A FIELD GEOLOGIST'S RETURN TO THE MOON.

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Field geologists are essential to the successful exploration of the moon. The presence of humans will continue to be the most productive and cost-effective approach to lunar and planetary scientific investigation, mineral exploration, and resource production. Robotic systems will and must make increasingly important contributions; however, the spontaneous human observation, integration, and interpretation of the total dynamic situation involved in lunar activities, and a calculated human response to that situation, will be as irreplaceable in the future as they have been throughout geology's past.

Two examples of the uniqueness of human intervention in geological exploration on the moon are the Apollo 17 discoveries of the cross-cutting relationships between old blue-gray breccias rich in crystalline clasts and younger vesicular tan-gray breccias (1) and of the existence of deposits of very old but unmodified pyroclastic debris (the orange soil) (2). It is well to remember that the results of the human exploration of the moon forms the scientific foundation for much of our interpretation of the data from other planetary science probes. Both the cost and the potential for failure in duplicating this initial foundation through automated or robotic means would have been very high, even in comparison to the cost of the Apollo program.

FUTURE INVESTIGATIONS

Field investigations of known features and of targets of geological opportunity relevant to detailed understanding of lunar and terrestrial evolution also will be of primary importance upon the return of geologists to the moon. Seven major stages of lunar evolution are apparent as a result of the Apollo investigations (3). These stages and their approximate times or durations are as follows:

1. The Beginning - 4.6 billion years ago.
2. The Melted Shell - 4.6-4.4 billion years ago.
3. The Cratered Highlands - 4.4-4.1 billion years ago.
4. The Large Basins - 4.1-3.9 billion years ago.
5. The Light-colored Plains - 3.9-3.8 billion years ago.
6. The Basaltic Maria - 3.8-3.0(?) billion years ago.
7. The Quiet Crust - 3.0(?) billion years ago to the present.

Each of these stages probably overlaps with the previous and following stages and needs further detailed study, as does the new emphasis on the possibility of an impact-related (4) "beginning," but they form a convenient basis for the present discussion.

The field data from Taurus-Littrow suggested that relatively unmodified large fragments of very old (4.5 billion years) and highly differentiated crystalline rocks concentrated in units of blue-gray breccia underlying and cut by tan-gray breccias generated by large impact events. A systematic field search for and sampling of these primordial clasts in the boulders and ledges in the radial valleys of large basins is critical to a full understanding of the beginning of the moon and its early differentiation.

Melting of the outer 200-300 km shell of the moon during or very soon after formation is supported (3,5) by Apollo seismic data that show a 60 km thick anorthositic crust and the need for a density reversal below the mantle, by the great antiquity of most pristine nonmare rocks, by the complementary Eu anomalies of mare and highland rocks, and by the noncrustal nature of the volatile elements in orange and green pyroclastic material. However, testing this hypothesis as well as concepts that call for melting of the whole moon and/or impact-induced splitting of the moon from the Earth requires field investigations designed to unravel lunar geological evolution. For example, we need studies of the stratigraphy and structure of deeply derived pyroclastic deposits, of KREEP and other materials in the most deeply derived boulders and subunits in the Imbrium ejecta blanket, and of crystalline clasts in very old breccias. The field investigations combined with data from a global geophysical net should provide conclusive tests for various early evolution hypotheses. A broader understanding of the chemical and structural homogenization of the outer lunar crust now exposed in the cratered highlands will be best served by orbital remote sensing, robotic traverses, and spot landings for ground calibration, and selected field investigations as appropriate to verify significant geological relationships.

The only clear way to fully characterize the role of large impact basin formation in planetary evolution is through systematic field studies of the youngest representative of each size category of lunar impact craters. These categories include craters that are hemispherical holes, that have central peaks, that have flat floors and no rings, and, finally, that have multiple outer rings. Developing insights into the various processes that influence the structure of each crater type and of the scaling laws that relate one type to the next is essential to understanding this fundamental environmental and structural process affecting planets.

Light-colored plains continue to be a puzzle that possibly reflects a variety of origins. Again, orbital remote sensing, robotic traverses, and spot landings, and selected field investigations will constitute the best strategy for understanding these largely pre-mare basin-filling processes. Such processes may have much to tell us about the dynamics of the ejecta blankets of large impact basins and about early partial melting in the Moon.

Possibly the most important issue related to the basaltic maria involves eruption rates and thus the thickness of cooling units. If cooling units are thick enough, then potentially large layered complexes may underlie the surfaces of mare basins and may be the source of important future resources as we have found on Earth. Field investigations of the ejecta blankets of post-mare basalt impact craters on the floors of the large basins will be the most fruitful means of addressing this issue and of determining the potential resource base within the maria.

The quiet crust period may have been quiet only in relation to earlier phases of lunar evolution. Although mare volcanism seems to have waned by 3 billion years ago, some volcanism may have continued to as recently as 1.0 billion years ago (6). Also, the 2000 km long ridge and volcanic systems in Oceanus Procellarum and the extensive surface alteration in the light colored swirls concentrated east of Maria Smithii and Crisium suggest flegling lunar processes related to terrestrial plate tectonics. Field geological traverses along and across the Procellarum ridge system and high resolution orbital and robotic sensing of regions of light-colored swirls may provide great insights into the earliest phases of the breakup and alteration of planetary surfaces through plate tectonics. These investigations also may disclose new lunar resources created through volcanic processes.

Although geological field investigations form the scientific basis for mineral exploration and resource production, the day-to-day commercial value of a field geologist is in directing programs that discover, evaluate, delineate, and mine minerals for a profit. Even if drilling, sampling, assaying, and mining operations at future lunar bases can be highly automated, as seems both likely and desirable, the general guidance of such a program as well as the evaluation of the unexpected will continue to require human intervention.

TAURUS-LITTROW REVISITED

One could not have field geology in the blood and not speculate on what would be of interest if a personal return to a field site were possible. In my case, the potential is great for the Apollo 17 landing site at Taurus-Littrow to become a site for a prototype lunar base providing resources to an earth orbital civilization (7). Oxygen is one of the principal elements contained in lunar materials and is essential to standard chemical space propulsion systems as well as to life. The probable raw ore for oxygen from the Moon is ilmenite. Ilmenite is present in significant quantities in the already pulverized deep lunar regolith that overlies some of the titanium-rich mare basalts of Taurus-Littrow. The multi-stage extraction process that may be used to ultimately produce oxygen from ilmenite also should produce iron, titanium, and a little hydrogen and helium-3 as by-products. In addition to iron and titanium, aluminum may be desired for use both in manufacturing and as a possible chemical rocket fuel. The main ore of aluminum on the moon probably will be the calcium-aluminum silicate-rich regolith of the lunar highlands. At Taurus-Littrow there is a thick layer of largely fine-grained regolith of this nature in an avalanche deposit that has spread over the valley floor. Silicon also may ultimately be derived from the same material.

From a scientific point of view, the most important follow-up field investigations (and the problems they would address) at Taurus-Littrow are as follows:

1. Determination of breccia chronologies in the boulders and ledges of the massifs and broad based sampling of crystalline clasts in the oldest breccias (study of the origin of the moon and its early evolution and of processes associated with large crater formation).
2. Systematic sampling of mare material in the ejecta blankets of craters that have penetrated to various depths beneath the valley floor (study of the nature of mare cooling units and potential resources within them).
3. Identification of deposits of orange and black pyroclastic soils and study of their variability (study of the chemical nature of the deep lunar interior and of potential volatile resources).

The initially most important follow-up field investigations for economic purposes is the determination of the distribution of ilmenite ore grades in the Taurus-Littrow regolith. This information is essential to the design of a mining plan and to the forecasting of oxygen production rates (8).

CONCLUSIONS

The nature of the moon's near surface materials and the impact processes that modify those materials permit an optimum integration of human, remote sensing, and robotic investigations. Human capabilities in the field will be most necessary where complex geological interrelations and subtle geological distinctions must be made. Remote sensing and robotic systems will be most helpful where geological parameters vary gradually over large areas or where large numbers of predictable and repetitive tasks (drilling, analyzing, grid sampling, etc.) must be performed. Even in these instances, overall human guidance and intelligent reactions to unexpected results will be essential.

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