FIELD EXPLORATION ANALYSIS TEAM[1]
(FEAT)

PLANETARY FIELD EXPLORATION PROJECT
WHITE PAPER

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Abstract

Apollo field exploration science, and subsequent analysis, and interpretation of its 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, particularly during the period that life formed and began to evolve on Earth and possibly on Mars. 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.

A lunar outpost as part of the Vision for Space Exploration, and sortie missions leading to its establishment or enabled by it, provide an opportunity to continue and expand the human geological, geochemical and geophysical exploration of the Moon. Specific objectives of future field exploration science include: (1) Testing of the consensus "giant impact" hypothesis for the origin of the Moon and near final accretion of the Earth by further investigation of materials that may augment understanding of the chondritic geochemistry of the lower lunar mantle; (2) Testing of the consensus impact "cataclysm" hypothesis by obtaining absolute ages on large lunar basins of relative ages older than the 3.8-3.9 Ga mascon basins dated by Apollo 15 and 17; (3) Calibration of the end of large impacts in the inner solar system; (4) Global delineation of the internal structure of the Moon; (5) Global sampling and field investigations that extend the data necessary to remotely correlate major lunar geological and geochemical units; (6) Definition of the depositional history of polar volatiles - cometary, solar wind, internal or otherwise; (7) Determine the recoverable *in situ* concentrations and distribution of potential volatile resources; and (8) Acquisition of information and samples related to relatively less site-specific aspects of lunar geological processes.

Planning for renewed field exploration of the Moon depends largely on the selection, training and use of the sortie crews; the selection of landing sites; and the adopted operational approach to extravehicular activity (EVA). The equipment necessary for successful exploration consists of that required for sampling, sample documentation, communications, mobility, and position knowledge. Other types of active geophysical, geochemical and petrographic equipment, if available, could clearly enhance the scientific and operational return of extended exploration over that possible during Apollo missions. Equipment to increase the efficiency of exploration should include the following, pressure suit-integrated systems: (1) voice activated or automatic, electronic, stereo photo-documentation camera that is photometrically and geometrically calibrated; (2) automatic position and elevation determination system; and (3) laser-ranging and target elevation device, aligned with the stereo camera axis. Heads-up displays and controls on the helmet, activated and selected by voice, should be available for control and use of this equipment.

1.0 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 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.

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. Lunar missions as part of the Vision for Space Exploration provide an opportunity to continue and expand the human geological, geochemical and geophysical exploration of the Moon. The planning, training and conduct of future lunar field exploration will draw on both the experiences of the Apollo missions and the new technologies and ideas developed since Apollo. Acceptance and implementation of this proposal for a Planetary Field Exploration Project (PFEP) would provide for the recreation and expansion of the "Lunar Field Geology Experiment" that successfully operated within the broader scientific and operational demands of Apollo.

1.1 NASA's Return to the Moon

NASA's implementation of President George W. Bush's Vision for Space Exploration has the following general objectives:

1. Redevelop a deep space operational infrastructure and discipline.
2. Define the distribution of potential lunar resources.
3. Answer major questions related to lunar exploration science, lunar science, and lunar-based science.
4. Establish an infrastructure for technical and operational testing of architectural and operational options for Mars exploration.
5. Define and answer new science questions.

More recently, NASA has selected a lunar outpost site on the rim of the South Polar crater Shackleton as the notional planning focus for a lunar architecture. The primary reasons stated for this selection are as follows:

1. Learn to use the moon's natural resources to live off the land,
2. Make preparations for a journey to Mars,
3. Conduct a wide range of scientific investigations, and
4. Encourage international and commercial participation.

In addition to preparing for field exploration around a lunar outpost, FEAT must also be prepared for exploration related to lunar sortie missions that likely will precede the first mission to a South Pole outpost or sortie missions to other sites on the Moon that will be justified largely for reasons of scientific interest or economic development.

1.2 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 and in part on 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 terranes where they probably can be addressed, currently are given below. These issues include many of those listed as “Findings” in the September 19, 2006, interim report on the “Scientific Context for the Exploration of the Moon” by the Space Studies Board of the National Research Council; however, the listed findings do not yet fully include relevant components of the SSB’s earlier Decadal Survey. Those “Findings” in the interim report that correspond with the issues given below are indicated as “**(SSB Interim Finding #).”** The SSB's work in this regard is clearly not complete and future drafts of this White Paper will correlate the following issues and tasks with the final report.

1. Testing of the consensus "giant impact" hypothesis for the origin of the Moon by further investigation of materials that may show the chondritic geochemistry of the lower lunar mantle, indicated in Apollo samples by the composition of the non-glass component of pyroclastic glasses:
    a. Task: investigate and sample layered pyroclastic deposits near the southwestern rim of the Serenitatis Basin or other pyroclastic statigraphic 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 Interim Finding 2)** (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 made up of impact melt breccias exposed in the inner rim wall of the ~2500 km diameter South Pole-Aitken 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 end of the formation of large impacts in the inner solar system **(SSB Interim Finding 2)** 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: 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 Interim Finding 3)**:
    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, crypto-mare 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. 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-class 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 orientations of remnant magnetic fields.
    g. Determine the origin of the Procellarum N-S 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 Finding Interim 4)**:
    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 Finding Interim 6)**:
    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:
    a. Task: Map and determine the *in situ* 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 titanium-rich and polar regions, 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 and geotechnical properties of the lunar regolith **(SSB Interim Finding 8)**.
    c. Task: Broaden understanding of the structure and geophysical properties of the crustal mega-regolith.
9. Testing of alternative methods to use the lunar regolith to provide protection from solar particle events:
    a. Task: Test explosive and other methods of excavation of trenches in the regolith over which an LRV can be driven to provide nearly full if not full protection.
10. 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.
11. 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 discussed in Section 3.0, below.)
    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.
    d. Task: Test stability and survivability of organic and hydrous compounds and representative life forms in extreme space environments.

2.0 Planning

Planning for the initial lunar portion of the Planetary Field Exploration Project depends largely on the selection and utilization of the sortie crews, the selection of landing sites, and the adopted operational approach to sortie extravehicular activity (EVA). The Apollo astronauts received extensive geologic field training to insure maximum scientific gain and minimum operational risk. These field exercises proved to be invaluable to crew, flight controllers, and scientists alike and contributed greatly to the achievement of all lunar surface science objectives, particularly with respect to the crew being able to react perspicaciously to new situations and to provide intelligent sample acquisition and documentation. Moreover, these field-based exercises also sharpened the skills and interaction of astronauts and the ground-based controller and science teams. A new astronaut geology training program should begin sooner rather than later because the art and skill of field geology can only be learned by work and time in the field. Field exploration geology is a cumulative science, meaning the more experience one gets the better one gets. Also the links should be forged between the science, operations, and astronaut communities now because it will take time to achieve the collective experience level necessary for efficient and productive interaction between these communities.

2.1 Crew selection and utilization

Considering the proposed Lunar Architecture and its potential derivatives, crew training and operational experience from Apollo, and lunar and terrestrial field exploration history, the success of the Planetary Field Exploration Project will be optimized if each four-person lunar crew consists of two experienced field geologists per four-person crew. The two non-geologists, one of whom would be in command of the mission, should be fully committed to active participation and training relative to the mission's exploration component. The field geologists on the crew should be equally committed to active participation and training relative to the missions additional objectives. Ideally, these geologists also would be active jet and helicopter pilots in order to be fully integrated into the realities of space operations and the necessary direct and indirect interactions within the flight crew as a whole.

Human spaceflight experience shows it is best to select a crew that includes members with the primary scientific skills for the extensive surface mission, and cross-train them to accomplish the spacecraft systems, operations, and maintenance functions. Apollo, Skylab and Space Shuttle experience indicates that scientists can successfully acquire the essential mission operations skills within about five years through intensive aircraft and spaceflight training, while the reverse process of training pilots, engineers and non-field experienced scientists for a primary field exploration role will not work on a similar time scale. Geologist and Apollo 17 astronaut Harrison H. Schmitt’s estimate is that during Apollo, the scientists had acquired about 75% of the operations skills of the pilots in the program, while the latter, after a 15-20 month training cycle, had attained about 25% of the field geology skills typical of active field geologists. Adequate cross-training for pilots was accomplished during Apollo over a period of about three years (backup and prime crew mission training), building on limited, pre-mission assignment, and class room and field trip exposure. Pre-mission assignment, a systematic field geology training program of about three additional years, integrated with other training requirements, would significantly increase the pilots' exploration skills, although it would not substitute for the concentrated experience of a professional field geologist.

A mission prime crew and its back-up crew should be selected no less than one and one-half years before the planned launch date to allow sufficient time for crew integration and mission specific training. The mission specific science training should be scheduled throughout the training cycle so that lessons learned in the field continue to be reinforced and are fresh in the crew’s mind when they launch. It is expected that each member of the prime crew would have received at least the equivalent of a full training cycle on a back-up crew and would have successfully completed the introductory field exploration curriculum outlined in Section 3.1, below.

Maximum returns from lunar field exploration will come from very physically fit, extremely well conditioned teams. The Apollo lunar explorers had convinced themselves that they were in top condition through the voluntary conditioning programs each had devised plus long, frequent training sessions in pressurized suits-. As forearm fatigue was a recurring problem during the long duration Apollo excursions, however, such conditioning appears to have been less that it could have been. The current Space Shuttle EVA astronauts appear to be in much better condition relative to long duration use of the EVA gloves, possibly due to many more training exercises prior to a given mission but also possibly due to a better general conditioning program and the use of personal trainers. Although the current EVA gloves are somewhat improved over the A7L-B suit gloves, there has not been a step function reduction in the work needed to use the fingers and grip. It is to be hoped that this will be a major area of emphasis in the development of the next generation lunar surface EVA pressure suit (see Section 2.4.1, below). A comprehensive and focused physical training protocol will need to be developed to fully realize the potential of human lunar exploration.

2.2 Site selection and mission planning (SSB Interim Finding 5)

Optimum planning for specific missions requires that the selection of a specific landing site and exploration area be finalized about one and a half years before launch; that is, at the time a prime and back-up crew are assigned. Site selection for each mission should include consideration of the number of potential EVAs, the available mobility and numbers of mobility units, the anticipated walk-back constraints, returned sample mass constraint, available active geochemical and geophysical sensors, as well as the potential of the site to address significant issues in lunar science, potential lunar outpost locations, and future Mars exploration.

The Planetary Field Exploration Project proposes to actively participate in the site selection processes that are related to lunar missions. If it appears desirable for the Project to organize the site selection process for specific sortie missions, all other interested scientific disciplines as well as all mission operational interests would be integrated into such activity.

2.3 Operational Approach

The Planetary Field Exploration Project anticipates than the four astronauts of a specific lunar crew will generally work in teams of two except when particular operations would be more efficient if worked by all four crew members. Each team normally would have at least one geologist. A normal sortie mission and early outpost build-up missions would have a planned five days of activity on the Moon after a pinpoint landing in a pre-selected location, although with experience, technical upgrades, and improved margins, longer sortie missions are probable. Within that context, general mission plans can be formulated. The details of such plans, however, remain subject to many future considerations related to final operational constraints such as available consumables, pressure suit reliability and performance, number of rovers or other mobility units, availability of external consumables for recharge or emergencies, outpost build-up requirements, and other, yet to be defined factors.

First Excursion - Each team will collect and document samples representative of various geological targets and sectors near the landing site followed by deployment of operational and scientific equipment assigned to the mission.

Second-Third Excursions - Each team will execute pre-planned, but flexible "Apollo 17-type" traverses independent of the other team, staying in periodic and emergency contact with each other and in continuous contact with its dedicated support team at the Mission Control Center (MCC). If only one mobility unit, such as a rover, is available, then the teams will use it on alternate excursions. If two rovers are available, then one team can use one rover to reach a special area of foot investigation. That rover can then be in position to support any walk-back requirement imposed on the second team, deployed to a greater distance from the landing point. Post-excursion debriefing and field data synthesis sessions, including map displays relayed from MCC (or created on site), will inform each team on the other's activity and findings.

Fourth and subsequent Excursions - Each team will undertake explorations based on the findings of their earlier activities, planned with the assistance of the other team and MCC. One or both teams may have additional duties related to other mission plans that would substitute for one or more of these exploration traverses. Once longer stays at an outpost are possible, a new routine will be required to avoid crew fatigue. After about six straight days of two team excursions, the teams will begin alternating EVA days, with one team resting and supporting the activities of the other. For those missions testing Mars exploration strategies, excursions will be planned using only the information available to the surface crew with MCC in a monitoring and data analysis role only.

With the establishment of an outpost as the primary initial operational objective of the initial lunar architecture, the operational approach probably will be altered over that of a pure sortie mission to a scientific or resource exploration site. On the early missions to the outpost site, EVAs would be largely concerned with deployment of facilities and site preparation for subsequent landings. Teams probably will begin alternating EVAs after one or two days to conserve physical capabilities, depending on stay-time possible for each crew. Until the outpost is functional and requires only sustaining attention, actual field exploration activities will probably be limited.

2.4 Basic Exploration Equipment (SSB Finding Interim 2R)

The equipment necessary for successful exploration consists of that required for mobility, sampling, sample documentation, communications, and position knowledge. Other types of surveying equipment, if available, could clearly enhance the scientific and operational return of extended exploration over that possible during Apollo (Section 2.4.5).

2.4.1 Pressure suit and backpack

The lunar surface pressure suit and backpack combination enables the crews to function during excursions and should be significantly improved over the A7L-B Extravehiclular Mobility Unit (EMU) used by the Apollo 15, 16 and 17 crews. The design goal should be an advanced EMU that, relative to the A7L-B, has half the mass, four times the arm, hip and leg mobility, and at least ten times the glove dexterity. (At the very least, advanced pressure garments should have mobility equivalent to, or better than, the present Mark III or Rear-entry I-Suit experimental pressure garment and gloves with mobility and dexterity at least equivalent to the present Phase VI Shuttle EMU flight glove assembly.) Although some components of the pressure suit probably can be in standard but adjustable sizes, others, particularly the gloves should be fitted closely to each individual crew member. Also, because of the potential to use consumables carried on a lunar rover or prepositioned at points of extended EVA duration, vacuum connect-disconnect of oxygen, cooling water, and power lines should be routinely and repetitively possible with the advanced EMU.

Because of the increased cycles of use imposed by the longer duration lunar stays, the advanced EMU should be designed to have indefinite life through routine maintenance and planned part replacement. This will require long duration testing of components and subsystems. Consideration should be given to embedded diagnostic sensors for critical components and subsystems.

Dust control relative to the EMU, lander, habitats and work areas during long duration lunar stays will be a critical design and operational objective for successful exploration. An engineering philosophy of using a layered design defense should be adopted for any equipment exposed to dust, particularly relative to the EMU. Specifically, research and development of dust repulsion techniques for EMUs should be initiated to take advantage of the ubiquitous negative charges and magnetic nanophase iron particles characteristic of dust particles. Further, the feasibility of keeping the EMUs permanently outside landers and habitats, and the various operational trade-offs of doing so, should be fully examined.

2.4.2 Lunar Roving Vehicle

Maintaining close and continuous contact with the ground has historically been the most effective method of geological field exploration having the objective of placing samples and observations in the context of all the potentially important features of a given area. This fact has been well demonstrated by human foot, horseback, jeep and lunar roving vehicle exploration for over 190 years since William Smith made the first comprehensive geological map of a specific area of the Earth. Modern use of point-to-point transportation, such as ships, aircraft and helicopters, to conduct spot checks of small areas has been effective in reconnaissance exploration on Earth, and lunar and planetary flyers may someday be equally effective for this purpose. Operational and training constraints, as well as their impracticality during detailed exploration of contiguous regions, probably will prevent use of point-to-point flyers on lunar sortie missions, as was determined when lunar flyers were proposed for Apollo exploration. At some point in the future, however, point-to-point transportation systems may become very useful for specific lunar and planetary reconnaissance activities, particularly when radiating outward from an outpost.

The Apollo Lunar Roving Vehicles (LRVs) served the last three Apollo exploration missions exceedingly well. On the last of these missions, the LRV traveled a total of 35km during three EVAs with average point-to-point speeds of about 12km/hr. It constituted a communication node for VHF voice and telemetry while in motion and for television transmission at each major stop after hand alignment of a high gain S-band antenna. Dust presented no problems to LRV operation except when protective dust flaps were damaged. On the other hand, navigation was crude and required significant crew time and the MCC-operated, single camera TV system provided inadequate documentation of many sampling activities. The following improvements should be incorporated in advanced LRVs to significantly enhance exploration efficiency and quality:

1. Automatic navigation system using a lunar Global Positioning Satellite system or a deployed radio beacon system in each landing area.
2. Mast-mounted, stereo, high resolution, color television that automatically tracks the crew. The capability to coaxially align remote compositional sensors should be part of this system. Over-ride of automatic tracking would be subject to specific guidelines so that valuable operational and geological documentation would not be lost as was the case during Apollo.
3. Configuration of communication modes should be automatic depending on need and should provide the necessary bandwidth to support all exploration requirements. An on-board back-up recorder should be provided for momentary or extended loss of direct voice communications and telemetry.
4. On-board oxygen, cooling water, and power consumables that can be routinely accessed by the crew during driving periods so as to save portable consumables for activities away from the LRV. This may allow a reduction in the mass of the Portable Life Support System (PLSS) but that must be traded off against the requirements for emergency walk-back consumables.

5. A battery recharge system should be provided, initially using a solar array but also compatible with other power systems.
6. Enlarged area for tool mounting, including an automatic coring drill, and for stowage of active geochemical, geophysical and geotechnical exploration equipment. Mountings should be designed to reject dust.
7. Power, telemetry and space provisions for various automatic geochemical, geophysical and geotechnical sensing systems.
8. Provision for the use of the bed of the LRV as a protective roof during rapid rise-time solar particle events (SPEs) and coronal mass ejections (CMEs), either by embedded protective materials or by providing the base for a cover of regolith. An explosively excavated trench and the availability of LRV consumables would provide the remaining needs for required several hours of SPE protection if return to adequate shelters was not feasible.

2.4.3 Communication System

The communications capabilities of Apollo 15-17 will need to be enhanced for modern lunar sortie missions. Specifically, transmission of large digital data sets anticipated from high resolution video systems and a variety of active and passive geochemical, geophysical and geotechnical sensors will need to be accommodated.. High data rate uplink communications to the lander will be needed to supply planning information based on the synthesis of downlink telemetry. As discussed further below, integration of a global satellite communications system with a global satellite navigation system should be evaluated in order to meet the needs of global exploration access.

2.4.4 Exploration and Sampling Tools

The basic tools required by each team of two for exploration and sampling are as follows:

1. Trenching and sampling scoop.
2. Chipping hammer
3. Numbered, geochemically neutral or tagged sample bags
4. Large rock numbering "labels"
5. Apollo 17-type core tubes (35cm long, 5cm diameter, very thin-walled)
6. Helmet mounted, voice activated or automatic, electronic, stereo photo-documentation camera that is photometrically and geometrically fully calibrated.
7. Helmet mounted, automatic position and elevation determination system, potentially integrated with a global satellite communications and navigation system or a local site specific relay and triangulation system
8. Helmet mounted laser-ranging device, aligned with the stereo camera axis (Items 6-8 together represent the technically upgraded capabilities of the "Surveying Staff" proposed for Apollo by the USGS team but subject to a failed development by a NASA contractor and management team.).
9. Chest or helmet mounted, small digital image camera, hand and voice activated, photometrically and geometrically calibrated (With an available Apollo-type

gnomon, this camera can back up the capabilities of the stereo camera system in item 6 as well as provide for special documentation needs.).

10. Voice activated, in-helmet display or visor-projected heads-up-display (HUD) for obtaining "cuff checklists," exploration-related data, ECS and consumables status, etc.
11. Hand-positioned, self-anchoring, portable geochemical sensors, such as Raman, XRF and Mössbauer units, for measuring concentrations of major or particularly diagnostic elements.

Tools that will significantly enhance the scientific, technical and economic data return of given sortie missions are as follows:

12. Hand-positioned, self-anchoring portable rock drill (inclusion samples, oriented samples from outcrop)
13. Hand-positioned, self-anchoring, portable geochemical sensor for measuring concentrations of major or particularly diagnostic elements
14. Hand-positioned, self-anchoring, portable geochemical sensor for measuring concentrations of solar wind and cometary volatiles
15. LRV mounted, automatic deep (6m) drill for coring and emplacement of heat flow and other systems for long-term monitoring of the lunar interior and for developing depth profiles of solar wind and cometary volatiles concentrations
16. LRV mounted, seismic tomographic sensor for mapping the depth and structure of underlying regolith (would include small multi-spectral seismic thumper in small trailer or satellitic sub-rover)
17. LRV mounted sensor package for continuous recording of the geotechnical properties of the surface of the regolith

Consideration should be given for the integration of a number of the portable exploration sensors and sampling tools into a robotic sub-rover that can act as a commandable field assistant for an exploring team. This same sub-rover can also act as the source of multi-spectral seismic energy for tomographic mapping.

Ideally, each team of two explorers would have a fully equipped LRV pertinent to the exploration plan for a particular landing site and/or traverse plan. This may not be feasible for the early lunar sortie missions and exploration planning would need to take into account that, during simultaneous EVAs, one team would need to concentrate on near-Lander objectives while the other team would move to more distant features. LRV transport of the team on foot to a starting point within their non-LRV walk-back constraint with consumables recharge from exterior ports at the Lander would add planning flexibility in the one LRV scenario.

2.4.5 Surveying-Mapping-Documentation System

Portions of the sampling and exploration equipment outlined in Section 2.4.4, taken together, constitute a EMU (probably helmet) mounted system that will provide continuous determination of the explorer's position and elevation at all times as well as stereo photo-documentation of all observations and sampling activities. A ranging laser would be aligned with the stereo camera axis and provide real-time distance and elevation information to designated features. Although the system can be commanded as required by the explorer for special purpose documentation and ranging information, ordinarily it would operate automatically and relieve him or her of the extraordinarily time consuming documentation tasks that occupied the Apollo astronauts.

3.0 Field Exploration Training (SSB Finding Interim 4R)

3.1 Background

Becoming a field geologist and performing field geological studies are both iterative processes. They both require actually performing field investigations, again and again. Most geologic field studies are founded on direct observation and measurement of features such as landforms, land cover, rock and soil grain sizes and morphologies, rock textures, and geometric relations between rock bodies. These are objective data, usually incorporated in geological maps, diagrams, photographs and field notes. But another kind of information is interpretive, for example, associations of rocks and rock structures imply specific genetic conditions or environments that have been defined by other observations or deductions accumulated by many geologists over hundreds of years since the first recorded insights of Nicolas Steno. This approach to observational science has great power because genetic insight can clarify a host of interrelated data (see R. R. Compton, Geology in the Field, 1985). The quality and perception of the interpretation, however, is highly dependent on the geologist’s experience.

Fieldwork in a specific area requires extensive pre-trip assessment and traverse planning, using all available data from previous surveys, remote sensing, and mapping. Once on the ground, however, it is not uncommon to find that pre-planned traverses must be altered due to unforeseen discoveries, insights or trafficability issues. This necessitates making immediate field decisions that can impact the overall work strategy planned for the duration of the field season (mission). This requires creativity and flexibility combined with experience gained from previous work in the field. Prior to beginning a field study, and while conducting it, preliminary genetic interpretations result in multiple working hypotheses. This dynamic flow of ideas stimulates the search for observations that either counter or confirm the hypotheses. The mental process for this activity is extraordinarily complex and depends greatly on experience and training to reach its full potential.

Terrestrial field geology is usually a slow, deliberate, iterative process. Field geology in a space suit is physically an even slower process, however, the very difficulty of that process in space and the inherent constraints of time, requires that the practitioner be able to deliberate and iterate at a much more rapid rate than normally expected on Earth. The terrestrial field geologist typically will reconnoiter a site, walk around a potentially interesting location, take photographs, record his observations in a notebook, break some rocks open, inspect each with his hand lens to determine the texture, structures, and mineralogy of the sample so that he can give it the correct name, and collect those samples that seem diagnostic of the locality as well as any ‘odd’ samples that may provide critical future insights. The geologist may often return to a specific location again and again. In contrast, a lunar field geologist must always be aware that time is relentless, that consumables are limited, that fatigue can be fatal, and usually, returning to a location is unlikely. Most of the normal terrestrial tasks will take longer if they can be done at all (hand writing notes and diagrams, for example). Planning, voice communications, automated location and sample documentation, and, most importantly, field experience all take on even greater importance than normal.

In this context, it is imperative that field training of future lunar crews begins sooner rather than later. The rationale for geological field training exercises is to reduce operational risk to the crew as well as increase crew and ground team productivity. The establishment of an ongoing program of scientific field exercises geared toward lunar surface exploration will allow astronauts to gain valuable experience in managing a field research program, practice on rapid, on the spot decision making, cope with changing traverse strategies based on new information, and develop the cross training necessary for a successful expedition. Once assigned to a mission, and to the degree possible even before, astronauts participating in lunar related fieldwork should be equipped with the same tools and equipment that they will use on the Moon in order to practice techniques and to allow the crew members to become familiar with the capabilities and limits of their equipment. These lunar related field expeditions should also blend real scientific fieldwork by the astronauts with a ground support team who have no more initial knowledge of the chosen site than the crew. These activities will foster the required interaction between the field team and ground support teams. Training the current cadre of astronauts is also important because some will have senior management positions by the time this new phase of lunar exploration is fully underway.

3.2 Apollo Field Training

As discussed above, training and experience form the keys to productive, efficient and meaningful human exploration of the Moon and planets. Although an experienced field geologist who was also a pilot explored the Valley of Taurus Littrow on the Moon during the last Apollo mission, training of the professional pilots was the primary reason for the success of the Apollo explorations and sampling activities. The major breakthrough in training of the professional pilot astronauts came with the early 1969 introduction of simulation-based field training to the Apollo 13 crew, commanded by Captain James Lovell. Such training consisted of lunar exploration-like traverses, over unfamiliar but mission-relevant geological terrain, employing and improving the techniques of observation, sampling and documentation that would be used on the Moon. Previously, geology training for astronauts had been more of the "Ge-101 style" of show-and-tell, although the Apollo 12 crew, commanded by Captain Pete Conrad, did benefit from simulation-based training late in their training cycle as the word fed back to them and the USGS trainers that this was now the way to proceed. The success of the Apollo 13 training approach impressed the Apollo 15 crew, led by Colonel David Scott, who incorporated it in their training scenario. Because Captain John Young was back-up Commander for Apollo 13 and Captain Richard Gordon was back-up Commander for Apollo 15, Apollo's 16 and 18 commanders began to plan on simulation-based training as well. Only Captain Eugene Cernan, back-up Commander for Apollo 14 and who eventually commanded Apollo 17 had not been exposed to this approach due to circumstances related specifically to Apollo 14. Apollo 17 training in this regard, however, was influenced by the precedents set by earlier missions and by the presence of geologist Harrison Schmitt as Lunar Module Pilot. Schmitt had introduced the simulation-based training approach to the Apollo 13 crew and also had served as back-up Lunar Module Pilot on Apollo 15.

One should not understate the importance of the training and logistical activities of the USGS personnel led largely by Dr. Gordon Swann and his team, supporting the Lunar Field Geology Experiment Principle Investigators (Eugene Shoemaker, Swann and William Muelhberger). In addition to providing administrative support to the Principal Investigators, these men and women organized the simulation traverses, provided a working mockup of the LRV, and set up necessary field communication links. This kind of institutional support is essential to the success of a major mission-oriented training program and it is the purpose of the FEAT to recreate and expand such support for the lunar sortie missions and those that follow. Also important to the success of this training approach was the adoption of each crew by a geological mentor of exceptional experience in teaching field geology. These individuals, principally Leon T. Silver of Caltech, Richard H. Jahns of Stanford, William Muehlberger of Texas, and Dale Jackson of the Geological Survey gave each team of four astronauts someone whom they could respect and with whom they could work on a very personal level. After each training traverse, the mentor would lead the walking debriefing over the same ground for a long discussion of what was seen, photographed and sampled and what else might have been of interest. The crews were always encouraged, for example, to keep and continually revise in their minds a sequence of relative ages of the geologic units and features they encountered.

The Flight Crew Support Division of the Manned Spacecraft Center (now the Johnson Space Center) worked closely with the USGS to coordinate crew schedules and the availability of training equipments such as tools and cameras. Geologists from the Center's Science Directorate also worked with those from the USGS in spite of the many early professional conflicts between these two groups. The Flight Directors for each mission were often observers of the various field exercises, and one exercise for each mission was integrated into a full-up Mission Simulation in which the MCC and its Science Support Room (SSR) in Houston participated by voice hookup. This has evolved into a dedicated “Exploration” console in Mission Operations Control Room, supported by the SSR.

The Planetary Field Exploration Project should plan to set up a FEAT- Oversight Group (FEAT-OG) consisting of persons who had been involved in the planning, training and operations related to Apollo exploration or had studied that experience extensively. Periodically, the FEAT-OG would be fully briefed the on the status of the Project. Its members also would participate in seminar discussions with crews so that their experiences and suggestions could be shared directly.

3.1 Lunar science background training (SSB Finding Interim 4R)

At least one of the astronauts making up each two-person exploration team on lunar sortie missions will be a professional pilot and not have experience in field geology. Most professional pilots, fortunately, begin with basic skills in engineering, observation, three-dimensional visualization, and efficient communication that also characterize the best professional field geologists. They primarily need experience in observation of geological features and as much background as possible on what may be important to observe and sample. Pilot astronauts, therefore, will need background training in 1) the basics of field geological observation and sampling, 2) the general concepts of geology relevant to lunar and planetary exploration, and 3) what is known and not known about the Moon. The Apollo experience makes it clear that the best approach to this background training includes the following elements:

1. Principles of field observation, sampling and mapping
2. Lunar analog igneous geology
3. Impact crater geology
4. Regolith geology
5. Element and isotope geochemistry
6. Exploration and planetary geophysics
7. Geology of the Moon

At the point in time when an outpost has been established, and petrological and geochemical examination of lunar materials and preliminary data processing tasks can be carried out at such an outpost, training in such activities should be added to the background training of at least two of the assigned crew and back-up crew. Such analyses will provide for refinement of returned sample payloads as well as a better understanding of how such analyses can be accomplished during Mars exploration.

3.1.1 Principles of field observation, sampling and mapping

No substitute exists for working in the field to learn the principles of field observation and sampling. Beginning with the Apollo 13 crew, the lunar mission astronauts were immersed for a week in a remote, highly diverse, geological area with their mentor and no other possible distractions, including no phones, internet, wireless remote communications, public relations, etc. This immersion resulted in a bonding with the mentor (or a clear indication that a different mentor would be required) and the development of a spirit of competition between prime and back-up crews that pushed each to do better and better. A specific area in the Orocopia Mountains of Southern California worked well for Apollo crews; however, the selection of an appropriate area for this initial immersion in field geology should be left to the crew mentor. The mentor, of course, should be and remain an active member of the field exploration advisory team for specific crew’s mission.

Of course, to communicate what one observes, it is necessary to have a consistent vocabulary that others will recognize and that will help organize the observer's thinking and recall. Field and classroom training in mineralogical, structural and geomorphic terms should be kept to a few basic terms with variations within those terms described by modifiers with which an engineer would be familiar. For example, a basic term can be "feldspar" with variations described by color, luster, or element modifiers such as "milky pink potassium feldspar." Another basic term could be "fault" with variations described by directional references such as "north side up." Some Apollo astronauts found if helpful to remember the basic silicates and their physical properties and appearances as variations in the geometric combinations of silica tetrahedra. The key was to keep the vocabulary as simple and as familiar as possible, remembering that the pilots did not intend to be professional geologists, and they do not need to be professional geologists to do the part of the job of exploration they will be asked to do.

Selection of instructors for various specialized training activities should be based on persuading the best teachers to provide this instruction, but always ask the best teachers who also are at the top of their fields of specialization. The best mix of NASA and outside instructors should be sought, as it is often difficult for NASA to employ the quality of experienced instructor desired. Although there have been and are clear exceptions, most are not interested in the bureaucratic challenges that come with being a government employee. For such classroom instruction during Apollo, teachers like the following participated: James B. Thompson (mineralogy), James Hays (petrology), Gene Simmons (geophysics), William Brace (structure), Eugene M. Shoemaker (cratering and regolith geology), Robert P. Sharp (land forms and "belly" geology), and Harold Masursky (lunar photo-geology). At this level of quality teaching, the interest of the astronauts was held throughout the background geological training.

3.1.2 Lunar analog igneous geology

Unlike the broad diversity of geological processes that have played major roles in the evolution of the Earth, only two major sets of related processes have dominated lunar history - 1) igneous magma generation, eruption and solidification, and 2) impact cratering, melting and breccia formation. Our current knowledge of the Moon is sufficient to outline the general areas for classroom discussion related to igneous petrology. They include magma generation, fractional crystallization, magma transport-modification-eruption, volatile component effects, and observational and sampling principles. A large number of terrestrial field sites exist that can be used to illustrate relevant aspects of igneous petrology.

3.1.3 Impact crater geology

Although major deficiencies exist in our understanding of the dynamics of formation of very large impact craters, our general knowledge of the geology of the most common, smaller impact craters on the Moon (up to about 100km in diameter) as well as on Earth is quite strong. The syllabus for impact crater geology would include the standard geological features of craters as a function of size and impact angle, the time-varying hydrodynamics of crater formation, the role of impact ejecta in covering and modifying surrounding areas, the time-varying modifications of crater morphology, the characteristics of impact melts, melt-breccias, and general breccias, the geophysical implications of large crater formation, and observational and sampling principles. As with relevant igneous geology, terrestrial field sites can provide significant hands-on experience in impact crater geology. Also, the well-photographed and studied impact features on the Moon will be significant assets to instruction.

3.1.4 Regolith geology

Almost all field observations on the Moon must contend with the overlay of impact-generated regolith, the depth of which is a statistical function of the time since the underlying bedrock was solidified. A detailed understanding of the geology of the regolith will be critical to comprehensive investigation and sampling of any particular location. Instruction should include processes of formation, internal structure, solar wind interaction, and geotechnical properties. True terrestrial field analogs do not exist; however, some of the characteristics of the lunar regolith can be illustrated by field studies of alluvial fans, glacial tills, and artificial crater fields formed by controlled explosions.

3.1.5 Element and isotope geochemistry

The various processes associated with igneous and impact geology can significantly modify the element and isotope geochemistry of pre-existing materials. It will be important for crews to understand these potential modifications and their potentially correlated visual and measurable changes in those materials. A vital part of this instruction will concern the compositional/geochemical attributes of rocks and regolith to which active field spectrometers respond.

3.1.6 Exploration and planetary geophysics

Active and passive geophysical techniques have played and will play an important part in the field exploration of the Moon. Understanding the general concepts behind both the techniques and the resulting data interpretation will be important to the proper deployment and use of active geophysical methods. Both classroom and field instruction will be important in developing such understanding as related to standard seismic, tomographic seismic, radar, magnetic and gravity sensing. It should be noted that, since 1999, the three, most recent astronaut classes have received field instruction in gravity, and now magnetic, data acquisition as part of their geological training.

3.1.7 Geology of the Moon

Well-coordinated discussions of the geology of the Moon as now known, illustrated by photographs and data compilations, should be integrated into all the areas of instruction discussed above.

4.0 Planning and Analysis

As soon as it can be supported institutionally and financially, FEAT will need to develop a long-term plan for the staffing and funding of the Planetary Field Exploration Project, particularly as it initially involves the Moon. This plan would include the following elements:

1. Definition of the institutional and governmental participants in FEAT and their general areas of responsibility.
2. Definition and evaluation of potential field training sites, considering logistics and budget as well as basic field training suitability.
3. A man-year schedule for staffing the planning, pre-mission, mission, and post-mission planning and analysis requirements.
4. Reporting plan to include final mission plan, end-of-day mission reports, 7-day end-of-mission quick-look reports, 30-day preliminary reports, 60-day next mission recommendations, 1-year full mission report, and 2-year full mission report.
5. Planning for public information/education and follow-through, particularly related to providing continuity of personnel through recruitment of young faculty and graduate students as participants in FEAT.

5.0 Concluding Remarks

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, Gene 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.

FEAT 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".

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