MEETING REPORT

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REPORT OF THE LUNAR RECONNAISSANCE ORBITER SCIENCE TARGETING MEETING

June 9-11, 2009
Old Main, Arizona State University, Tempe, AZ

Sponsor:
Lunar Reconnaissance Orbiter Project Science Working Group
Lunar and Planetary Institute
Arizona State University

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The Atlas V carrying the LRO and LCROSS spacecraft launches from SLC-41 at the Cape Canaveral Air Force Station on June 18th, beginning a new era in human lunar exploration and utilization (Photo credit: Pat Corkery, United Launch Alliance).

Lunar Reconnaissance Orbiter Science Targeting Meeting

Introduction

The Lunar Reconnaissance Orbiter (LRO) mission will provide unprecedented information about the lunar surface to address fundamental questions in lunar science and to prepare for future exploration and utilization of the Moon. The principal objective of the LRO Science Targeting Meeting, hosted by Arizona State University's School of Earth and Space Exploration at Old Main in Tempe, AZ, from June 9-11, was to solicit ideas and priorities from the lunar science community for LRO targeting both in terms of focused science themes and specific features on the Moon. This objective was accomplished by fostering an understanding of LRO capabilities and the mission planning processes necessary for high-resolution targeting of lunar features by the LRO Narrow Angle Cameras (NAC), Mini-RF synthetic aperture radar, and Diviner Lunar Radiometer Experiment (DLRE). The meeting included overview presentations and focused discussions concerning six major areas of active lunar research that have specific application to the capabilities and targeting of LRO instruments.

The level of interest from the science community was reflected in the size (90) and makeup of the participants. Participants included many of the most respected members of the lunar science community comprising well known senior scientists, but also particularly, many of the productive young scientists that will be contributing to their fields and reaping the benefits from LRO measurements in the upcoming decades as NASA continues its return to the Moon.

The meeting agenda reflected topical research areas with significant scientific interest. The organizers posed questions that directly tie to those articulated at the NASA Advisory Council's 2007 Workshop on Science Associated with the Exploration Architecture and the recommendations of the National Research Council's report on the Scientific Context for Exploration of the Moon. As a result of the meeting, the proposed list of high priority science targets is being assessed by the LRO instrument teams for subsequent incorporation into targeting plans.

Meeting Overview

The goals of the meeting are summarized as follows:

1) Maximize science return from the LRO mission. Provide the LRO mission stakeholders (ESMD, SMD, LRO project, and the lunar science community) with an understanding of LRO instrument capabilities, measurements to be made during the exploration and science mission phases, and planned products.
2) Engage the lunar science community. Present LRO instrument targeting plans and planning process to foster a better understanding of LRO capabilities that will enable the broader science community to contribute effectively to targeting lunar features by the LRO Narrow Angle Camera, Mini-RF synthetic aperture radar, and the Diviner Lunar Radiometer Experiment.
3) Prepare for the future of lunar exploration. Ensure that LRO results feed forward to planning for future robotic and human exploration and utilization of the Moon.

Meeting Format

Plenary presentations summarized the LRO mission and instruments, and presented measurement objectives for exploration and science. Participants discussed plans for science during the Science Mission Directorate (SMD) phase of the mission with input from both the LRO project and instrument team members. The agenda of the meeting is provided as Appendix I. Presentations emphasized LRO instrument capabilities, specifically LROC and Mini-RF, but also including Diviner and LOLA (Lunar Orbiter Laser Altimeter) that will be used to acquire synergistic targeted data for science applications. LRO science measurement goals were presented along with instrument targeting plans and current targeting database(s), and operational constraints on targeting. The online public targeting tool for the LRO Camera system (NAC) was activated and demonstrated during the meeting.

Lunar science goals in six major themes were addressed in breakout sessions, with moderator-led topical science (panel) presentations and contributed talks. Talks focused on aspects of lunar science that can be addressed by LRO measurements, with emphasis on specific targets. *Lunar Missions and Measurements for Science* was included as part of the opening plenary session that set the stage by presenting expected results from other ongoing lunar missions. Carle Pieters (Brown University) presented materials provided by the Kaguya and Chandrayaan mission science teams. Emphasis was placed on making synergistic observations with LRO of targets associated with existing and newly discovered science priorities. An example is the discovery with positive spectral identification of numerous large exposures of nearly pure anorthosite. Two presentations were made in the opening plenary detailing the 50 Constellation high-priority targets (provided herein as Appendix II) and the process by which these were selected (John Gruener, NASA Lyndon B. Johnson Space Center) and reviewed (Paul Lucey, University of Hawaii at Manoa).

Breakout session (panels) ran two-at-a-time for 4 hours duration to maximize time for input and discussion of prioritized targets. All breakout session presentations were accompanied by abstracts (available at the Lunar and Planetary Institute meetings webpage). Invited presentations covered the state of knowledge of major lunar science questions with emphasis on targets that will be characterized by LRO. Contributed presentations (talks and posters with accompanying 2-page abstracts) addressed possible LRO targets.

The LROC Science Operations Center was opened for tours and demonstrations to help participants of the meeting better understand the targeting process and targeting tools.

This meeting summary was prepared with inputs from the moderators of each topical session. Summaries are presented in the following sequence:
Panel 1. Volcanism (Moderator: Ron Greeley, Arizona State University)
Panel 2. Regolith Processes (Moderator: Michael Duke, Colorado School of Mines, Emeritus)
Panel 3. Crust and Interior (Moderator: Paul Lucey, University of Hawaii at Manoa)
Panel 4. ISRU and Habitability (Moderator: Jeffrey Plescia, The Johns Hopkins University, Applied Physics Laboratory)
Panel 5. Impact Cratering (Moderator: Barbara Cohen, NASA George C. Marshall Space Flight Center)
Panel 6. Polar Volatiles (David Lawrence, The Johns Hopkins University Applied Physics Laboratory)

Panel Reports

Lunar Volcanism: Timing Form, and Composition Panel Summary

Moderator: Ron Greeley, Arizona State University

Speakers: James Head (Brown University)
Lisa Gaddis (United States Geological Survey)
Charles Shearer (University of New Mexico)
Laszlo Keszthelyi (United States Geological Survey)
David Williams (Arizona State University)

Key Questions

Based on the goals and objectives from National Research Council and NASA studies, the following key questions relating to LRO and studies of lunar volcanism were discussed at the meeting:

- What are the morphologic / morphometric characteristics of volcanic vents and effusive lavas, and what do these tell us about origin and emplacement of magmas within the crust and at the surface?
- What is the variety of volcanic structures, styles, and associations and what do they mean for mantle and crustal petrogenesis?
- What is the range of ages of volcanic materials and what do those ages indicate about the volcanic flux over time?
- What is the distribution and what are the characteristics of lunar pyroclastic deposits, and what do these reveal about their origin, eruption and emplacement, and the thermal and magmatic evolution of the mantle?
- What is the global distribution and range of ages of "cryptomare" (ancient, mare surfaces buried beneath more recent crater ejecta)?

Panel Overview

Introduction: Volcanism has played an important role in the formation and evolution of the lunar surface, providing insight into the history of the surface and interior. The *Lunar Reconnaissance Orbiter* affords the opportunity to advance our knowledge of lunar volcanism by identifying key targets for detailed observations consistent with the overarching scientific goals for lunar exploration. These goals were articulated by the National Research Council (NRC, 2007) and were refined and detailed by NASA at a Lunar Science Workshop (NAC 2008) from which 16 science objectives were defined, three of which are related to volcanism:

a) *Determine the composition and evolution of the lunar crust and mantle to constrain the origin and evolution of the Moon and other planetary bodies.*

b) *Determine the origin and distribution of endogenous lunar volatiles as one input to understanding the origin, composition, and structure of the Moon and other planetary bodies.*

c) *Characterize the impact flux over the Moon's geologic history to understand early solar system history.*

The "Key Questions" were addressed by panel speakers, each of whom discussed their top five prioritized LRO targets. These presentations were followed by open discussion among the speakers and panel attendees, and the results were codified by the panel moderator and the speakers.

Panel Findings

The following targets were identified and given in priority order for the "Key Questions" for lunar volcanism. For the most part, these do not include sites already identified as "Constellation" targets [Appendix I] on the assumption that those targets will be acquired.

What are the morphologic / morphometric characteristics of volcanic vents and effusive lavas, and what do these tell us about origin and emplacement of magmas within the crust and at the surface? (Jim Head, Brown University, Discussion Leader)

1. Schroeter's Valley, Cobra Head (source of major sinuous rille, location of dome and dark mantle deposits)
2. Ina (unusual caldera-like feature; recent degassing?)
3. Mendeleev crater (reflective of possible explosive eruptions?)
4. Gruithuisen Domes (viscous lava construct?)
5. Kopff crater (possible caldera?)

What is the variety of volcanic structures, styles, and associations and what do they mean for mantle and crustal petrogenesis? (Charles Shearer, University of New Mexico, Discussion Leader)

1. SPA Basin (farside ancient basalts for comparison with existing samples from nearside to assess models of lunar mantle)
2. Aristarchus Plateau (assessment of major putative pyroclastic deposits and role of volatiles in mantle evolution)
3. Tsiolkovskiy crater (assess significant farside mare lava flow)
4. Lichtenberg crater (assess magma evolution)
5. Balmer-Kapteyn Region (sample cryptomare materials to assess mantle evolution)

What is the range of ages of volcanic materials and what do those ages indicate about the volcanic flux over time? (Dave Williams, Arizona State University, Discussion Lead)

1. SPA Basin (possible oldest lavas)
2. Lichtenberg (possible youngest lavas)
3. Mare Imbrium flows and vents (well-documented lava sequence)
4. Procellarum (olivine-rich flows)
5. Mare Fecunditatis/Luna 16 (intermediate-age flows)

What is the distribution and what are the characteristics of lunar pyroclastic deposits, and what do these reveal about their origin, eruption and emplacement and the thermal and magmatic evolution of the mantle? (Lisa Gaddis, United States Geological Survey, Discussion Leader)

1. Aristarchus (massive pyroclastic materials; possibly Ti-rich)
2. J. Herschel (possibly young, olivine-rich materials)
3. Orientale (determine source(s) for the pyroclastic materials
4. Oppenheimer (assess possible multiple vents)
5. Rima Parry V (possible association with buried dikes)

What is the global distribution and range of ages of "cryptomare" (ancient, mare surfaces buried beneath more recent crater ejecta)? (Lazlo Keszthelyi, United States Geological Survey, Discussion Leader)

1. Balmer-Kapteyn (classic location for cryptomare materials)
2. SPA Basin (possibly oldest materials)
3. Mendel-Rydberg (assessment of high-latitude materials)
4. Tsiolkovsky (assessment of additional farside site)
5. TBD, to be based on early LRO data

Panel Discussion

Many of the targets identified can address two or more of the "Key Questions" and "feed-forward" aspects relevant to the science goals of future exploration, especially sample return.

It is also important to note that many of the proposed targets and target areas are in regions that are well-known through existing data. This reflects the maturity of the scientific questions that are being posed for lunar volcanism. In addition to these targets, poorly-known sites of potential relevance to lunar volcanism should also be targeted in an "exploration mode." Such areas would include higher latitudes and additional areas of the far side.

Lunar Regolith Processes Panel Summary

Moderator: Michael Duke, Colorado School of Mines (retired)

Speakers: Bonnie Cooper (Oceaneering, Inc.)
Jeffrey Plescia (The Johns Hopkins University, Applied Physics Laboratory)
Stewart Nozette (Lunar and Planetary Institute)
Ian Crawford (Birkbeck College, London)
Benjamin Greenhagen (University of California, Los Angeles)

Key Questions

Based on the goals and objectives from the National Research Council and NASA studies, the following key questions relating to LRO and studies of lunar regolith processes were discussed at the meeting:

- What are the thicknesses of regolith and how does thickness vary? How does thickness correlate with maturity, age, and composition of surface?
- Is the regolith within permanently shadowed craters different in fundamental ways from regolith outside the permanent shadow?
- Can areas be identified where fossil regoliths occur?
- How do rays from recent large impact craters modify the regolith such that they are visible and what is the mechanism for their disappearance? How well can they be used to determine the age of craters?
- Are there local variations (10s to 100s of meters) of regolith within mare or highlands units?

Panel Overview

The lunar regolith is the layer of fragmental material, created and altered by meteorite impact, that lies nearly everywhere on the lunar surface. It is generally 3-10 meters in thickness in the lunar mare, where it overlies the last mare-filling basalt flow at a given site. In pre-mare highlands areas, the regolith is thicker, up to several kilometers in some areas, created by overlapping, stirred and mixed debris blankets from ancient impact craters. Regolith deposits from depths of up to three meters were studied using surface samples and drills during the Apollo program. Particularly in the mare, it is expected that between successive basalt flows, layers of regolith formed which have been preserved from later disruption by the overlying flow (these covered layers have been termed “fossil regolith”). The regolith is important because it interacts with the external surface environment, including radiation, impact and volcanic materials and records several aspects of lunar (and potentially Earth) history. Most of the questions identified for discussion in the regolith session at the workshop are aimed at what the regolith can tell us about lunar and solar system processes, rather than the regolith formation process itself.

Panel Findings

Five questions were formulated by the Workshop program organizers. Invited and contributed talks (see abstract volume) in the workshop's regolith session addressed these and other regolith-related issues. In addition, presentations to other sessions included material relevant to the regolith issues. For each question, a brief summary of workshop considerations is provided.

What are the thicknesses of regolith and how does thickness vary? How does thickness correlate with maturity, age, and composition of surface?

Regolith thickness can be estimated at specific points by studying small crater morphology. The high spatial resolution of LRO's narrow angle camera (NAC) will allow areas of anomalously thin regolith to be identified and improve regolith thickness data previously obtained. Mini-RF and DIVINER data may be useful in addressing regolith maturity (e.g., grain size) and rock degradation, which are significant in regolith formation and growth.

Is the regolith within permanently shadowed craters different in fundamental ways from regolith outside the permanent shadow?

The regolith within permanently shadowed craters may be different from the regolith elsewhere. The lower temperatures, inducing rock brittleness, may lead to a higher abundance of finer-grained particles in the regolith, which in turn could increase the content of implanted solar wind gases, such as hydrogen. The lower temperature (possibly as low as 70K) may also change the manner in which agglutinates form, reducing the amount of melt formed. In addition, if water ice occurs in shadowed craters, hydrated weathering products may exist in and around the craters, which might be detected using visible-IR mappers.

Can areas be identified where fossil regoliths occur?

Fossil regoliths can exist where they are covered by later materials. Two well-defined possibilities exist. One is in regolith layers between individual basalt flows in the mare. In order for solar wind gases to be retained in regoliths overlain by basalt flows, the regolith layer must be more than about 1/10 the thickness of the flow. Another possibility is finding ancient regolith beneath pyroclastic or impact deposits, which can be dated. In this case, the process by which the regolith is covered may be gentler and less thermally intense than in the case of basalt flows. LRO should collect data around the perimeter of pyroclastic deposits to determine what the nature of the underlying regolith may have been and the relative age of the surface. In addition, sites should be identified where basalt units were deposited with a significant time hiatus, in regions suitable for later detailed sampling by robotic or human missions. These sites represent opportunities to investigate a host of scientific questions.

How do rays from recent large impact craters modify the regolith such that they are visible and what is the mechanism for their disappearance? How well can they be used to determine the age of craters?

Rays containing impact debris from relatively recent large lunar meteorite impacts are ubiquitous. It is not totally clear what factors contribute to the visibility of rays, but they probably include the burial of mature regolith by immature material, excavation by secondary craters, and compositional differences between the ray material and the underlying regolith. Rays fade with age due to the "gardening" of the regolith by micrometeoroids. It would be useful to have better means of judging the age of rays, which could then be used to date the craters from which they emanate. High resolution NAC images may be useful in studying the topographic component of rays, including the distribution and extent of filling of secondary craters that lie along rays, which could be a measure of their age. This might be associated with subtle compositional signatures detectable by other means.

Are there local variations (10s to 100s of meters) of regolith within mare or highlands units?

One would expect that, particularly in the highlands, the distribution of regolith thickness would be quite variable, due to the intensity and scale of bombardment that occurred prior to mare formation. The processes by which downslope movement of materials contributes to regolith formation and the filling of valleys in highlands terrains could be investigated using high resolution imaging of the walls of massifs to study landslide features. Studies of the interior of Copernicus, which has unexplained irregularities in the distribution of regolith vs. blocky material, may contribute to an understanding of regolith formation in high relief regions.

Can geotechnical properties of the regolith be measured for future landing sites? (added by workshop participants)

The physical properties of the regolith are important in a range of applications, including lunar facility siting, surface mobility/trafficability, and resource excavation and processing. The physical properties of the Moon are generally well known, except for within polar shadowed craters, where both physical and chemical differences might exist. The uppermost few meters of the regolith are most important for these sorts of applications. LRO has several instruments that can address these features. The NAC can determine surface morphology, rock/crater frequency, slopes, and high-resolution topography; the WAC can address issues of surface mineralogy and regolith maturity; Mini-RF can determine surface morphology in shadowed regions, electrical properties, and surface roughness/rock distribution, with depth resolution to about 2 m; DLRE can investigate thermal inertia, rock distributions, regolith thermal properties and some aspects of mineralogy; LEND will determine neutron absorption of the regolith allowing estimates of the H content; and LOLA will determine topography, slopes and surface roughness.

Panel Discussion

The regolith lies practically everywhere on the lunar surface, therefore, many regolith problems can be addressed at many places on the Moon. In order to focus investigations, however, it could be valuable to select a number of the Constellation sites to be studied by multiple techniques.

There are some questions which should be addressed at specific sites. These include: (1) ray studies that require a set of locations exhibiting rays at various stages of maturation; and (2) searching for evidence of fossil regolith at the edges of both mare basalt flow sequences where flows of different age can be distinguished and at locations of pyroclastic deposits, either at the edges or where later craters have penetrated the pyroclastic materials; and (3) in SPA there is a thick sequence of debris layers overlying the initial melt sheet that resulted from the impact. Studies of the morphology of impact craters that have penetrated through these layers to the melt sheet could yield important information dealing with the filling process, the formation of the megaregolith, and possibly a fossil regolith on top of the melt sheet.

The major new influx of data from the LRO will provide many opportunities for regolith studies. These studies should be specifically mentioned in any NASA research announcement.

Composition of the Lunar Crust and Clues to the Interior Panel Summary

Moderator: Paul Lucey, University of Hawaii at Manoa

Speakers: Bradley Jolliff, Washington University at St. Louis
Randy Korotev, Washington University at St. Louis
Steve Mackwell, Lunar and Planetary Institute
Marc Norman, Australian National University
Lon Hood, University of Arizona

Key Questions

Based on the goals and objectives from RC and NASA studies, the following key questions relating to LRO and studies of the composition of the lunar crust and interior were discussed at the meeting:

- What is the range of compositional and lithologic variation of lunar crustal rocks?
- How can LRO aid in determining the lateral and vertical compositional variations within the lunar crust?
- What are the characteristics of geologic contacts between mare and/or highlands units, and what do these tell us about mixing of surface materials?
- What are the predictions of thermal evolution models for the Moon and how do they compare with observations of structures and topography?
- What are the characteristics of compressional and extensional tectonic features, and what do these reveal about surface stresses and the lunar interior?

Panel Overview

LRO includes instruments that will collect global data that are sensitive to the mineralogy and geochemistry of the lunar surface, and exploit wavelengths and techniques not previously used from lunar orbit. The measurements both complement and extend findings made by previous missions and those currently on-going.

This session featured presentations that summarized current problems in lunar composition, tectonics and thermal evolution and explained how LRO measurements would support investigations into these problems.

Lunar Crustal Lithology and Variations: Presentations and Panel Discussions

From a compositional perspective, most lunar rocks fall into a relatively small number of categories. The lunar maria are basalts primarily composed of mixtures of the minerals plagioclase, pyroxene, olivine and ilmenite. The iron-titanium oxide ilmenite varies widely in abundance, making titanium the most variable element among basalts from the lunar maria and the basis for subdivisions among these rocks, with subordinate subdivisions using aluminum and trace elements as discriminators. Lunar highlands rocks are broadly divided into plagioclase-rich anorthosites, including geochemically related but more mafic rocks, a distinct class of more magnesian mafic rocks, incompatible element rich KREEP basalts (distinct from mare basalt in aluminum content and abundance incompatible elements and radioactive elements), and a separate class of anorthosites with distinct feldspar contents called alkali anorthosites. This understanding, derived from the Apollo and Luna samples, has been recently expanded by the recognition of meteorites from the Moon. These samples, with random (though not necessarily uniform) geographic origin, extend our understanding of lunar compositions. The differences between the meteorites and the deliberately returned samples supports the concept that rock types distant from the Apollo and Luna landing sites differ in some respects from lithologies sampled within the Apollo zone.

LRO instruments will measure compositional parameters relevant to the mapping of lunar rocks. The premier compositional instrument is the Diviner Lunar Radiometer Experiment (DLRE) that collects three color bands in the region of thermal emission designed to distinguish feldspar, pyroxene and olivine. Three other wave bands deep in the infrared provide sensitivity to ilmenite as well as the other minerals. The LROC WAC camera collects ultraviolet images at 400-m/pix resolution aimed at detecting ilmenite in the lunar maria. The LEND neutron spectrometer is sensitive to the weighted sum of iron and titanium, as well as the rare earth elements samarium and gadolinium, useful for detecting rocks enriched in incompatible elements. The LOLA laser altimeter features an experiment to characterize the abundance of the mineral pyroxene by comparing the laser reflectance captured on the lunar dayside to measurements of the same locations during the lunar night, where temperatures can dip to 100 K. The Mini-RF radar can map ilmenite because of the strong difference in radar properties between that oxide and other basaltic minerals. Finally, the LAMP UV spectrometer is sensitive to the mineralogy of the Moon through spectral measurements deep in the UV.

LRO sensors also provide key supporting data for other compositional sensors both on LRO and on other spacecraft. The LOLA instrument will provide topographic data to correct reflectance and emission data for the orientation of the surface. The DLRE can detect the presence of bare rock through high nighttime temperatures that will reduce the ambiguity of interpretation of some spectral measurements.

In addition to composition, LRO data can be used to investigate lunar tectonics and thermal evolution. Some features on the Moon caused by lateral stresses in the lunar crust, both compressional causing “wrinkle ridges” in the lunar maria and lobate scarps in the lunar highlands, and fault bounded graben in the lunar maria and highlands. These features reveal a change in the lunar tectonic environment from net extensional, causing the ancient graben, to compressional, that gave rise to the wrinkle ridges and may be causing formation of lobate scarps even today. This change probably is a function of the evolution of the thermal state of the lunar interior. The shallow moonquakes detected by Apollo may be due in part to formation of lobate scarps or other phenomena that may be detect by LRO cameras.

Lunar magnetism and its origin is a persistent question. Magnetic anomalies are frequently accompanied by unusual albedo markings such as the Reiner Gamma formation. Researchers have noted that these magnetic anomalies are often associated with the antipodal positions of the youngest large impact basins, and also with unusual textured terrain attributed to seismic focusing of the impact energy of the basin. Imaging of these terrains are important targets for understanding of lunar magnetism and the full range of effects of large impacts.

Panel Findings

1. LROC images of sample return sites, Apollo and Luna, will aid in a new understanding of the geologic context of the lunar sample collection.
2. Images of a large, or comprehensive, sample of fresh craters, may aid in identifying the source craters for lunar meteorites.
3. Images of lunar swirls (Figure 1) and antipodes of large basins will contribute to understanding of lunar magnetism and basin formation. In particular, the intense magnetic anomaly near Descartes has an associated albedo feature and may be the premier example of a near-surface magnetic source.
4. Images of steep slopes and immature locations where rocks (as opposed to regolith) are exposed will aid in understanding lunar compositions.
5. Image pairings of both low and high sun (very near zero phase) will enable both identification

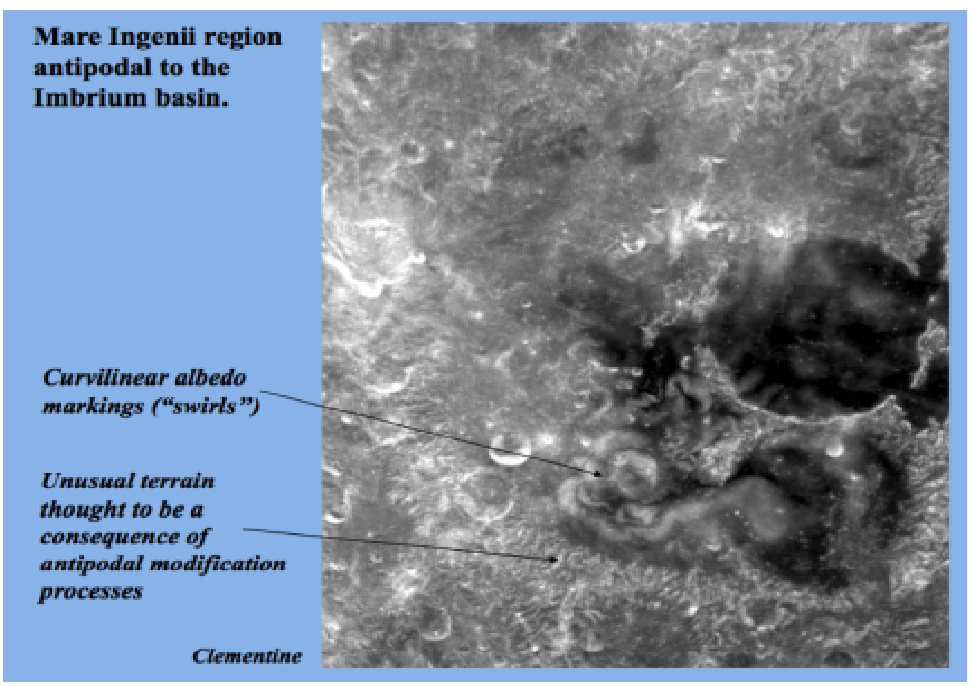


Figure 1: Mare Ingenii is an excellent example of a lunar swirl.

of rocks, and distinguishing melt breccias from anorthositic rocks.

6. Hand-offs between instrument teams will improve understanding of anomalous locations. For example, small regions with extreme nighttime temperatures as detected by DLRE indicate abundant rocks where LROC imaging would be profitable.

Habitation and Lunar Resources Panel Summary

Moderator: Jeffrey Plescia, The Johns Hopkins University, Applied Physics Laboratory

Speakers: Michael Duke, Colorado School of Mines (retired)
Larry Taylor, University of Tennessee
Leslie Gertsch, Missouri University of Science and Technology
Samuel J. Lawrence, Arizona State University
Nathon Schwadron, Boston University

Key Questions

Based on the goals and objectives from the National Research Council and NASA studies, the following key questions relating to LRO and studies of lunar habitability and resources were discussed at the meeting:

- What are the surface characteristics (morphology, topography, hazards, mobility, lighting) of potential sites for human outposts or bases?
- What do we need to know about in situ characteristics of potential lunar resources before decisions are made regarding their use or exploitation?
- What are the thicknesses, maturity, and extents of regolith developed on titanium-rich basalts and pyroclastic deposits?
- How can LRO data be used to better define lunar resources?
- Where are features such as roofed lava tubes that may prove useful for future habitation?

In addition to this set, the discussion during the workshop clearly indicated that the nature of the radiation environment is a critical aspect of long term human habitation of the Moon and thus should be included among these questions.

Panel Overview

There were five oral presentations in the session by Mike Duke, Larry Taylor, Leslie Gertsch, Samuel Lawrence, and Nathan Schwadron which ranged in subject matter from overall strategies of exploiting lunar resources to considerations about how the regolith might be mined to the radiation environment.

Panel Findings

1. A few ISRU sites should be identified and studied in detail, in a manner analogous to the 50 Constellation sites. These sites would include all of the major ISRU type sites (e.g., high Ti basalt,

pyroclastics, polar light). For each site, the complete set of LROC observations that would be made for the Constellation sites would be obtained including creating a mosaic, obtaining both high- and low-illumination images, and stereo observations for the development of a digital elevation model. LROC WAC color images, LOLA topography, Mini-RF, and Diviner thermal data would also be included. This would facilitate a complete understanding of the surface conditions and the potential resources of a site with a sufficient characterization of the surface conditions to understand how to mine the regolith. In addition to the LROC data, LOLA data would provide detailed topography and Diviner would provide information on the surface roughness and thermal properties.

Because the original Constellation sites were in part chosen to examine sites with high ISRU potential, this goal can be achieved without placing any additional requirements on LROC or the other instruments. There would be additional analysis related to the ISRU potential. Four sites were identified for such definitive studies: Aristarchus 2 (pyroclastics), Mare Tranquillitatis (high Ti), Compton (Th / KREEP), and the south pole (light).

2. Develop a well-defined resource search strategy. Since the specific resources of interest have not yet been defined, the suggested strategy is to map all resources in a global sense with as much spatial resolution and precision as possible. This ensures that a data base will exist which could be exploited when the necessary resources are selected. Resources include not only elements and minerals (e.g., H and ilmenite) but also the regolith as a radiation shield and light for solar power.

The polar regions potentially have sites that are illuminated for most, if not all, of the time. Understanding their locations, how the lighting varies over a year, and the detailed topography around them is critical to selecting the appropriate location for a solar power installation. The high spatial resolution of the LROC NAC is particularly important to define the specific location. Comparison between Clementine and SMART-1 images has shown that what appear to be single areas of continuous illumination in the lower resolution Clementine images are actually multiple smaller areas of light and shadow that have different positions with time. The higher resolution of the LROC images could show an even more complicated pattern.

Lava tubes are another landform resource. It has been suggested that lava tubes would provide a ready location to place habitat modules as the roof material (uncollapsed lava and regolith) would provide the necessary mass for radiation protection. Locating lava tubes and determining their dimensions should be a goal.

Water ice in areas of permanent shadow at the poles might be the most important potential resource, although whether it even occurs is currently unknown. Because surface ice would certainly occur only within permanently shadowed areas and would lie below the surface elsewhere, normal optical imaging system may not be able to contribute to the question. However, two LRO instruments, the neutron spectrometer (LEND) and the imaging radar (Mini RF) can provide relevant data. LEND will be able to determine the near-surface H distribution and may be able to resolve the extent to which H is enhanced in areas of permanent shadow. The Mini RF experiment can image these dark areas and through an analysis of the Stokes parameters differentiate between surface scattering (rocks) and volume scattering (ice). If bi-static measurements can be made between LRO and the radar on the Chandrayaan spacecraft (Forerunner), a definitive determination of the presence of ice could be made.

Pyroclastics are a particularly important area to map with respect to resources, as are high-ilmenite basalts and immature regolith.

3. The complete scope of a potential mining operation should be defined and studied. As part of an analysis of resource utilization, the scope of topics extending from legal issues associated with resource ownership to the determination of the appropriate equipment and mining techniques should be examined. Given that none of the commercialization and specific resource decisions have yet to be made, many of these issues can not be resolved. However, understanding the physical properties of the regolith (not only specific geotechnical properties but also aspects such as topography, slope and rock and crater distribution) would allow an evaluation of different mining techniques. For regolith mining, one might chose to collect a thin layer over a large area as opposed to a thick layer over a more limited area. Depending upon which strategy was chosen, a bucket-wheel excavator might be used as opposed to a back hoe / shovel.

4. The lunar radiation environment is perhaps the greatest challenge to human habitation. Radiation from Galactic Cosmic Rays (GCR) and Solar Proton Events (SPE) are the two most relevant radiation sources. GCRs are generally more or less constant flux, although it is tied to the solar cycle, hence the flux and dose can be reasonably predicted. SPE events are not well understood, vary by orders of magnitude in particle flux and dose, and are unpredictable. SPE events can also have very short rise times, making the requirement for immediate, proximate protection absolutely necessary. While the CRaTER instrument will provide additional data relevant to understanding the GCR and SPE environments, much of the work that is necessary is a better understanding of how SPE events are generated and a well-defined strategy to protect the crew.

Impact Cratering Panel Summary

Moderator: Barbara Cohen, NASA George C. Marshall Space Flight Center

Speakers: Veronica Bray, University of Arizona
Matija Cuk, Harvard University
David Kring, Arizona State University
Christian Koeberl, University of Vienna

Key Questions

Based on the goals and objectives from the National Research Council and NASA studies, the following key questions relating to LRO and studies of lunar impact cratering were discussed at the meeting:

- What can be learned about the current impact flux from the identification of impact craters formed since the Apollo era?
- What lithologic variability can be identified in central peaks, peak rings, and other ring structures, and what are the implications for bedrock formations and diversity?
- What are the thicknesses, extents, and effects of basin-ejecta-emplaced plains and melt deposits?
- What are the detailed characteristics of craters and their ejecta blankets and ray deposits, and what do these tell us about the physical and compositional properties of the substrate and degradation processes?
- What is the relationship of impact-basin formation and subsequent volcanic filling?

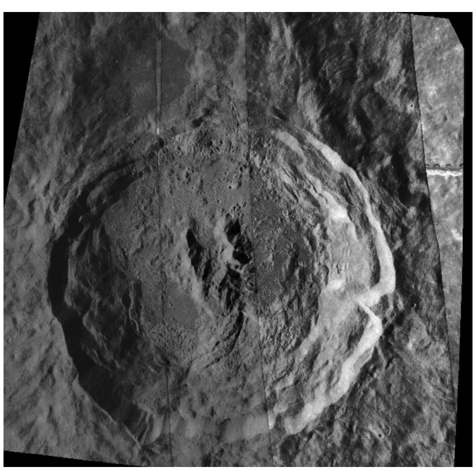


Figure 2: Figure 2: King Crater, ~77 km diameter, ~4 km deep.

The importance of impact crater targets

The Moon is a laboratory for understanding the impact process. Craters are obviously numerous and range over all sizes and terrains. The Moon is airless and largely volatile-free, so some variables in the formation process are removed from consideration. After formation, the paucity of surface erosional processes preserves lunar impact craters better than on most other planets.

The Moon preserves a temporal record of the Earth-Moon bombardment flux, which is vital to understanding the history of impacts on our home planet. Relative crater densities on lunar surfaces can be tied to absolute ages based on samples collected on those surfaces. Because craters are ubiquitous landforms, they and their ejecta blankets form useful stratigraphic markers. Crater densities and size-frequency distributions also serve as reflections of impactor populations, constraining dynamical models of solar system formation and evolution.

Many high-priority science goals in the Scientific Context for the Exploration of the Moon (2007) will rely heavily on sample return, either by humans or robotic missions, from craters and basins. LRO data can help indirectly address these science goals by acquiring data to facilitate future surface operations and sample collection on targets for future robotic and human exploration.

How LRO can help test the impact process

Current understanding of impact crater formation is heavily based on terrestrial craters, where we can use field work, drill cores, seismic profiling, and gravity and magnetic anomalies. Advancing understanding and validating models can come from explosion tests, laboratory experiments, and hydrocode simulations. However, as these advances refine our understanding of the process, they will need to be bounded by data, particularly the composition and structure of the target and observations of pristine craters.

Fresh simple craters serve as pristine examples of crater morphology. The characteristics of these fresh craters (dept/diameter, slopes, etc.) will serve as data to constrain formation models and as the starting morphology to model post-formation floor and rim modification. Targets should include a significant database of young, fresh craters (<5 km), including those of human origin (e.g. RKA's Luna probes, JAXA's Hiten, NASA's Lunar Prospector, China's Chang'E, JAXA's Kaguya, and LCROSS). Additional images of apparently anomalous craters will also provide insight – for example, the depth/diameter ratio of Copernicus is much smaller than the comparably-sized Schluter

Several morphological features are common in craters on ice-rich bodies (Mars, icy satellites, etc.), such as central pits, alluvial fans, viscous flow features, and ponded regions of pitted material. It is not yet clear how these features are related to crustal ice content. There are no typical pit-craters on the Moon, but several have "pitted peaks," such as King Crater and Lansberg Crater. (Figure 2)

The exact mechanism of the formation of central peaks and central uplifts in impact structures is still not clear. On Earth, most craters are either deeply eroded or covered, and thus not accessible or not in pristine condition. A high resolution study of lunar craters in the transition diameter range (15-30 km diameter) would provide data on structural elements of central uplifts of impact craters of various sizes.

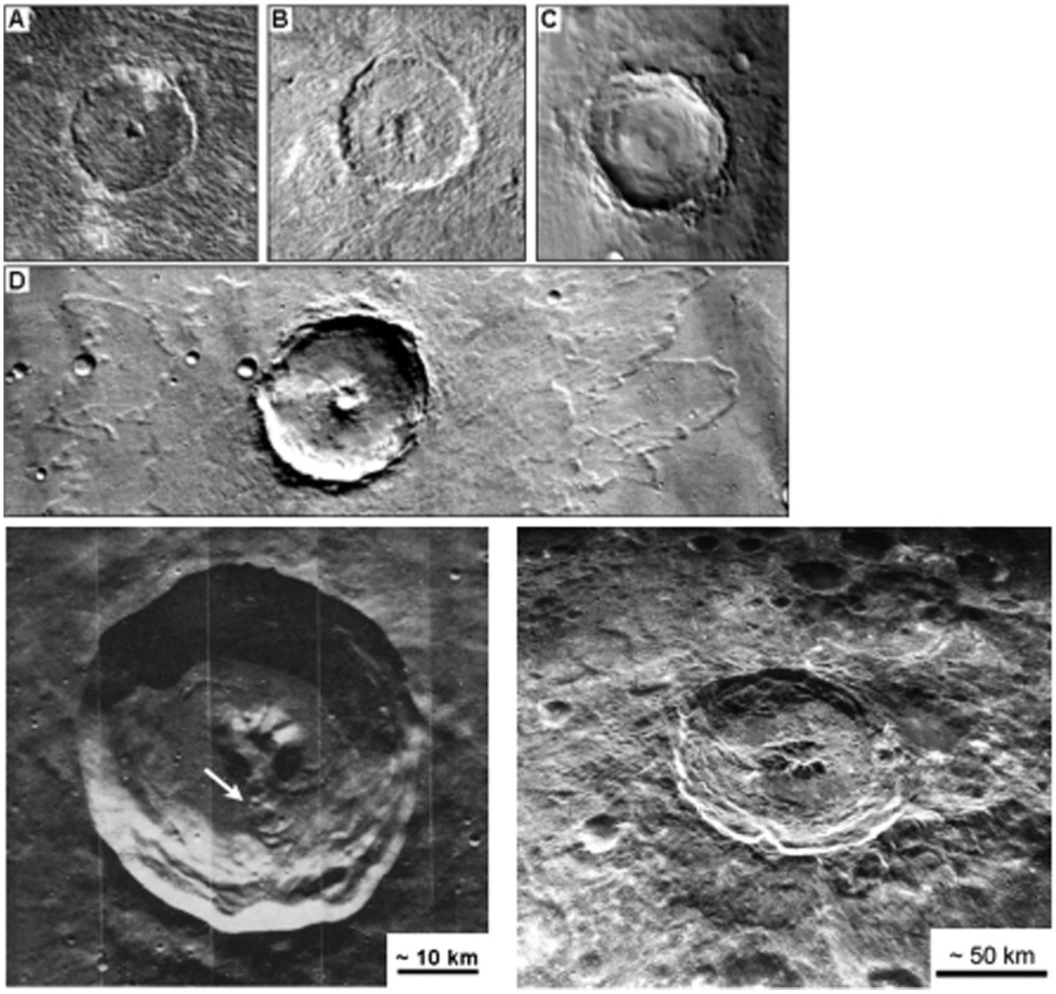


Figure 3: (Top): A&B) 61 km and 75 km pit crater on Ganymede. C&D) 17.4km and 25km pit craters on Mars. (Bottom Left): 93 km King Crater on the Moon. (Bottom right): 40 km Lansberg Crater on the Moon.

Impact melt sheet characteristics, such as compositional variability, are poorly understood because melt sheets are rarely preserved in terrestrial craters. Melt sheets and melt pools should be high-priority targets for both NAC and multifigure WAC images. In particular, craters that straddle terrain boundaries could be extremely useful in providing unique compositional information in their floor materials. This search could be conducted in coordination with data from Chandrayaan's Moon Mineralogy Mapper (M3).

How LRO can help constrain flux

To determine that flux and any variations in it, we need to target impact craters and multi-ring basins that are representative of the flux in both space and time. To provide a temporally broad chronometer, we also need to target impact craters that provide surfaces (e.g., crater floors) that can be used to calibrate crater counting chronologies and/or target impact craters that provide stratigraphic horizons

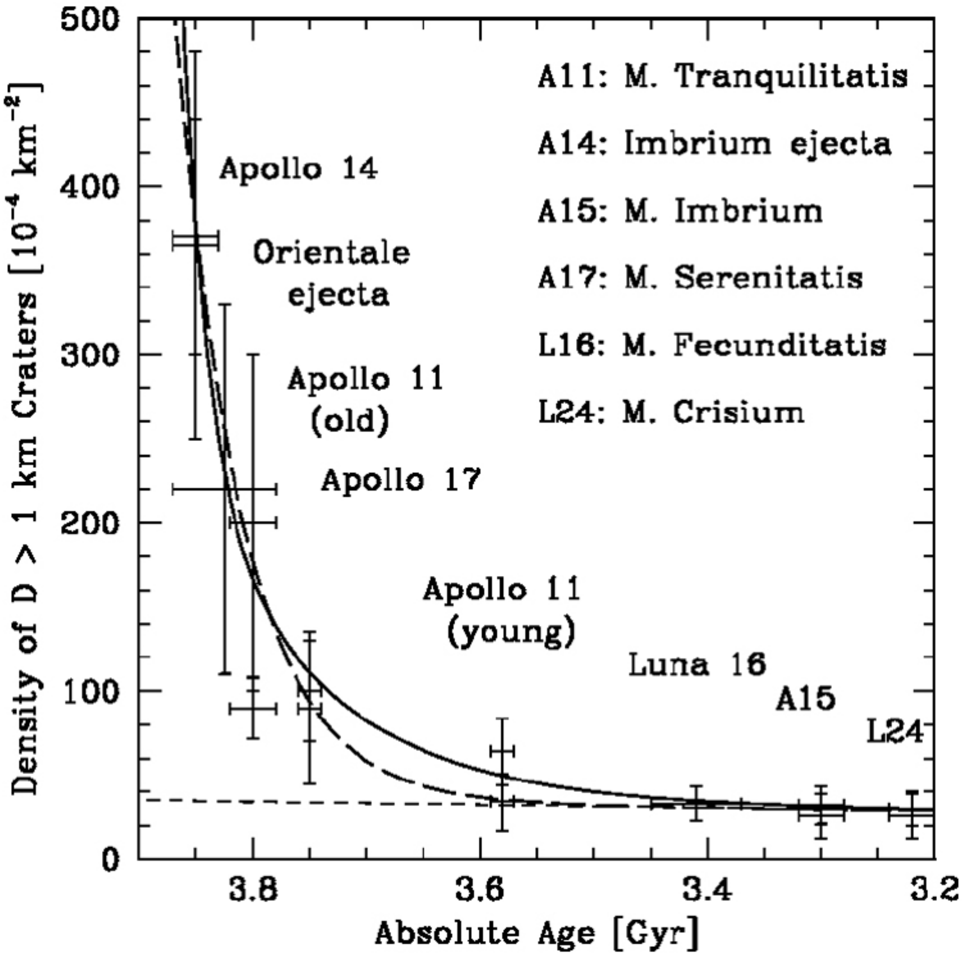


Figure 4: Crater counts on well-dated mare surfaces and ejecta blankest of established basins (Imbrium and Orientale). The possibility exists that uncertainty in the y-axis could be significantly improved using LROC images.

(e.g., ejecta blankets) that can be used for relative chronologies.

Representative complex craters and multi-ring basins should be imaged to better evaluate relative chronology and prepare for sample return missions. Those samples will test the lunar cataclysm (inner solar system cataclysm) hypothesis and provide a measure of the impact flux (and its variations) throughout lunar history.

The age of only a single large impact event (Tycho) is known during the Phanerozoic of Earth, which is the period of complex life on our planet. The impact rate during this time cannot be constrained with only a single data point. Pulses of activity are inferred by meteorite showers on Earth at 800 and 500 Ma; these should be reflected in lunar crater ages.

Refinement of the impact flux curves requires improved age determinations of benchmark craters (those that define breaks in time epochs) as well as representative craters from within each epoch. The

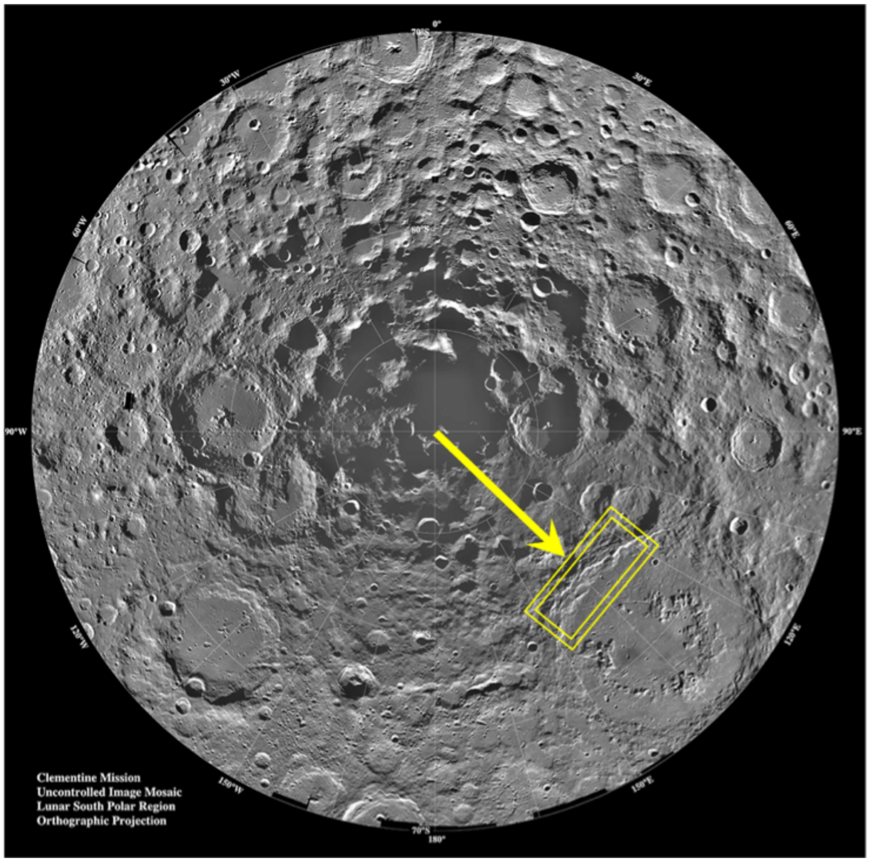


Figure 5: Southern margin of Schrodinger Basin, which is potentially accessible from a polar outpost.

craters should have a broad geographic distribution to assist calibration of relative surface chronology and to recognize the effect of different types of lunar crust.

Representative Pre-Nectarian Basins: South Pole-Aitken Basin, Apollo, Smithii, Nubium

Representative Nectarian and Early Imbrian Impact Basins: Orientale, Schrödinger, Serenitatis, Crisium, Nectaris

Representative Eratosthenian craters: Theophilus (rayed), Pythagoras, Maunder, Eratosthenes

Representative Copernican craters: King [Figure 3], Kepler, Aristarchus, Copernicus, Tycho

Crater-counting on the far-side lunar basins is not yet well-constrained, but many improvements to crater counting can be done with WAC or Kaguya Multi-band Imager data. The youngest lunar basin, Orientale, is of particular use in crater counting –the interior flat floor and the hummocky ejecta blanket should record the same density and size-frequency distribution of impact craters, unmasked by subsequent blanketing by large ejecta. Targeted NAC images of representative areas in the Orientale interior and exterior will be useful in collating crater-counting techniques applies in areas of challenging terrain.

Improving stratigraphy and crater counts on sampled basalt flows can reveal the rate of impactor depletion at the end of the Late Heavy Bombardment (LHB). The size distribution of craters on Imbrium and Orientale ejecta blankets places constraints on the LHB. A change in crater size distribution on Nectarian terrains can tell us when the LHB began (esp., Humorum, Hertzsprung, Bailly). Improving the crater statistics on young maria of different ages to determine if ~3 Gya flux is the same as the average on maria immediately following the LHB [Figure 4].

Stratigraphic relationships between such ancient basalt flows and basin ejecta may help bound basin formation ages. Some of these flows have been identified on the eastern limb by crater counting (Hiesinger et al., 2000, 2005). Others may be identified based on their mineralogical or elemental affiliation with ancient basalt samples in our collection, such as the high-Al basalts, possibly in coordination with M3 data.

How LRO can help support exploration

Several groups have been planning candidate science scenarios to help derive lunar architecture requirements and capabilities. Multiple scenarios are intended to address issues related to the lunar impact flux. LROC, LOLA, Mini-RF, and Diviner could both target these areas to aid traverse planning to more accurately plan routes (=distance) and set realistic goals (steep slopes, boulders) to maximize success. These areas are large (tens of km on a side); it will be impossible to completely cover them with NAC imagery. Focus should be placed on ingress/egress routes to important terrains (such as the southern margin of Schrödinger Basin to assess its accessibility from an outpost site; Figure 5) and small, representative areas to validate and/or inform the interpretation of lower-resolution imaging of adjacent areas.

Identification and mapping of extant melt sheets in nearside basins such as Nectaris and in far-side basins would be important in guiding future missions to sample such lithologies. Additional potential sample-collection sites, such as within SPA Basin or in the Aristarchus region, should be targeted.

Lunar Poles and Exospheric Volatiles Panel Summary

Moderator: David Lawrence, The Johns Hopkins University, Applied Physics Laboratory

Speakers: William Feldman, Planetary Science Institute
Dana Hurley, The Johns Hopkins University, Applied Physics Laboratory
Randy Gladstone, Southwest Research Institute
Ben Bussey, The Johns Hopkins University, Applied Physics Laboratory
Gwen Bart, University of Idaho

Key Questions

Based on the goals and objectives from the National Research Council and NASA studies, the following key questions relating to LRO and studies of lunar polar and exospheric volatiles were discussed at the meeting:

- What are the potential sources of polar and exospheric volatiles?
- What are the solar illumination and thermal conditions in the polar regions over diurnal, seasonal, and longer-period cycles?
- How will LRO data and observations expand our knowledge of the polar volatiles, volatile transport in the lunar environment, and endogenous/exogenous volatile concentrations?
- What are the exchange mechanisms and relationships between hot and cold surface regolith and exospheric volatiles?
- What are the detailed characteristics of sites of observed transient lunar phenomena, and are changes observed by LRO?

Panel Overview

The lunar poles are an area of great exploration and scientific interest owing to the fact that the poles have permanent shaded craters that may harbor a variety of cold-trapped volatile materials. The existence of such deposits of volatiles are important to exploration activities because of their resource potential as well as science relating to the information they can provide about Solar System volatiles and accumulation, transport, and loss processes. Other related areas of scientific research include lunar exospheric studies and lunar polar lighting conditions. Global exosphere studies will provide key information about volatile transport and accumulation processes. Studies of the lunar exosphere are important to carry out early in NASA's exploration program as human activities on the Moon will make significant perturbations to the lunar exosphere. Lunar polar lighting conditions are important both for exploration studies – e.g., understanding maximal sunlit regions for a human outpost – and scientific studies – e.g., delineating in detail locations of permanently shaded regions.

Discussion Summary

The discussion of lunar polar and exospheric volatiles was provided by five talks in the Volatiles session (Bill Feldman and David Lawrence, Dana Hurley, Randy Gladstone, Ben Bussey, and Gwen Bart). Other presentations in this meeting were also related to the polar and exospheric volatile topic (e.g., Stu Nozette [two talks], David Paige). In general, the topics that were covered include what is known about polar volatile deposits, discussions of volatiles transport, segregation, accumulation, and loss processes, lunar atmospheric measurements, LCROSS targeting, lunar polar lighting conditions, lunar polar thermal measurements, and lunar radar measurements.

First, overviews were given regarding the current state of knowledge of lunar polar volatiles. The main types of measurements to date that have given information about lunar polar volatiles are space- and Earth-based radar data and orbital neutron data. Interpretation of radar data are ambiguous regarding the conclusions of whether water-ice has been detected at the lunar poles (in contrast, Earth-based radar data show strong indications of relatively pure volatile deposits in similar permanently shaded regions at Mercury's poles). New radar data from the Chandrayaan-1 mission are currently being returned, but calibration work needs to be completed before solid conclusions and interpretations can be made with these data.

Orbital neutron data from the Lunar Prospector (LP) mission have been used to conclude that enhanced hydrogen deposits are present at both lunar poles. Field-of-view averaged values show that the hydrogen abundances are 100–150 ppm [H] above equatorial values. If it is assumed that most of the neutron signal originates from permanently shaded regions, derived hydrogen contents are ~1–1.5 wt.% water-equivalent hydrogen (WEH). Up to 10s of wt.% WEH are consistent with the neutron data averaged over small portions of the permanently shaded regions. If the interpretation of the Clementine and Chandrayaan radar data are correct, indicating the presence of water ice, then it must occur as blocks or more or less solid ice with dimensions of a few wavelengths (i.e., locally 100% ice). The major limitation of existing neutron data is that the spatial resolution is sufficiently poor that isolated permanently shaded regions are not resolvable.

LRO Targeting for Lunar Polar and Exospheric Volatiles

Much of the LRO mission was designed with the goal of comprehensively understanding the lunar poles, specifically the polar hydrogen content, temperatures, and lighting conditions. Since the LRO spacecraft will be in a polar orbit, every orbit will enable measurements of each lunar pole. A consistent theme for this topic is that integration of multiple datasets is needed to provide good understanding of the lunar poles. Specific measurements include: polar hydrogen content and distribution (LAMP, LEND, Mini-RF), polar temperatures (Diviner), and lighting (LROC). Based on recent polar temperature modeling, particular attention was given to isolated regions near polar cold traps that may spend a large majority of time in permanent shade, but have short times in sun light. It is not known how such regions will retain hydrogen compared to the long term permanently shaded locations. It is expected that if LRO measurements are successful, polar lighting conditions will be sufficiently understood for most exploration and scientific topics requiring this information. Finally, there was discussion about the possibility of anomalous regolith properties in permanently shaded regions – e.g., soil grain sizes that are smaller than the sunlit portion of the Moon. Maximum hydrogen saturation abundances could be significantly larger in regions with smaller grain sizes since hydrogen saturation on grains depends on grain surface area, and the surface area to total volume in regolith is larger when grain sizes are smaller. There were discussions about how such properties might be identified from orbit, such as, in part, using Diviner temperature measurements.

Another major topic of discussion was LRO targeting for the LCROSS mission. Pre-impact targeting was discussed with particular attention being paid to using early LRO data to identify sites that meet all the LCROSS selection criteria. Post-impact targeting was also discussed with an emphasis of looking for time variable signatures as possible volatile plume deposits may migrate from their original locations during a full lunar night/day cycle.

Measurements of the lunar atmosphere were discussed where these measurements would be made with the LAMP instrument. Since such measurements, for the most part, require off-nadir pointing of the LRO spacecraft, it is expected that the bulk of such data will be acquired during the extended science portion of the mission. In addition, to address some science questions (e.g., nighttime deposition patterns), statistical analysis of long term measurements will likely be required.

Finally, other targeted measurements related to this topic include measurements from various instruments of possible locations of lunar outgassing (e.g., Ina, Aristarchus), non-hydrogen cold-trapped volatiles (e.g., argon), transient phenomena (e.g., meteorite impacts) and possible horizon glow.

Conclusion and Implementation of Scientific Targeting

The LRO Targeting Meeting met its objectives of providing a forum for the scientific community to learn about LRO capabilities and the team's approach to targeting, and also to articulate the fundamental scientific questions in areas that can be addressed by LRO and to voice priorities, approaches, and in many cases specific science-rich targets. Using this summary report, meeting abstracts, and presentations, the LRO instrument science teams will augment current targeting strategies and specific target lists accordingly. The main instrument requiring active targeting is the LRO Narrow Angle Camera (NAC) system; however, strategies were also articulated that involve synergistic or coordinated measurements that will be of interest across LRO instruments. In cases such as coordinated LROC and Diviner observations or LROC and Mini-RF observations, the observations may not be made at the same time so that coordination will involve careful overlay and analysis of data sets to insure data for high-priority targets are obtained. In addition to LROC and other LRO team targeting, mechanisms were discussed to enable interested members of the scientific community (and public) to provide input to ongoing targeting or to make inputs directly through a public targeting interface developed by LROC.

Panel discussions also articulated the need to incorporate consideration of key questions into NASA plans for data analysis programs related to LRO. For example, the major new influx of data from the LRO will provide many opportunities for regolith studies. These studies should be specifically called out in any LRO data analysis program.

LROC Targeting Activities

From this report, the LROC Science Team will develop a plan for incorporating suggested targets and targeting strategies that parallel the focus session of the workshop. LROC has a Targeting Action Team that includes scientists with interests and expertise in each of the focus areas. Many of the suggested targets and priorities are already reflected in the master targeting database for the camera systems. As images are acquired covering these targets, the Team will continuously evaluate target coverage and progress toward attainment of images needed to address key questions along the lines of those articulated in this report.

References

NASA Advisory Council (2008) *Lunar Science Workshop,* NASA Advisory Council, NP-2008-08-542-HQ.

National Research Council (2007) *The Scientific Context for Exploration of the Moon*, National Research Council, The National Academies Press.

Appendix I: Meeting Agenda

Tuesday, June 09, 2009

8:00 a.m. Welcome and Opening Plenary

8:00 a.m. Robinson M. S. *Welcome and Introduction*

8:10 a.m. Robinson M. S. * *Agenda Overview and Logistics*

8:20 a.m. Schmitt H. H. * *LRO Science Measurments from Jack's Perspective*

9:00 a.m. Vondrak R. * *LRO Mission Overview: Instrument Capabilities and Science Objectives*

9:30 a.m. Jolliff B. L. * *LRO Science Measurements: Targeting Strategy and Constraints*

10:00 a.m. BREAK

10:15 a.m. Gruener J. E. * Joosten B. K. *NASA Constellation Program Office Regions of Interest on the Moon: A Representative Basis for Scientific Exploration, Resource Potential, and Mission Operations* **[#6036]**

10:30 a.m. Lucey P. G. * Gillis-Davis J. T. Hawke B. R. Taylor L. A. Duke M. B. Brady T. Mosher T. *LEAG Review of Constellation Program Regions of Interest for Human Exploration of the Moon* **[#6022]**

10:45 a.m. Paige D. * *LRO Diviner Imaging Strategies*

11:15 a.m. Nozette S. * *Mini-RF Capabilities and Limitations for Science Measurements*

11:45 a.m. Pieters C. M. * Boardman J. Buratti B. Clark R. Combe J.-P. Green R. Head J. W. III Hicks M. Isaacson P. Klima R. Kramer G. Lundeen S. Malaret E. McCord T. B. Mustard J. Nettles J. Petro N. Runyon C. Staid M. Sunshine J. Taylor L. Tompkins S. Varanasi P. [INVITED] *Characterization of Lunar Mineralogy: The Moon Mineralogy Mapper (M3) on Chandrayaan-1* **[#6002]**

1:00 p.m. Lunar Regolith

1:15 p.m. Mendell W. W. * [INVITED] *The Lunar Regolith as a Remote Sensing Target for the Lunar Reconnaissance Orbiter (LRO)* **[#6018]**

1:45 p.m. McKay D. S. * [INVITED] *Do Lunar Pyroclastic Deposits Contain the Secrets of the Solar System?* **[#6014]**

2:15 p.m. Plescia J. B. * [INVITED] *Understanding the Physical Evolution of the Lunar Regolith Using LRO Data* **[#6032]**

2:45 p.m. Nozette S. * Bussey D. B. J. Butler B. Carter L. Gillis-Davis J. Goswami J. Heggy E. Kirk R. Misra T. Patterson G. W. Robinson M. Raney R. K. Spudis P. D. Thompson T. Thompson B. Ustinov E. *Joint LROC — Mini-RF Observations: Opportunities and Benefits* **[#6041]**

3:15 p.m. Crawford I. A. * Joy K. H. Fagents S. A. Rumpf M. E. *The Importance of Lunar Palaeoregolith Deposits and the Role of Lunar Reconnaissance Orbiter* **[#6007]**

3:35 p.m. Greenhagen B. T. * Paige D. A. *Diviner Lunar Radiometer Targeting Capabilities* **[#6028]**

3:55 p.m. Plenary Discussion of Target Priorities

1:00 p.m. Volcanism: Timing, Form and Composition

1:15 p.m. Greeley R. * [INVITED] *Lunar Volcanism: Timing, Form, and Composition* **[#6001]**

1:45 p.m. Head J. W. III* Wilson L. [INVITED] *Lunar Volcanism in Space and Time: Range of Eruption Styles and Implications for Magma Ascent and Emplacement* **[#6024]**

2:15 p.m. Gaddis L. R. * Robinson M. S. Hawke B. R. Giguere T. Gustafson O. Lawrence S. J. Stopar J. D. Jolliff B. L. Bell J. F. III [INVITED] *LRO Targeting of Lunar Pyroclastic Deposits* **[#6025]**

2:45 p.m. Shearer C. K. * [INVITED] *Lunar Basalts as Probes of the Moon's Mantle and Recorders of Crustal Growth* **[#6021]**

3:25 p.m. Keszthelyi L. P. * *Imaging Rilles and Flood Lavas with LROC* **[#6029]**

3:45 p.m. Williams D. A. * Garry W. B. Keszthelyi L. P. Kerr R. C. Jaeger W. L. *Lunar Sinuous Rilles: Reassessing the Role of Erosion by Flowing Lava* **[#6008]**

6:00 p.m. Poster Session

Crawford I. A. Smith A. Gowen R. A. Joy K. H. UK Penetrator Consortium
MoonLITE: Science Case and Targeting Considerations **[#6006]**

Foing B. H. Koschny D. Grieger B. Josset J.-L. Beauvivre S. Grande M. Huovelin J. Keller H. U. Mall U. Nathues A. Malkki A. Noci G. Sodnik Z. Kellett B. Pinet P. Chevrel S. Cerroni P. de Sanctis M. C. Barucci M. A. Erard S. Despan D. Muinonen K. Shevchenko V. Shkuratov Y. Ellouzi M. Peters S. Borst A. Baxkens F. Boche-Sauvan L. Mahapatra P. Almeida M. Frew D. Volp J. Heather D. McMannamon P. Camino O. Racca G.
SMART-1 Results and Targets for LRO **[#6049]**

Joy K. H. Grindrod P. M. Crawford I. A. Lintott C. T. Smith A. Roberts D. Fortson L. Bamford S. Cook A. C. Bugiolacchi R. Balme M. R. Gay P.
Moon Zoo: Utilizing LROC Lunar Images for Outreach and Lunar Science **[#6035]**

Beyer R. A. Archinal B. Li R. Mattson S. McEwen A. Robinson M.
LROC Stereo Observations **[#6046]**

Cloutis E. Norman L.
Reflectance Spectroscopy of Single Mineral Grains: Implications for Lunar Remote Sensing **[#6020]**

Hiesinger H. Klemm K. van der Bogert C. H. Reiss D. Head J. W.
Lunar Mare Basalts: Scientifically Important Targets for LROC **[#6038]**

Stopar J. D. Hawke B. R. Lawrence S. J. Robinson M. S. Giguere T. Gaddis L. R. Jolliff B. L.
LROC Targeting of Lunar Domes, Cones, and Associated Volcanic Features **[#6039]**

Bell J. F. III Pritchard M. E. Schiff A. C. Gustafson J. O. Williams N. R. Watters T. R.
LRO Targeting of Lunar Tectonic Features **[#6011]**

Wyatt M. B. Donaldson Hanna K. L. Pieters C. M. Helbert J. Maturilli A. Greenhagen B. T. Paige D. A. Lucey P. G.
Diviner Constraints on Plagioclase Compositions as Observed by the Spectral Profiler and Moon Mineralogy Mapper **[#6026]**

Conrad A. R. Lyke J. E. Wooden D. Woodward C. Lucey P.
Acquisition and Tracking of the LCROSS Impact Site with Keck-II **[#6023]**

Wingo D. R. Lundquist C. A.
Coordinating LOIRP Enhanced Lunar Orbiter and Lunar Reconnaissance Orbiter High Resolution Images for Selected Science and Exploration Targets **[#6044]**

Crotts A.
High Resolution Imaging of Sites of Rapid Changes on the Lunar Surface **[#6013]**

Chaufray J.-Y. Retherford K. D. Gladstone G. R. Hurley D. M. Hodges R. R.
Lunar Argon Cycle Modeling **[#6015]**

Wright S. P. Newsom H. E.
Targeted Search near Lunar Poles for Potential Alteration Resulting from Impact Cratering into Volatile-"rich" Terrains **[#6045]**

Retherford K. D. Gladstone G. R. Stern S. A. Kaufmann D. E. Parker J. Wm. Egan A. F. Greathouse T. K. Versteeg M. H. Slater D. C. Davis M. W. Steffl A. J. Miles P. F. Hurley D. M. Pryer W. R. Hendrix A. R. Feldman P. D.
LRO/LAMP Expected Data Products: Overview of FUV Maps and Spectra **[#6047]**

Wednesday, June 10, 2009

8:00 a.m. Composition of the Crust and Clues to the Interior

8:10 a.m. Jolliff B. L. * [INVITED]
Lunar Crustal Rock Types, Global Distribution, and Targeting **[#6040]**

8:40 a.m. Korotev R. L. * [INVITED]
Lunar Surface Geochemistry and Lunar Meteorites **[#6005]**

9:10 a.m. Norman M. D. * [INVITED]
Lunar Anorthosites as Targets for Exploration **[#6012]**

9:40 a.m. Johnson C. L. Watters T. R. Mackwell S. J. [INVITED]
What new can LRO tell us About Lunar Thermal Evolution, Interior Structure and Dynamics? **[#6051]**

10:20 a.m. Hood L. L. * [INVITED]
Lunar Magnetism **[#6004]**

10:50 a.m. Lucey P. G. * Lawrence S. J. Robinson M. R. Greenhagen B. T. Paige D. A. Wyatt M. B. Hendrix A. R. [INVITED]
The Compositional Contribution of LRO **[#6019]**

LUNAR RECONNAISSANCE ORBITER SCIENCE TARGETING MEETING

8:00 a.m. Habitation and Lunar Resources

8:10 a.m. Duke M. B. * [INVITED]
Lunar Resources and LRO **[#6033]**

8:40 a.m. Taylor L. A.* [INVITED]
How In-Situ Resource Utilization (ISRU) Fits into Lunar Outpost Concepts and Requirements on LRO Target Selection

9:10 a.m. Gertsch L. S. * [INVITED]
Lunar Mining: Knowns, Unknowns, Challenges, and Technologies **[#6031]**

9:40 a.m. Lawrence S. J.* [INVITED[
LRO and Remote Observations of Lunar Resources

10:20 a.m. Schwadron N. * [INVITED]
Lunar Radiation Environment

10:50 a.m. Mitrofanov I. G. * Sanin A. S. Mokrousov M. I. Litvak M. L. Kozyrev A. S. Malakhov A. A. Trety'akov V. I. Vostrukhin A. V. Shvetsov V. N. Sagdeev R. Boynton W. Harshman K. Enos H. Trombka J. McClanahan T. Evans L. Starr R.
Lunar Exploration Neutron Detector for NASA LRO Mission **[#6050]**

1:00 p.m. Impact Cratering and History

1:00 p.m. Kring D. A. * [INVITED]
Targeting Complex Craters and Multi-Ring Basins to Determine the Tempo of Impact Bombardment While Simultaneously Probing the Lunar Interior **[#6037]**

1:30 p.m. Bray V. J. * Tornabene L. L. McEwen A. S. [INVITED]
The Moon as a Laboratory for Understanding Impact Processes **[#6034]**

2:00 p.m. Cohen B. A. * [INVITED]
The Lunar Cataclysm and How LRO can Help Test It **[#6048]**

2:30 p.m. Cuk M. * [INVITED]
The Dynamics Behind Inner Solar System Impacts — Past and Present **[#6042]**

3:00 p.m. BREAK

3:10 p.m. Oberst J. * Wählisch M. Hempel S. Knapmeyer M.
Locations and Morphology of Spacecraft Impact Craters for Re-Calibration of Apollo Seismic Data **[#6003]**

3:30 p.m. Koeberl C.
Central Uplift Formation in Complex Impact Craters — Comparison of Lunar and Terrestrial Craters **[#6030]**

1:00 p.m. Lunar Volatiles: Polar and Exospheric

1:00 p.m. Feldman W. C. * [INVITED]
Our Current Understanding of Lunar Polar Hydrogen Deposits **[#6009]**

1:30 p.m. Hurley D. M. * [INVITED]
Current Understanding of Lunar Volatile Transport and Segregation **[#6027]**

2:00 p.m. Gladstone G. R. * Retherford K. D. [INVITED]
The Lunar Atmosphere and its Study by LRO **[#6010]**

2:30 p.m. Bussey D. B. J. * [INVITED]
A Review of Lunar Polar Lighting Condiitons: What We Know Now, and What We Will Learn Soon **[#6043]**

3:10 p.m. Bart G. D. * Colaprete A.
The Importance of LRO Observations to the LCROSS Mission **[#6016]**

Thursday, June 11, 2009

8:00 a.m. Panel Discussion of LRO Targeting, Closing Plenary

Appendix II: Project Constellation Priority 1 Sites

Site Name	*Latitude*	*Longitude*
Aitken Crater	-16.76	173.48
Alphonsus Crater	-12.56	-2.16
Anaxagoras crater	73.48	-9.3
Apollo 15	26.08	3.66
Apollo 16	-9	15.47
Apollo Basin	-37.05	-153.72
Aristarchus 1	24.56	-48.95
Aristarchus 2	27.7	-52.4
Bullialdus Crater	-20.7	-22.5
Copernicus Crater	9.85	-20.01
Gruitheisen Domes	36.03	-40.14
Hertzsprung	0.09	-125.56
King Crater	6.39	119.91
Malapert Massif	-85.99	-2.93
Mare Crisium	10.68	58.84
Murchison Crater	4.74	-0.42
North Pole	89.6	76.19
Orientale 1	-26.2	-95.38
Peary Crater	88.5	30
Rima Bode	12.9	-3.8
South Pole	-89.3	-130
South Pole-Aitken Basin Interior	-60	-159.94
Stratton	-2.08	166.88
Sulpicius Gallus	19.87	10.37
Tycho Crater	-42.99	-11.2
Balmer Basin	-18.69	69.82
Compton/Belkovich Th Anomaly	61.11	99.45
Dante Crater	26.14	177.7
Flamsteed Crater	-2.45	-43.22
Hortensius Domes	7.48	-27.67
Humboldtianum Basin	54.54	77.14
Ina ('D-Caldera')	18.65	5.29
Ingenii	-35.48	164.42
Lichtenberg Crater	31.65	-67.23
Mare Frigoris	59.8	26.1
Mare Moscoviense	26.19	150.47
Mare Smythii	2.15	85.33
Mare Tranquillitatis	6.93	22.06
Marius Hills	13.58	-55.8
Mendel-Rydberg Cryptomare	-51.14	-93.07
Montes Pyrenaeus	-15.91	40.81
Orientale 2	-18.04	-87.91
Plato Ejecta	53.37	-5.21
Reiner Gamma	7.53	-58.56
Riccioli Crater	-3.04	-74.28
Rimae Prinz	27.41	-41.72
Schrödinger	-75.4	138.77
South Pole-Aitken Rim	-51	170.92
Tsiolkovskiy Crater	-19.35	128.51
Van de Graaf Crater	-26.92	172.08

Appendix III: Named Targets From Workshop Abstracts

Key: First Author, (abstract #), feature, Latitude, and Longitude (if supplied)

Greeley (6001): small shield volcanoes in Lacus Veris, Orientale

Oberst (6003): artificial impacts

LM-12 -3.94 -21.2

LM-14.-3.42 -19.67

LM-15 26.36 0.25

LM-17 19.96 30.5

S4B-13 -2.75 -27.86

S4B-14 -8.09 26.02

S4B-15 -1.51 -11.81

S4B-16 1.3±0.7 -23.8±0.2

S4B-17 -4.21 -12.31

Hood (6004): mountains near A16 site, strongest magnetic anomaly on the near side

Mare Ingenii on far side

Crawford (6007): lava flow contacts

Williams (6008): sinuous rilles

Bell (6011): tectonic features

Norman (6012): anorthositic massifs – Inner Rooks, Grimaldi eastern rings (near Procellarum contact) northwestern region of Nectaris near Theophilus, Kant Plateau

Crotts (6013): TLP in Phys. Earth Planetary Int., 14 (1977)

http://arvix.org/abs/0706.3947

http://arvix.org/abs/0706.3952 and 3954

Bart (6016): LCROSS impact candidate sites

Bryne (6017): Near Side Megabasin site: 52S, 85.5 W

Mendell (6018): thermal anomaly spots

Head (6024): generic: rilles with pyroclastic cones, craters chains with no linear rilles, linear rilles with associated crater chains, domes and cones

Gaddis (6025): pyroclastic deposits

Wyatt (6026): areas where crystalline plagioclase has been identified

Keszthelyi (6029): rilles, flood lavas

Koeberl (6030): central uplifts (numerous examples in ppt)

Plescia (6032): generic regolith, QO/OQ craters, rock fields, ejecta

Duke (6033): ISRU sites

Bray (6034): fresh impact craters, melt sheets, simple to complex transition

Kring (6037): surfaces that can be used to calibrate chronology. melt from SPA, Nubium, Smythii, Schrödinger and Apollo Basins; Humboldt, Tsiolkovsky, Antoniadi, Archimedes, Hansen, Pythagoras, Theophilus, Eratosthenes, Maunder, Kepler, Aristarchus, King, Copernicus, Tycho.

Hiesinger (6038): the lunar maria, specifically different flow and compositional units to determine ages from crater densities

Stopar (6039): domes, cones, et al. e.g., Marius Hills along has 80 domes and 15 cones.

Jolliff (6040): fresh rock exposures (central peaks, peak rings, crater walls and terraces, melt sheets, impact ejecta deposits, basin massifs); nonmare volcanic domes, geologic contacts between compositionally distinctive units

Bussey (6043): polar craters – extended illumination

Wright (6045): polar craters

Taylor (9999): map various resource categories

Crustal Theme: Targets

Brad Jolliff:

- Compositional anomalies

  (Domes, Aristarchus and its ejecta, Kepler and its ejecta, Compton-Belkovich, Dewar anomaly)
- Steep slope features in SPA craters and basin constructs
- Features with steep topography

Randy Korotev:

- Small, fresh Craters to locate possible sources for LMs – combined with compositional remote sensing.

Marc Norman:

- Kant Plateau
- Orientale ring massifs (see Marc Norman's presentation)
- Geologically interesting features near potential landing sites and existing landing sites (Ranger, Surveyor, Apollo, Luna)

Steve Mackwell:

- Epicenter map

- Crater degradation in areas near shallow moonquake centers – see plot in Steve's presentation.
- Wrinkle ridges (all associated with basalt-filled basins) & graben (outer edges of basins and associated highlands) – Tom W.
- Rupes Recta normal fault
- Lobate scarp near Morozov crater; Moro'zham(?) crater – most recent, youngest features – not deformed by superposed craters (see Tom Watters)
- Timing of shift from extensional tectonics to compressional tectonics..
- Thermal models that predict change in lunar radius of about 1 km – are the tectonic features consistent?

Lon Hood:

- Magnetic Anomalies
- Reiner Gamma
- Area south of Ingenii and associated Imbrium antipodal terrain – alternate model is seismic shaking at the point of convergence – or maybe a combination of deposition and seismic shaking. Relevant also to Caloris basin. Geochemical anomalies in region Thorium -– how are these related? Look at the grooved terrain.
- Descartes Anomaly – strongest one on near side 10.5S 16E why is albedo higher in the middle of the anomaly than say just south of it.
- Other antipodal anomalies? Compare to other antipodal terrain
- Central magnetic anomaly in Moscoviense

Paul Lucey

- Compositional Contributions of LRO
- Note: WAC – space weathering effects of UV bands
- Diviner and mineral sensitivity
- Christiansen Feature vs. SiO_2 – pretty sensitive. But how well will it be measured?
- Tycho crater hot spots
- MiniSAR sensitivity to ilmenite – correlate to WAC color mosaic and calibrated TiO_2
- Central peak of Jackson - anorthosite

Jim Head

- Orientale and other young basins – target the potential analog sites e.g., where the landing sites have their analogs.

Appendix IV: Volcanism Targets

Panel 1: Lunar Reconnaissance Orbiter Science Meeting

LUNAR VOLCANISM: KEY QUESTIONS

1. Morphology and magma (Jim Head)

   What are the morphologic / morphometric characteristics of volcanic vents and effusive lavas, and what do these tell us about origin and emplacement of magmas within the crust and at the surface?

   - Cobra Head-Aristarchus Plateau (sinuous rille, dome, pyroclastics)
   - Ina: D-Caldera (recent degassing?)
   - Mendeleev Crater Chain (explosive vent)
   - Gruithuisen Dome (explosive vent?)
   - Kopf Crater (caldera?)

Greeley 4

1. Morphology and magma

   What are the morphologic / morphometric characteristics of volcanic vents and effusive lavas, and what do these tell us about origin and emplacement of magmas within the crust and at the surface?

2. Volcanism and petrogenesis

   What is the variety of volcanic structures, styles, and associations and what do they mean for mantle and crustal petrogenesis?

3. Ages and volcanic "flux"

   What is the range of ages of volcanic materials and what do these ages indicate about the volcanic flux over time?

4. Pyroclastic and volatiles

   What is the distribution and what are the characteristics of lunar pyroclastic deposits, and what do these reveal about their origin, eruption and emplacement and the thermal and magmatic evolution of the mantle?

5. Cryptomaria

   What is the global distribution and range of ages of "cryptomare" (ancient, mare surfaces buried beneath more recent crater ejecta?

Greeley 2

LUNAR VOLCANISM: KEY QUESTIONS

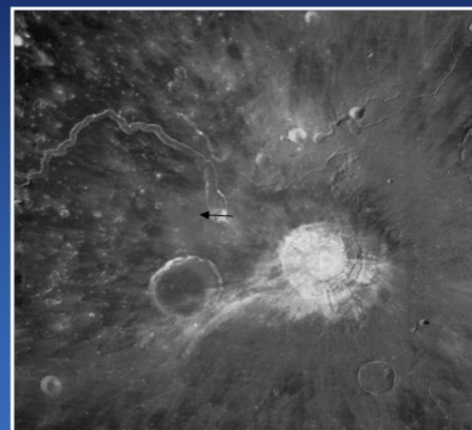
Priority 1: Schroeter's Valley - Cobra Head

Coordinates: -48.95° E, 24.56° N

Scientific rationale and logic: This is at the origin of Schroeter's Valley, one of the most prominent sinuous rilles on the Moon. There is a dome at the source of two superposed rilles. It appears to be related to the dark mantle deposits that cover the Aristarchus Plateau. Analysis would establish the relationships between the dome, rilles and the pyroclastics.

Type of future exploration required (human/robotic?): Both robotic and human.

Instruments and requirements: LROC NAC strip down the middle of the Cobra Head dome and crater out into the surrounding dark mantle deposits. Stereo data are required for DEM of the crater walls to look at stratigraphy.



Greeley 5

LUNAR VOLCANISM: KEY QUESTIONS

2. Volcanism and petrogenesis (Chip Shearer)

What is the variety of volcanic structures, styles, and associations and what do they mean for mantle and crustal petrogenesis?)

	SPA Basin	Aristarchus Pleateau	Tsiolkovsky	Lichtenberg	Balmer-Kapteyn
What is the nature and origin of lateral asymmetry in the Moon's mantle?	X		X		
What is the nature of volatiles in the lunar mantle?	X	X			
How does lunar magma change with time?	X		X	X	X
Potential sample return	X	X	X	X	X

Greeley 6

LUNAR VOLCANISM: KEY QUESTIONS

2. Volcanism and petrogenesis (Chip Shearer)

What is the variety of volcanic structures, styles, and associations and what do they mean for mantle and crustal petrogenesis?)

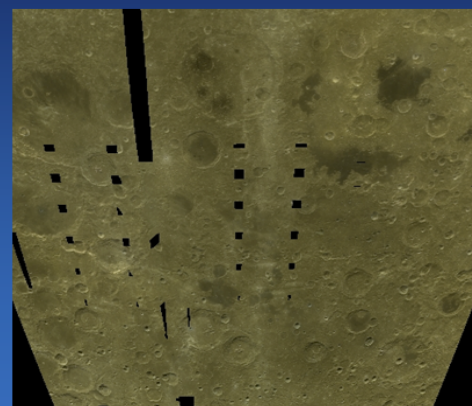
Priority 1: SPA Basin

Scientific rationale: Farside mare lavas and pyroclastics to test models of lunar mantle. Explore how basalt compositions change with time. Cryptomare deposits will address early magmatism

Attributes: Site(s) must include mare basalt, pyroclastics, and cryptomare

Data required: Requires multiple 10 x 10 km polygonc

Feed forward: Enables human or robotic exploration and sampling



Greeley 7

LUNAR VOLCANISM: KEY QUESTIONS

3. Ages and volcanic "flux" (David Williams)

What is the range of ages of volcanic materials and what do these ages indicate about the volcanic flux over time?

Rationale: Oldest flows and vents, youngest flows and vents, sample diversity of volcanism with time

- Cryptomaria in SP-Aitken basin (oldest?)
- Lichtenberg lava flows (youngest?)
- Mare Imbrium flows and vents
- Oceanus Procellarum olivine-rich flows
- M. Fecunditatis and Luna 16 landing site

Greeley 8

LUNAR VOLCANISM: KEY QUESTIONS

4. Pyroclastic and volatiles (Lisa Gaddis)

What is the distribution and what are the characteristics of lunar pyroclastic deposits, and what do these reveal about their origin, eruption and emplacement and the thermal and magmatic evolution of the mantle?

- How variable are the compositions of the deposits?
- How representative are "sampled" pyroclastic compositions?
- What are titanium contents of unsampled pyroclastics?
  - *Aristarchus*
- Can "juvenile" materials (e.g., olivine) be distinguished?
  - *J. Herschel*
- Where are the source vents?
  - *Orientale*
- Can multiple units be recognized in pyroclastic deposits?
  - *Oppenheimer*
- Where are the "new" (previously unrecognized) deposits?
  - *Rima Parry V*

Greeley 10

LUNAR VOLCANISM: KEY QUESTIONS

Priority 1 (Pyroclastics): Aristarchus Plateau (Lisa Gaddis)

Science rationale

- High-Ti "black spot" deposits may be useful resource
- Aristarchus pyroclastics may be end member with quenched red/orange glasses
- Recent results suggest ~low Ti (Hagerty et al., 2009)

Target

- 27° , 310° E
- Spectrally homogeneous site (~10x10 km) in pyroclastic deposit on plateau
- Secondary site would include small, fresh crater that has exposed fresh materials and/or penetrated thru deposit

Greeley 11

LUNAR VOLCANISM: KEY QUESTIONS

Priority 1 (Pyroclastics): Aristarchus Plateau (Lisa Gaddis)

LRO instruments

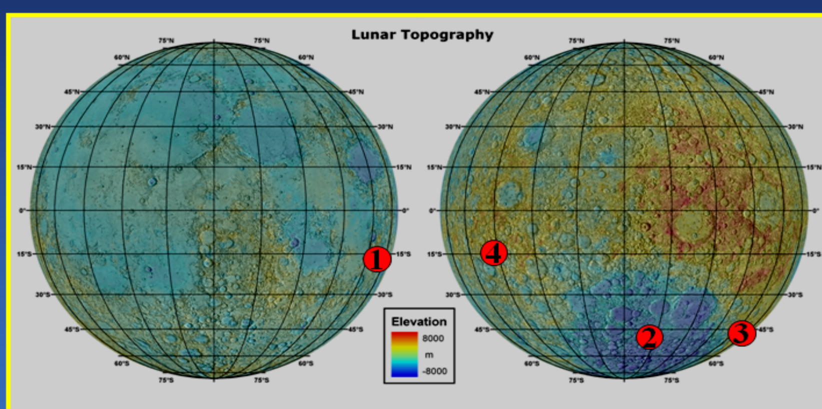
- LROC NAC nadir views of deposit
- LROC WAC multispectral images
- Mini-RF (S-, X-band)
  - Roughness/texture of deposit
  - Thickness, blockiness of units
  - Dielectric constant?
- Diviner
  - Blockiness, rock abundance
  - Bulk thermal properties of surface units
  - Mineraogy, titanium content?

Greeley 12

LUNAR VOLCANISM: KEY QUESTIONS

5. Cryptomaria (Laszlo Keszthelyi)

What is the global distribution and range of ages of "cryptomare" (ancient, mare surfaces buried beneath more recent crater ejecta?



1. Balmer-Kapteyn
2. SPA Basin
3. Mendel-Rydberg
4. Tsiolkovsky

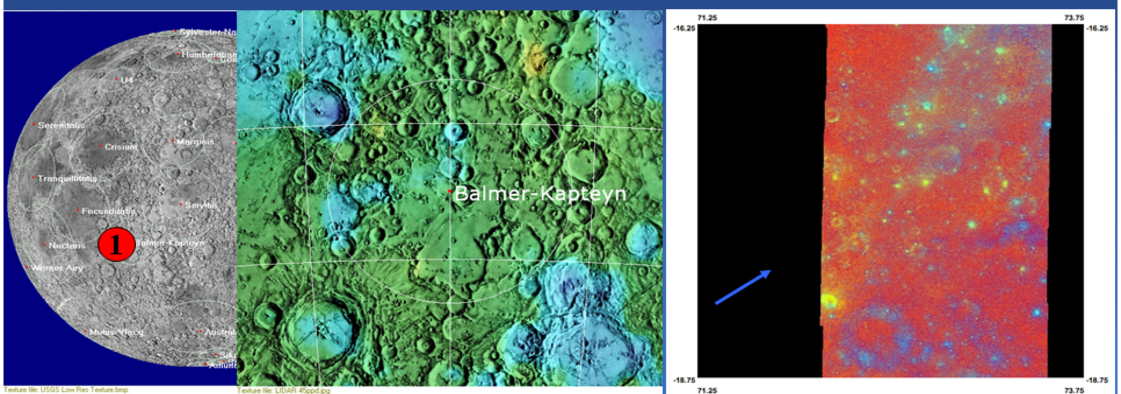
Future targesys (TBD)

Greeley 13

LUNAR VOLCANISM: KEY QUESTIONS

Priority 1 (Cryptomaria): Balmer-Kapteyn

- Basin center at 15˚ S, 70˚ E
- Most popular of cryptomaria (ancient buried lavas excavated by impact craters) targets
- Samples desired and Cx site at 18.69˚ S, 69.82˚ E
- Precise LROC NAC target location TBD, but possible example at -18.23˚ , 72.12˚ E shown



Greeley 14

Panel 1: Lunar Volcanism Conclusions

- Some sites are common for multiple questions
  - *Aristarchus Plateau*
  - *SPA Basin*
  - *Tsiolkovsky*
  - *Balmer-Kapteyn*
- Need to determine *specific* locations in common sites to address multiple questions
- Sites are "science objective-driven" (tend to focus on well-studied areas)
- Need also to explore poorly-known areas
  - Higher latitudes
  - Farside

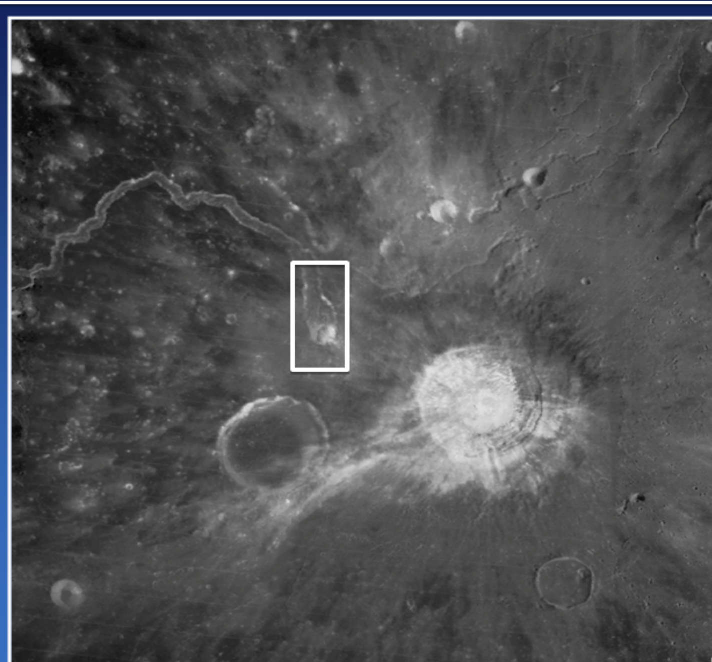
Greeley 15

Target 1: Schroeter's Valley - Cobra Head

Coordinates: -48.95° E, 24.56° N.

Scientific Rationale and Logic: This is at the origin of Schroeter's Valley, one of the most prominent sinuous rilles on the Moon. There is a positive dome at the source, which has a central depression that is the source of two superposed rilles. It appears to be related to the dark mantle deposits that cover the Aristarchus Plateau. Analysis would establish the relationships between the dome, rilles and the pyroclastics.

Type of future exploration required (human/robotic?): Both robotic and human. Instruments and requirements: LROC NAC strip down the middle of the Cobra Head dome and crater out into the surrounding dark mantle deposits. Stereo data is required for DEM of the crater walls to look at stratigraphy.



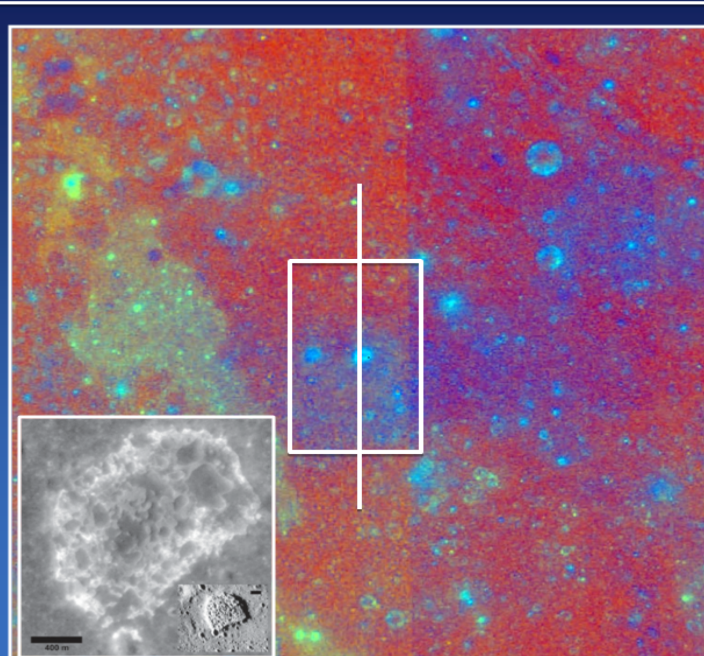
Target 2: Ina Feature - Recent Degassing(?)

Coordinates: 5.29° E, 18.65° N

Scientific Rationale and Logic: This feature is very unusual in terms of its freshness, immaturity, paucity of craters, and spectral properties. It has been attributed to very young volatile degassing (less than 10 million years!), and is thus a target of extreme importance. If venting is still occurring, this would be a fundamental discovery. Need information on the age, nature and composition of process and deposits. Schultz et al. Nature, 444, 14, (2006).

Type of future exploration required (human/robotic?): Human and robotic; sample return.

Instruments and requirements: LROC NAC; need illumination to emphasize topography; need stereo.



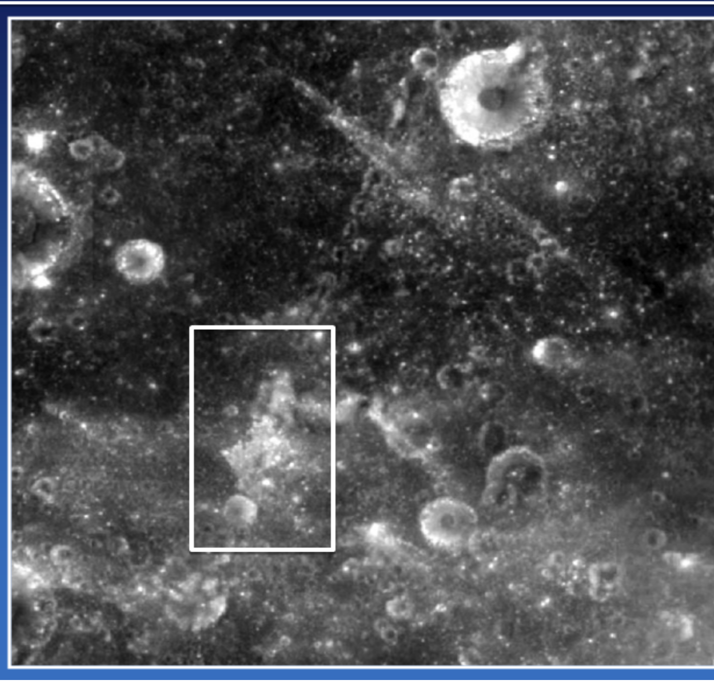
Target 3: Mendeleev Crater Chain - Explosive Vent(?)

Coordinates: 139.4° E, 6.3° N.

Scientific Rationale and Logic: This is a crater chain that may represent emplacement by gas-rich magmas that erupted explosively at the surface (a kimberlite analogy and thus possible mantle xenoliths) or a shallow dike that was not shallow enough to produce a graben, but was shallow enough to degas and form explosive and collapse craters. Alternatively, this may represent an unusual type of impact crater chain of a set of projectiles broken up by a close encounter with another body. If this is of internal origin, this is a critical part of understanding lunar volcanism.

Type of future exploration required (human/robotic?): Robotic exploration of crater deposits; possible future sample return (could be mantle xenoliths).

Instruments and requirements: Need LROC NAC data strip across larger craters in the chain and stereo imaging for rim topography and depth.



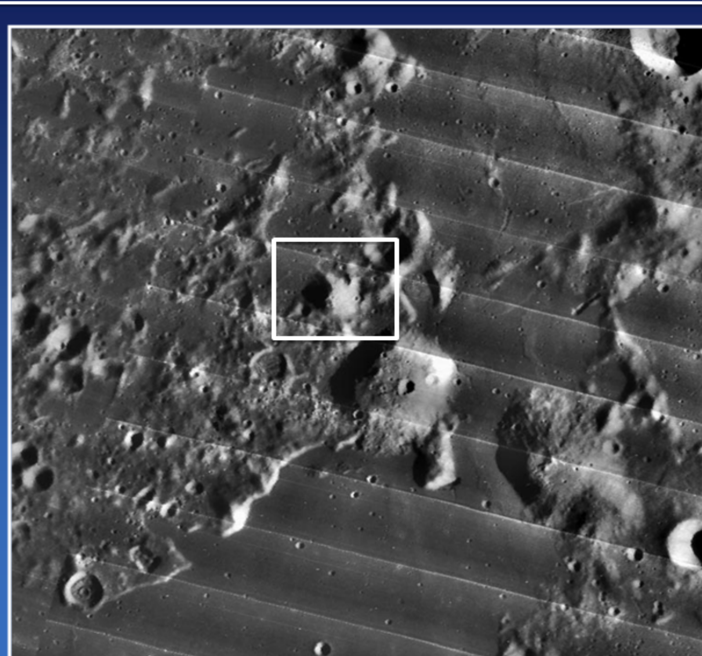
Target 4: Gruithuisen Dome - Possible Explosive Vent

Coordinates: -41.1° E, 37.1° N

Scientific Rationale and Logic: The Gruithuisen and Mairan domes represent spectrally distinct (downturn in the UV) features that are very different from the surrounding highlands and maria. They date to the earliest Imbrian period about 3.7 billion years ago. Do they represent explosive eruptions, and/or highly viscous felsic material, as models and morphology would suggest?

Type of future exploration required (human/robotic?): Definite robotic and human exploration, sample return.

Instruments and requirements: LROC NAC image strip across the summit of the NW dome to emphasize morphology and stereo; DIVINER data for composition and mineralogy, and other mineralogy and elemental data.



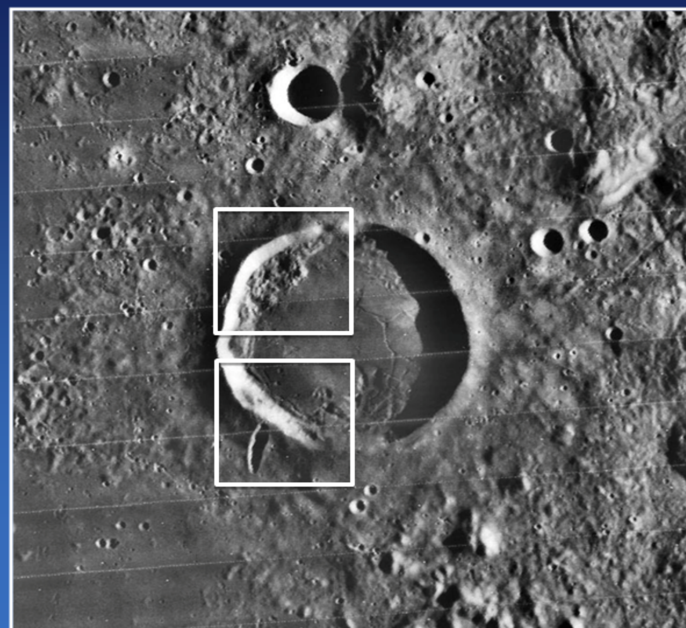
Target 5: Kopff Crater - Candidate Caldera Structure

Coordinates: -89.6° E, 17.4° S.

Scientific Rationale and Logic: This crater is very unusual and has been heavily modified by volcanic activity, but differs substantially from the nearby Maunder impact crater. It may be a caldera in which case it is really unusual and needs to be better characterized. This could provide much new insight about shallow magma reservoirs and their properties.

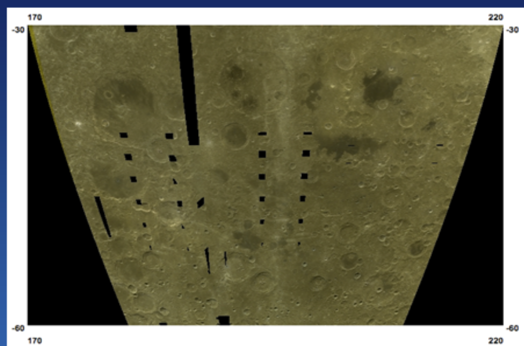
Type of future exploration required (human/robotic?): Robotic exploration and possible sample return.

Instruments and requirements: Need LROC NAC coverage strip across the crater interior and out to its exterior deposits, and stereo. DIVINER data would also be important, as would LOLA data.



Q2. What is the variety of volcanic structures, styles, and associations and what do they mean for mantle and crustal petrogenesis?

Target 1. SPA Basin



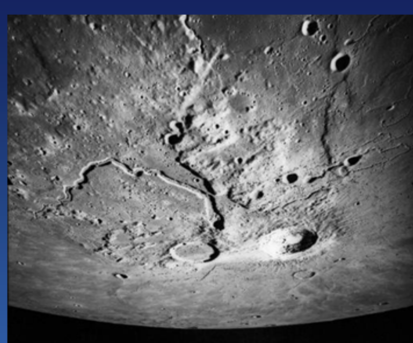
Location or site characteristics: Site must include mare basalt, pyroclastic deposits, and cryptomare.

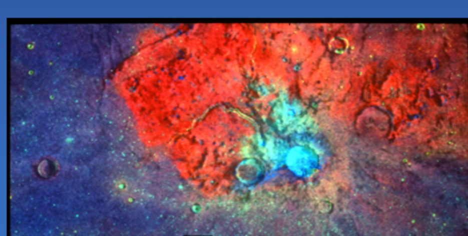
Scientific Rationale: Far side mare basalts and small pyroclastics deposits. Test models for the nature of lunar mantle (composition, thermal history) on far side. Cryptomare deposits will address nature of early (pre-3.8 Ga) magmatism. Explores how basalt compositions change with time.

Data Required: May require multiple 10 x 10 km LROC images to cover multiple volcanic features.

Feed forward: Enables human or robotic exploration and sampling.

Target 2. Aristarchus Plateau





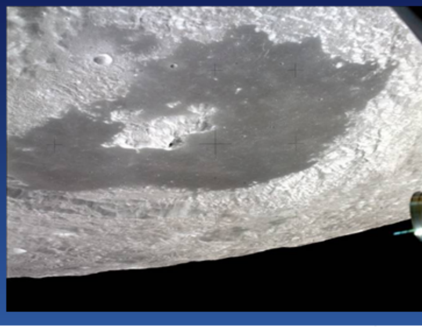
Location or site characteristics: Site must contain stratigraphy of pyroclastic deposits. Perhaps this stratigraphy could be exposed in a medium size crater.

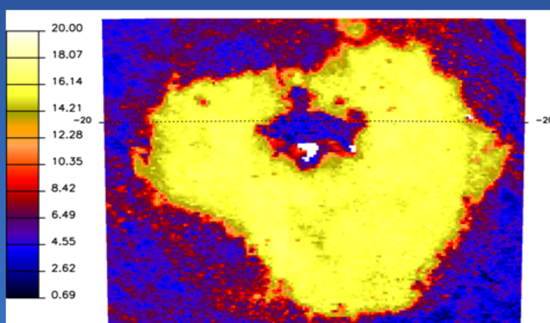
Scientific Rationale: Sampling of a large pyroclastic deposit will address the composition of mare basalt sources, dynamics of lunar mantle, the volatile composition of the mantle, and eruptive processes. thermal history) on far side.

Data Required: LROC imaging and Laser Altimeter.

Feed forward: Enables human exploration and sampling.

Target 3. Tsiolkovsky





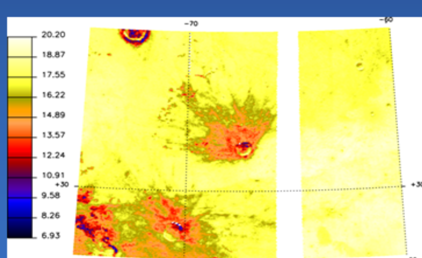
Location or site characteristics: Site must include mare basalt and lithologic variations in the northern portion of central peak.

Scientific Rationale: Far side mare basalts and central peak. Test models for the nature of lunar mantle (composition, thermal history) on far side.

Data Required: LROC imaging and Laser Altimeter.

Feed forward: Enables human exploration and sampling.

Target 4. Lichtenberg Crater



Location or site characteristics: Site must include multiple flow units. This could be reveled in small craters to the northwest o Lichtenberg crater.

Scientific Rationale: One of the youngest flows on the Moon may provide insights into sources melted during the last stages of lunar magmatism. Explores how basalt compositions change with time.

Data Required: LROC imaging and Laser Altimeter.

Feed forward: Ideal site for future robotic exploration and sampling.

Target 5. Balmer-Kapteyn Region

Location or site characteristics: Site must include the oldest cryptomare basalts exposed in the region.

Scientific Rationale: Cryptomare deposits will address nature of early (pre-3.8 Ga) magmatism, sources that are melting in the lunar mantle, and early thermal conditions of lunar mantle. Explores how basalt compositions change with time.

Data Required: LROC imaging and Laser Altimeter.

Feed forward: Enables robotic exploration and sampling.

LUNAR VOLCANISM: PANEL 1

Q3: What is the range of ages of volcanic materials and what do these ages indicate about the volcanic flux over time?

Targets: Oldest flows and vents, youngest flows and vents, sample diversity of volcanism with time

Top Five Targets:

1) Cryptomaria in SP-Aitken Basin

2) Lichtenberg Lava Flows

3) Mare Imbrium Flows and Vents

4) Oceanus Procellarum Olivine-rich Flows

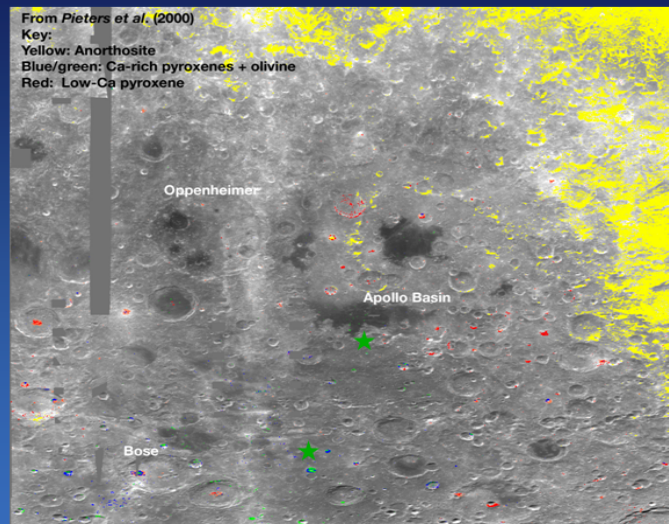
5) M. Fecunditatis & Luna 16 Landing Site

Other: Fe Anomalies & Dark-Halo Craters along western margin, Procellarum Basin

No. 1: CRYPTOMARIA IN SP-AITKEN BASIN

Rationale:

- Target oldest(?) lava flows preserved on Moon
- Requires multiple targets over large area
- Coordinate targeting with previous & current multispectral studies



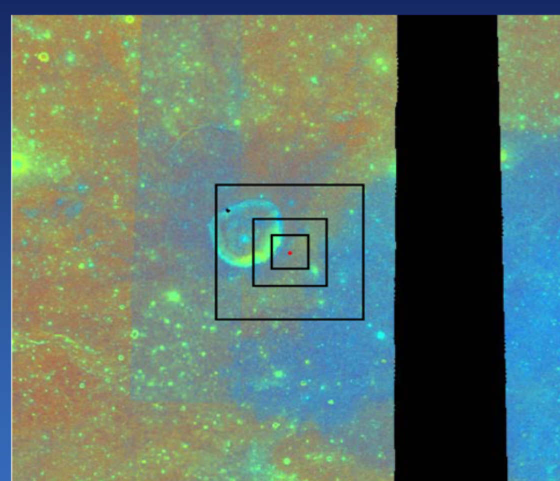
Application:

- Locate best landing sites for future rovers or *in situ* missions (SP-Aitken sample return)

No. 2: LICHTENBERG LAVA FLOWS

Rationale:

- Target youngest(?) lava flows preserved on Moon
- Also a Constellation Program target (Tier 2)
- Location of young (Copernican?), thin lavas



Application:

- Constrain end of effusive lunar volcanism in NW Oceanus Procellarum

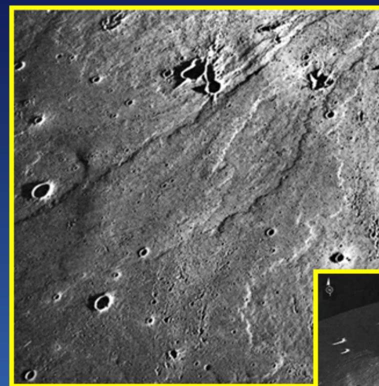
No. 3: MARE IMBRIUM VENTS & FLOWS

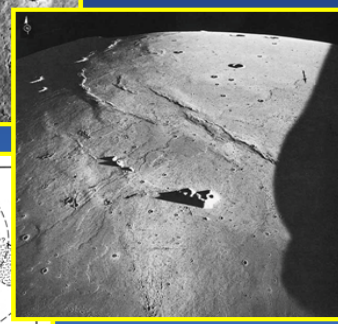
Rationale:

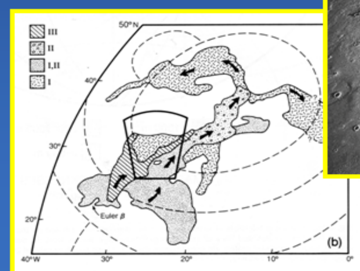
- Very high effusion rate lava flows
- Implications for dike widths, sinuous rilles
- Phases separated in time: Implications for source
- Pyroclastics at vent sites: What is relationship?
- Relation to basin loading and tectonic evolution
- Flow behavior on cratered surfaces

Application:

- Compare/contrast styles of lunar lava flow emplacement with terrestrial flows



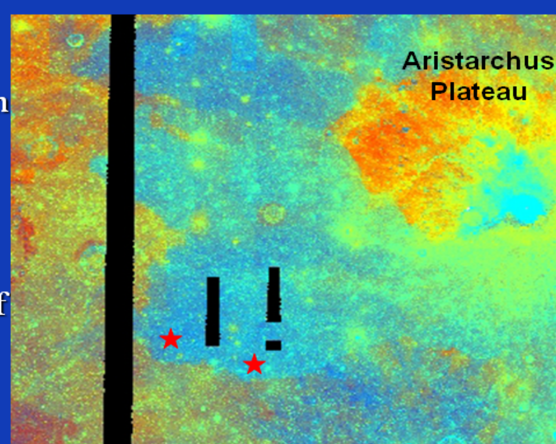




No. 4: PROCELLARIUM OLV-RICH FLOWS

Rationale:

- Target late-stage, high-Ti lava flows (*Staid & Pieters*, 2001)
- Spectroscopy suggests that these flows are both Fe-rich, and contain abundant olivine
- Coordinate with previous & current multispectral studies to target ideal locations
- NAC imaging for crater counts of specific flows



Application:

- Constrain final effusive volcanism in Central Oceanus Procellarum

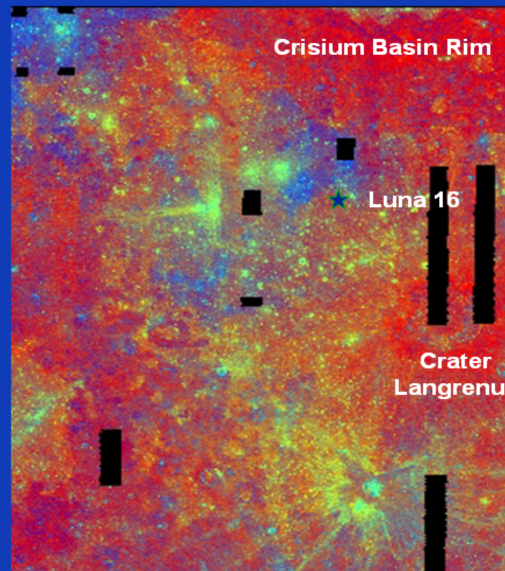
No. 5: M. FECUNDITATIS & LUNA 16 LANDING SITE

Rationale:

- Assess ages of compositionally diverse mare units in Fecunditatis basin & Luna 16 landing site (cf., *Hiesinger et al*., 2000, 2001, 2003)
- Requires multiple targets over large area
- Coordinate targeting with previous & current multispectral studies

Application:

- Further identify diversity of lunar mare volcanism



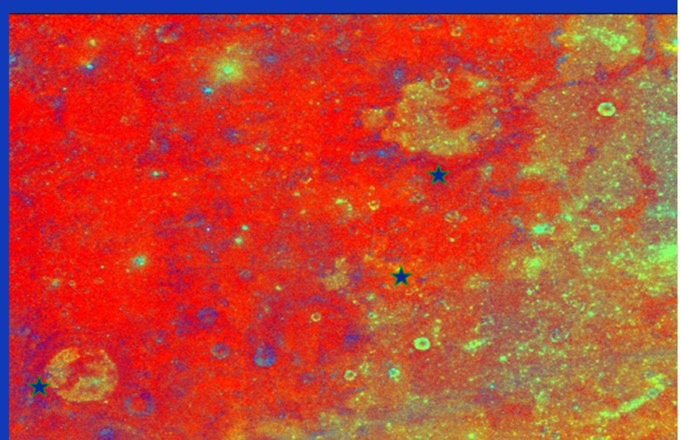
OTHER: FE ANOMALIES & DHCs AROUND PROCELLARUM BASIN

Rationale:

- Assess morphology and ages of Fe anomalies & DHCs in the margins of Procellarum basin
- Requires multiple targets over large area
- Coordinate targeting with previous & current multispectral studies

Application:

- Further identify diversity of lunar mare volcanism



Lunar Pyroclastic Deposits

Specific Questions for LRO

- How variable are the compositions of the deposits?
  - Between, within deposits
- How representative are sampled pyroclastic compositions?
- What are titanium contents of unsampled pyroclastics?
  - **Aristarchus**
- Can 'juvenile' materials (e.g., olivine) be distinguished?
  - **J. Herschel**
- How big are the deposits?
  - Areal extent, thickness, vertical relief
- Where are the pyroclastic source vents?
  - **Orientale**
- Can multiple units be recognized in pyroclastic deposits?
  - **Oppenheimer**
- Where are the 'new' (previously unrecognized) deposits?
  - Linear rilles
    - Possible buried dikes (e.g., Wilson and Head, 2009a, b)
    - **Rima Parry V**

Note 10x10 km boxes.

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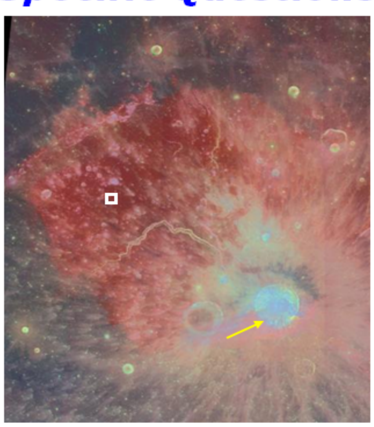
Lunar Pyroclastic Deposits

Specific Questions for LRO



Aristarchus Plateau (18N-32N, 42W-57W). Clementine UVVIS color-ratio mosaic: R=750/415nm, G=750/1000nm, B= 415/750nm (McEwen et al., 1994). Aristarchus crater is 42 km in diameter.

- **Titanium content (#1)**
  - High-Ti 'black spot' deposits may be useful resource
    - Rima Bode, Apollo 17/Taurus Littrow
  - Aristarchus pyroclastic may be endmember with quenched red/orange glasses, but recent LP results suggest ~low Ti (Hagerty et al., 2009)
- **Target: Aristarchus Plateau**
  - **27˚ , 310˚ E**
  - Spectrally homogeneous site (~10x10 km) in pyroclastic deposit on plateau
  - Secondary site would include small, fresh crater that has exposed fresh materials and/or penetrated thru deposit
- **LRO Instruments:**
  - LROC NAC nadir views of deposit
  - LROC WAC multispectral images
  - Mini-RF (S-, X-band)
    - Roughness/texture of deposit
    - Thickness, blockiness of units
    - Dielectric constant?
  - Diviner
    - Blockiness, rock abundance
    - Bulk thermal properties of surface units
    - Mineralogy, titanium content?

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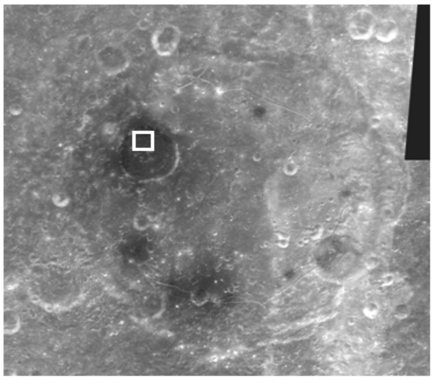
Lunar Pyroclastic Deposits

More Specific Questions for LRO



Clementine 750-nm mosaic of Oppenheimer Crater (dia. 208 km) in SPA basin on the lunar far side

- **Multiple eruptive deposits (#2)**
  - Single or multiple eruptive events?
  - Size of individual explosive eruptions
  - Change in composition over time?
- **Targets: Oppenheimer**
  - **-35°, 300° E**
  - Examine fractures in unit in NW floor (largest lunar 'dark halo' crater?)
  - Look for multiple units, compare to deposits at other fractures in floor and Alphonsus deposits
- **Instruments:**
  - LROC NAC nadir views of vents
  - LROC WAC context images of region
  - Mini-RF
    - Roughness/textural variations near vents?
    - Thickness variations
  - Diviner
    - Bulk thermal properties of surface units
    - Rock abundance, surface roughness

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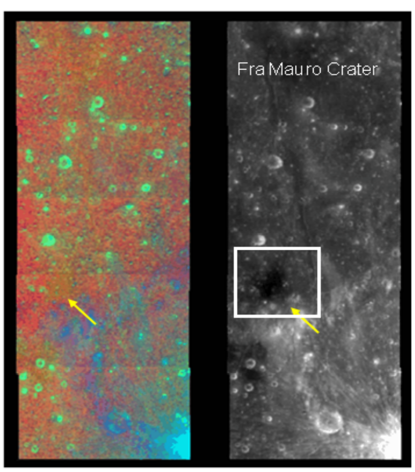
Lunar Pyroclastic Deposits

More Specific Questions for LRO



Clementine color-ratio (left) and 750-nm (right) mosaics of Rima Parry V. View is ~25 km across. (Head et al., LPSC XXIX,1998)

- **'New' deposits (#3)**
  - Lunar linear rilles
  - Surface expression of buried dikes?
  - Near Apollo 14 landing site
- **Targets: Rima Parry V**
  - **-9.5°, 346° E**
  - Smooth-surfaced (low albedo?) units on/adjacent to fracture(s)
- **Instruments:**
  - LROC NAC nadir views of low-albedo deposits
  - LROC WAC context images of region
  - Mini-RF
    - Roughness/textural variations near vents
  - Diviner
    - Bulk thermal properties of surface units
    - Rock abundance, surface roughness

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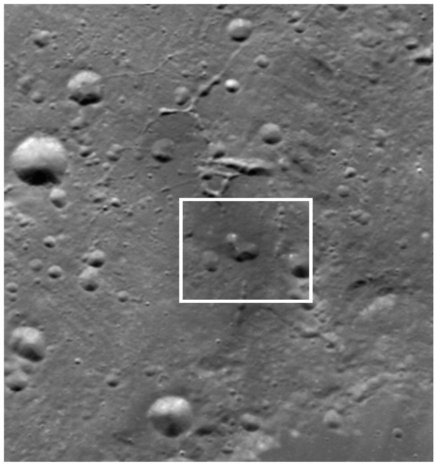
Lunar Pyroclastic Deposits

Specific Questions for LRO

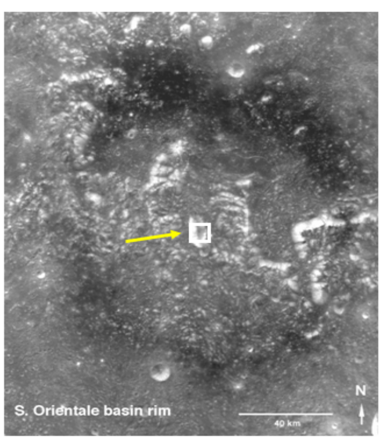


Clementine 750-nm mosaic
View is ~30 km across

- **Juvenile materials (#4)**
  - Origin, composition of primitive materials
  - Depth of volcanic source materials
  - Telescopic data suggest presence of olivine (McCord et al., 1981)
- **Targets: J. Herschel**
  - **62°, 324° E**
  - 10x10 km box centered on largest vent structure
- **Instruments:**
  - LROC NAC nadir views of vents
  - LROC WAC context images
  - Mini-RF
    - Roughness/textural variations
  - Diviner
    - Bulk thermal properties of units
    - Rock abundance, surface roughness
    - Mineralogy

Lunar Pyroclastic Deposits

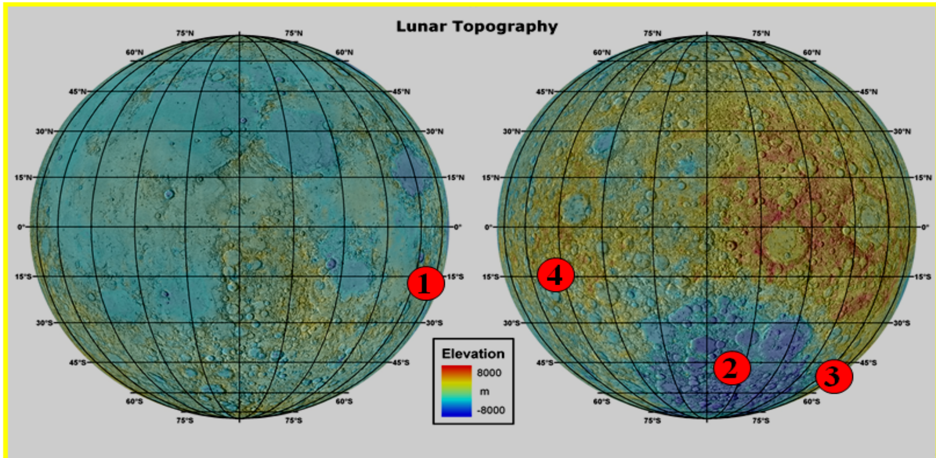
More Specific Questions for LRO



Clementine 750-nm mosaic
View is ~180 km across

- **Source Vents (#5)**
  - Eruption mechanism(s), single or multiple?
  - Location of buried dikes
  - Compare to small cones in ff craters
- **Targets: Orientale 'Kiss'**
  - **-31°, 263° E**
  - Centered on irregular depression ('vent')
- **Instruments:**
  - LROC NAC nadir views of possible vent
  - LROC WAC context images of region
  - Mini-RF
    - Roughness/textural, thickness variations
    - Dielectric properties?
  - Diviner
    - Bulk thermal properties of surface units
    - Rock abundance, surface roughness

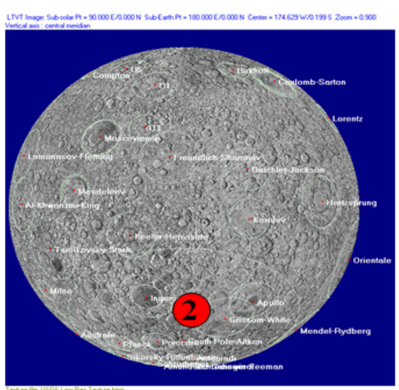
Cryptomaria Targets

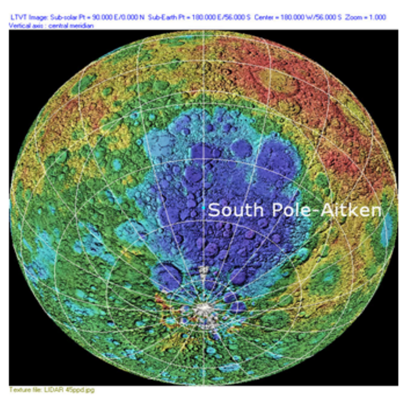


1. Balmer-Kapteyn.
2. SPA Basin.
3. Mendel-Rydberg.
4. Tsiolkovsky.
5. Future Targets.

Cryptomaria: SPA Basin

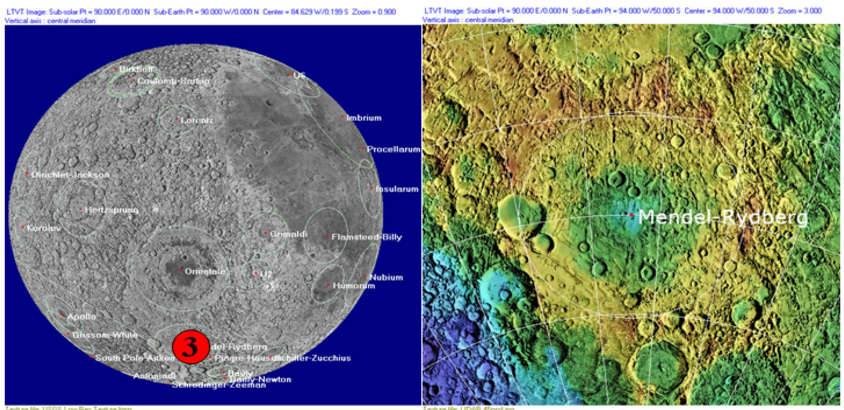
Basin center at 56° S, 180° E.
Important cryptomare to compare nearside and farside lavas.
Samples desired and Cx site at 60° S, -159.94° E.
Precise LROC NAC target location TBD.





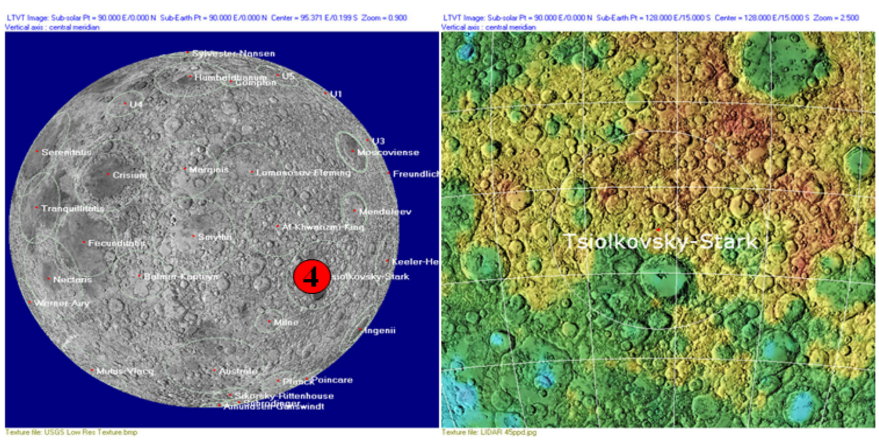
Cryptomaria: Mendel-Rydberg

Basin center at 50° S, 94° W, example at
Important cryptomare to obtain global sampling.
Samples desired and Cx site at 51.14° S, -93.07° E.
Precise LROC NAC target location TBD.



Cryptomaria: Tsiolkovsky

Basin center at 50° S, 94° W.
Important cryptomare to obtain global sampling.
Samples desired and Cx site at 51.14° S, -93.07° E.
Precise LROC NAC target location TBD.



Cryptomaria: Future Targets

Cryptomaria, as their name implies, are difficult to identify in the current data. However, the new spectral data from the international missions should help identify new targets. Even more powerful is the combination of this spectral data with even higher multi-band LROC WAC data. These future data sets are useful for all types of targets, but are especially important for cryptomaria.

General considerations for selecting specific target locations are related to the nature of the crater that has excavated the buried lava(s). Of particular interest is the stratigraphy that is exposed in the crater walls. Thus DIVINER and mini-RF data indicative of good outcrops should help drive the selection of specific targets.