

Lunar Field Geological Exploration¹

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Introduction

Apollo field explorations of the Moon, and subsequent analysis and interpretation of their findings and collected samples, underpin our current understanding of the origin and history of the Moon. That understanding, in turn, continues to provide new and important insights into the early histories of the Earth and other bodies in the solar system, including the period during which life and its precursors formed and began to evolve on Earth. Those early explorations also have disclosed significant and potentially commercially viable lunar resources that might help satisfy future demand for both terrestrial energy alternatives and space consumables, such as life support, power and propulsion. If future lunar exploration does not fully utilize the capabilities of the best available field geologists, and the proven techniques of field geology, planetary science will not benefit fully from a future return to the Moon.

Lunar sample analysis from which these conclusions are drawn rest to a significant degree on a foundation of geological field observations, detailed locations, and photo-documentation provided by the Apollo astronauts, as well as the context established by photo-geological mapping and active and passive geophysical data collection. Remote sensing data collection, beginning with the 1964 Ranger program, has become increasingly sophisticated and has added significantly to the global extension

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of sample context. Crewed Lunar missions as part of the Constellation Program provide an opportunity to continue and expand the human geological, geochemical and geophysical exploration of the Moon. The planning, astronaut training, and operational conduct of future lunar field exploration will draw on both the experiences of the Apollo missions and the new technologies, ideas and hypotheses developed since Apollo. Future scientific returns from lunar exploration will depend on recreation and expansion of the "Lunar Field Geology Experiment" that successfully operated within the broader scientific and operational demands of Apollo.

Lunar Science Issues for Field Exploration

The Apollo explorations of the Moon, and interpretations of additional remotely sensed data in the light of the samples and observations provided by Apollo, have provided a first order understanding, if not total agreement, about the constraints surrounding the origin and evolution of the Moon and its relationship to the origin and early evolution of the Earth. A significant consensus has developed in recent years relative to some of the major issues of lunar origin and history, based in part on the advance of computer modeling but greatly constrained the absence of new field data and samples. There remain, however, major questions about the validity of portions of this consensus. For example, computer modeling does not necessarily reflect 1) the reality of lunar geology, 2) that the Apollo sample collection and seismic data come from only a small portion of the lunar front side, and 3) that absolute ages from lunar samples and meteorites do not span the known range of relative ages of lunar basin formation and eruptive activity. As a result of these uncertainties, major challenges face the next phase of lunar site selection, planning and execution as related to long-term field exploration science.

The major lunar science issues, and lunar terrains where they probably likely can be addressed, currently are given below. These issues include many of those listed as "Concepts" in the National Research Council's 2007 Space Studies Board (SSB) report, "The Scientific Context for the Exploration of the Moon" as well as in the NASA Science Advisory Council's (NAC) Recommendations contained in the report on the "Lunar Science Workshop" held in Tempe, Arizona, February 27 through March 2, 2007.

1. Testing of the consensus "giant impact" hypothesis for the origin of the Moon by further investigation of materials that may show the volatile reservoirs and chondritic geochemistry of the lower lunar mantle, indicated in Apollo samples by the composition of the non-glass component of pyroclastic glasses (**Not discussed by SSB or the NAC**):
 - a. Task: Investigate and sample layered pyroclastic deposits near the southwestern rim of the Serenitatis Basin or other pyroclastic stratigraphic units elsewhere on the Moon.
 - b. Task: Investigate and sample deep ejecta from the transient crater rim of the South Pole-Aiken Basin.
 - c. Task: Investigate and sample materials excavated, erupted or rebounded from beneath the floor of the South Pole-Aiken Basin or other very large, deeply penetrating basins.
2. Testing of the consensus impact "cataclysm" hypothesis by obtaining absolute

- ages on large lunar basins older than 3.9 billion years, particularly those non-mascon basins that have relative ages greater than the mascon basins visited by Apollos 15 and 17. **(SSB Concepts 1 and 6)** This spectrum of absolute ages also would calibrate the Hadean impact history of the Earth and inner solar system and would potentially define the history of giant planet migration in the outer solar system.):
- a. Task: Investigate and sample materials consisting of impact melt breccias from non-mascon large basins and those exposed in the inner rim wall of the ~2500 km diameter South Pole-Aitken basin and the inner rim walls of a global sample of old, large non-mascon basins.
 - b. Task: Investigate and sample materials from the apparent, western inner rim wall of the ~3200 km diameter Procellarum Basin.
3. Calibration of the timing of the end of the formation of large impacts in the inner solar system **(SSB Concepts 1 and 6)** and the relationship, if any, between lithostatic pressure release by large impacts and the generation of mare basalt magmas:
- a. Task: Investigate and sample materials made up of impact melt breccias exposed in the inner rim and melt breccia floor units of the Orientale Basin, the youngest of the large basins on the Moon.
 - b. Task: Systematic investigation of boulders with traceable boulder tracks at the base of large basin radial grabens to define the local stratigraphy of the lunar crust.
 - c. Task: Investigate and sample mare basalt units that constitute some of the floor units of the Orientale Basin.
4. Global delineation of the internal structure of the Moon, including **(SSB Concepts 2, 3 and 5)**:
- a. Global depth of the lunar magma ocean
 - i. Task: Deployment of a global, long-lived seismometer network.
 - ii. Task: Global investigation and sampling of materials, such as pyroclastic glasses and their non-glass volatile components as well as lavas, derived from deep magma sources.
 - b. Lateral and vertical structure of the upper mantle:
 - i. Task: Global investigation and sampling of mare basalts, cryptomare and pyroclastic glasses to determine composition and depth of magma sources.
 - c. Original distribution of the magma ocean's residual liquid (urKREEP) (testing of the hypothesis that original urKREEP had a non-uniform global distribution):
 - i. Task: Global investigation and sampling of KREEP-bearing igneous rock types.
 - ii. Task: Mapping and sampling of key locations in the Procellarum-Imbrium region to determine the three-dimensional, distribution of KREEP materials prior to the superposition of these two very large basins.
 - iii. Task: Mapping and sampling of key locations in the South Pole-Aitken basin to correlate the post impact, three-dimensional

- distribution of KREEP material with the pre-Imbrium distribution in the Procellarum basin.
- d. Distribution and characterization of Mg-suite parent igneous bodies and other apparently igneous rock types that exist in the lower crust but so far are known only as clasts in large basin impact breccias:
 - i. Task: Mapping and sampling of the central peaks of a selected group of Copernicus-age impact craters.
 - ii. Task: Continued collection of samples of Mg-suite and other rock types forming clasts in large basin ejecta material.
 - e. Structure and compositional details of the lower mantle and the transition zone above it (probable source region for the diverse non-glass volatile components in the pyroclastic glasses):
 - i. Task: Deployment of a global, long-lived seismometer network (4.a.i, above).
 - ii. Task: Global investigation and sampling of materials, such as pyroclastic glasses and their non-glass volatile components, derived from deep magma sources (4.a.ii, above).
 - f. Three-dimensional nature of the lunar core, the core-lower mantle boundary, the transition zone above the core, and the timing of lunar core formation and dynamo circulation.
 - i. Task: Deployment of a global, long-lived seismometer (4.a.i, above) and other potentially useful geophysical networks.
 - ii. Task: Deployment of a modern network of active laser retro-reflectors on the lunar near side.
 - iii. Task: Investigate the global distribution and ages of remnant magnetism in mare basalts and impact-generated materials.
 - iv. Task: *In situ* measurement of the intensity, age and structures of remnant magnetic fields and collection of oriented bedrock and in situ impact glass samples.
 - g. Determine the origin of the Procellarum North-South line of volcanic centers and the potential role of magma plumes in a small, non-convecting planet:
 - i. Task: Investigate and sample two or more such volcanic centers.
5. Global Sampling and field investigations that provide the data necessary to correlate major lunar geological and geochemical units (**SSB Concept 3**):
 - a. Task: Obtain globally as well as locally representative suites of documented samples, particularly from the lunar far side, far Southern Highlands, and polar regions.
 6. Define the depositional history of polar volatiles, cometary or otherwise (**SSB Concept 4**):
 - a. Task: Investigate, image and sample the stratigraphy of permanently shadowed polar regolith to its maximum depth using seismic and radar imaging, drill sampling techniques, detailed investigation of fresh impact crater walls and ejecta.
 - b. Task: Investigate and sample the stratigraphy of any frozen volatile deposits in deep, permanently shadowed craters.

7. Determine the recoverable concentrations and distribution of potential volatile resources (helium-3, hydrogen, carbon, nitrogen, methane, etc.), particularly in polar regions and titanium-rich (oxide-rich) regolith, and define other geotechnical parameters relevant to the economic geology of lunar volatile resources (**SSB Concept 7**):
 - a. Task: Map and perform *in situ* analysis of the concentrations of volatiles in the regolith of potentially resources-rich areas to a depth of at least 3m.
 - b. Task: Determine the *in situ* geotechnical parameters of the regolith in potential lunar mining areas, particularly in titanium-rich and polar regions as well as over pyroclastic deposits, that are relevant to the design and operation of lunar mining and processing equipment and the economics of such operations.
8. Gather information and samples related to relatively less site specific aspects of lunar geology:
 - a. Task: Investigate and sample the structural, petrologic and dynamic aspects of large impact basins that will provide insight into the process of their formation as a function of size (This information is particularly relevant to understanding the role of large impacts, particularly very large impacts, on Earth and in the lead-up to the evolution of replicating life forms during the Hadean.).
 - b. Task: Broaden understanding of the geology, radiation history, and geotechnical properties of the lunar regolith (**SSB Concept 8**).
 - c. Task: Broaden understanding of the structure and geophysical properties of the crustal mega-regolith.
9. Gather data on lunar specific geological phenomena:
 - a. Task: Investigate and sample structures and materials related to global stress-strain history.
 - b. Task: Investigate and sample structures and materials related to sinuous rilles and determine if any remain covered, if they represent collapse of lava tubes.
 - c. Task: Investigate and sample structures and materials related to large-scale mass wasting in the lunar gravitational, impact and tectonic environment.
10. Testing of Mars sampling systems and field investigation strategies:
 - a. Task: Undertake Mars field exploration simulations in new lunar geological situations without real-time MCC support. Utility of support from an orbiting team of astronauts would be an additional simulation case to be tested. (These realistic mission simulations would be comparable to those simulation-based training activities pioneered by Apollo, particularly Apollos 15-17.)
 - b. Task: Test methods of integrating robotic and tele-operated rovers and other mobility systems into Mars exploration activities.
 - c. Task: Test the capabilities of Mars sample gathering and containment systems to prevent introduction of lunar dust as well as life forms and atmospheric gases upon return to Earth. (Mars, because of the low pressure atmosphere bracketing triple point of water and because of presence of water, clay minerals and salts (e.g. perchlorate), is very

different than the Moon and in turn sampling approaches and exploration strategies will need to take these differences into account.)

- d. Task: Test stability and survivability of organic and hydrous compounds and representative life forms in extreme space environments.

Conclusion

Astronauts have not explored the lunar surface since December 1972. NASA's new plans for the human and robotic return to the Moon revolve notionally around the construction and establishment of a lunar polar outpost starting around the year 2020. Inherent in the outpost concept will be the capability to conduct sortie missions to locations anywhere on the Moon. In order to achieve NASA's new exploration objectives, it seems prudent to dust off certain aspects of the Apollo playbook as it developed over the course of the 1960s and early 1970s. The six Apollo lunar landing expeditions provide us with the only experience for lunar and planetary surface exploration by humans. Many of the guiding principles and lessons learned from Apollo should be useful in the preparation of future exploration of planetary surfaces and the scientific training of the crews for these new expeditions.

In 1964, as NASA and the National Academy of Sciences were considering the attributes necessary for individuals to be selected as the scientists for the astronaut corps, the late Eugene M. Shoemaker suggested that "perspicacity" was the key trait that should be sought. Shoemaker, as Chairman of the initial selection committee, insisted that the "perspicacity" criterion be included in the announcement of opportunity for the first scientist-astronaut selection. If defined as it is in Webster's Third International Dictionary, namely, "*...the quality or state of being...of acute mental vision or discernment*," "perspicacity" is the essential ingredient for a successful field geologist. Demonstration of "perspicacity" in space exploration should show not only a person's ability to make an observation but also the observer's immediate awareness that it was an important observation.

The authors would concur in Shoemaker's assessment, but also would add that "perspicacity" is the trait that should be developed in all exploration astronauts through a well-conceived and well-conducted field geology training program for future lunar and planetary exploration. A good exploration astronaut needs to be a keen, smart observer, one who increasingly knows to ask the right questions or, better yet, knows what questions to ask. What really separates the "good" from the "excellent" field geologist is the ability, born of education, intellect and experience to interpret the "unexpected," or at least collect the data that can eventually be used to interpret the "unexpected."
