pressurized roving vehicle.

Prior to base establishment, autonomous or semiautonomous rovers would be tested. As noted by Spudis and Taylor (1990), these will be important ingredients in the detailed geologic exploration of the Moon and can provide a testbed for the concept of a teleoperated robotic field geologist (Spudis and Taylor, 1988; Taylor and Spudis, 1990). By permitting field work at sites great distances from the outpost, the development of robotic field geologists with telepresence will transform a local outpost into a global base.

4. THE ESTABLISHMENT OF A LUNAR BASE: A PHASED APPROACH

An evolutionary approach will be needed to establish a permanently manned base on the surface of the moon (Duke, 1989). Several phases will be required. An unmanned Precursor Phase for detailed global mapping as well as the characterization and prioritization of potential base sites was described in a previous section. The first step in the establishment of a permanent base is the Emplacement Phase. The major geoscience goal for this phase is the astronaut-assisted, intensive characterization of the base locale (50-km radius). The strategy for meeting this goal includes crew-assisted experiments, crew observations and sampling, instrument emplacement, and regional reconnaissance with teleoperated vehicles controlled from Earth. Sample storage, preparation, and preliminary analysis will be necessary at the outpost during the Emplacement Phase. A curatorial facility and a preliminary examination laboratory will be critical to meeting the goals of this phase. The initial curatorial facility should have the capability for robotic sample storage in the ambient lunar atmosphere. Photographic documentation and sample splitting equipment will be required. Because of extremely limited crew time, the preliminary examination laboratory must make maximum use of teleoperation and automation. The instrumentation and analytical requirements are as follows: 1) A stereoscopic microscope for sample examination and characterization, 2) X-ray fluorescence instrumentation, and 3) A scanning-electron microscope.

The regular return of samples to Earth for detailed study is essential. It is clear that a major task of the preliminary examination laboratory on the Moon is to "high-grade" samples for shipment to Earth. An Earth-based support system must be put in place. The ground-support team will collect, curate, and evaluate returned lunar samples. Detailed chemical and isotopic analyses will be obtained in laboratories operated by principal investigator teams.

A major goal of the Consolidation Phase will be to extend intensive, manned characterization of local geology to regional scale. The region will be explored in detail up to 500 km from the outpost. During the Consolidation Phase, teleoperated work will be conducted at selected near side sites. This will include field geology, sample collection, and the emplacement of long-baseline geophysical stations. The curatorial facility will continue

activities begun during emplacement. However, the storage capacity must be enhanced. The preliminary examination laboratory should be up-graded during the phase. Thin sectioning equipment and a petrographic microscope will be required. Duplicate X-ray fluorescence instrumentation would be useful at this stage. It will be necessary to install a ferromagnetic resonance spectrometer as well as a survey radiograph and X-ray spectrometer during the Consolidation Phase.

During the Utilization Phase of lunar base development, a variety of global sites will be explored in detail. During the phase, the geophysical net should become global. Long-range manned traverses to specific sites including far side locations, will be conducted (Cintala et al., 1985). Teleoperated activities, including full telepresence, will continue on the near side and extend to the far side. These robotic vehicles must have multispectral vision as well as multiple articulated limbs with tactile feedback. X-ray fluorescence/gamma-ray spectrometers might be included on these vehicles.

The need for curation and analysis will be increased during the Utilization Phase. The curatorial facility must continue and enhance the activities initiated during the earlier phases. It will be necessary to enhance sample storage capabilities and to add a core-storage facility. The requirement for the preliminary examination laboratory will be much the same as during the previous phases. However, an enhanced analytical laboratory would be extremely useful. This enhancement facility should have the capability for trace-element analysis and geochronology. A mass spectrometer is called for. Earth-based support must continue and expand during the Utilization Phase.

5. CONCLUSIONS

It now seems likely that a lunar outpost will be established during the early years of the 21st century. The initial return to the Moon will be largely for scientific reasons. These include the establishment of astronomical observatories, physical science studies, and geoscience investigations. Chief among the reasons for lunar geologic investigations is the fact that the Moon is a baseline for understanding planetary surface processes as well as the early history of the terrestrial planets.

A phased approach is needed to establish a permanent lunar base. Increasingly more sophisticated equipment for chemical analysis will be required during the evolution of the lunar outpost.

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