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 = 10^9 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 reconnaisance 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 (Boyce, 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

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

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 ALSEPs; 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 ALSEPs could record large meteorite impacts and greatly improve knowledge of the Moon's third dimension. Because the ALSEPs were shut down in 1977, new instruments are required. Also, a much greater spatial spread than that of the ALSEPs, 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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