Expectations for ESM5 (Sept 2022 to Sept 2025)

- Proposal similar except that mission support is key part of proposal evaluation
- Science divided into 4 themes

ESM5

LEADS

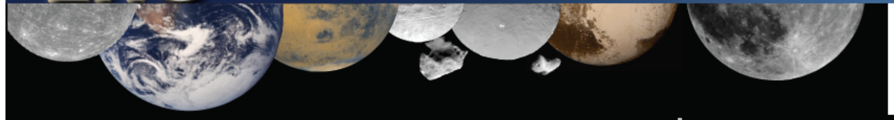
- Volatiles: Angela Stickle
- Impacts and Regolith: Catherine Elder
- Volcanism and Tectonism: Julie Stopar
- Mission Support: Maria Banks

Timeline (presented on PSWG tcon)

- **Now: teams work on what science investigations to highlight in the proposal.**
- **Are new measurement modes needed? We have to run those requests through the MOT/MD.**
- Theme leads organize sessions to share ideas, start outlining what is possibly included, draft up “Quad Charts”
- Summer 2021: writing science ESM5 sections (we used 22 of the 32 pages for ESM4)
- Rough draft of all sections by near end of this FY.
- Submit proposal 14 Jan 2022. (Senior review in Feb 2022)

Previous theme objectives (ESM3 & ESM4)

- Timing of Copernican to recent volcanic history (LROC, DLRE rock abundances and regolith characteristics)
- KREEP basalts & “unusual” volcanic materials (LROC morphology)
- Extent of ancient volcanism (cryptomare) – LROC, DLRE
- Volcanism & tectonics/stresses tied to GRAIL data (basins, gravity anomalies)
- Long-lived volcanism evidence (LROC)
- Shallow magma intrusions (e.g., floor fractured craters)
- Distribution of Pure Anorthosite rock type & crustal structure (LROC, DLRE, CRaTER)
- Timing and composition of Silicic volcanism (LROC, DLRE)
- Ages and flows of maria (LROC, MRF, LOLA)
- Extent and range of pyroclastics (LROC, DLRE, LAMP, MRF, LOLA)
- Pits and Lava tubes (LROC, LOLA, DLRE)
- Composition of maria (esp. TiO2 content) (LROC, DLRE)
- Timing of recent tectonic stresses (LROC)



LRO's Orbital History (A) shows the evolution of the mission and our operations of the spacecraft. In 2011 we entered a quasi-stable orbit that minimizes fuel consumption. In ESM4 (B) we will allow our orbit to natrually drift, which raises our periapse and lowers the apoapsis, maintaining an average orbit altitude of ~90 km. As a consequence of our orbit being inertially fixed, the Moon moves under the spacecraft, meaning that we no longer pass directly over the South Pole. During ESM4 we move ~1.5° further from the poles (C), however this enables an increase in coverage over an area known as the "Ring of Fire" near both poles. This density of coverage is illustrated in the figure (D).

The LRO mission has acquired fundamental data that are changing lunar and planetary science. With additonal data, LRO addresses new questions during the ESM4.

The instruments will operate in innovative modes, showcased below, to acquire the required data for the ESM4 objectives.

The LRO ESM4 will address fundamental questions about the evolution of the Moon and our Solar System.

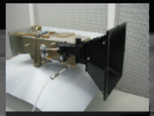
CRaTER measures lunar response to radiation.

Measures energetic ions (>10 MeV) in front of and behind tissue-equivalent plastic

CRaTER off-nadir ①

Off-nadir CRaTER observations will measure grazing-angle albedo protons to help us understand time-of-day presence and transport of water in the subsurface.

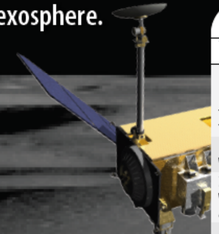
LAMP measures UV albedo and probes the exosphere.



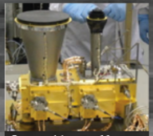
UV imaging (57-196 nm; 0.18-nm resolution) with ~300-m spatial resolution

LAMP surface hydration ②

By opening the failsafe door, the LAMP dayside signal-to-noise ratio has improved. This constrains surface hydration variability during a lunar day, meteor streams, and Solar Energetic Particle events.



LOLA measures surface shape and albedo.



5-spot altimeter 10-cm vertical precision 25-m horizontal spacing

LOLA high phase angle observations ③

The Laser Ranging telescope on LRO's High Gain Antenna will make unique high phase angle reflectance measurements to help constrain how geologic and exposure histories affect surface textural properties.

Mini-RF detects solid subsurface ice and measures changes in surface roughness.

100-m pixel scale SAR imagery

Mini-RF Targeted Bistatic Observations ④

Mini-RF will target nearside and polar features, at X- and S-band wavelengths, with single and multi-axis slews to characterize the opposition response of a range of terrains.

Mini-RF Non-Targeted Bistatic Observations ④

Mini-RF will acquire non-targeted data, at X- and S-band wavelengths, of the nearside equatorial and mid-latitude regions (i.e., without spacecraft slews) to characterize the scattering phase function of a range of terrains.

Diviner data probes regolith properties through the lunar thermal environment.

0.35-400nm in 9 channels 150-500m pixel scale

Diviner targeted ⑤

Targeting of specific sites at night (when temperature contrast between rocks and regolith is highest) with high temporal resolution will reveal important differences in thermal properties of key geologic features.

Diviner off-nadir ⑤

Off-nadir targeted and global observations by Diviner will constrain the phase angle-dependence of infrared emissions, making the Moon a benchmark for thermal studies of small bodies.

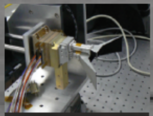
Diviner eclipse ⑤

Diviner observations during lunar eclipses isolate the properties of the top mm of the regolith, compared to ~10cm from the diurnal cycle.

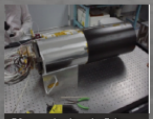
Twilight Campaign ⑤

Targeted multi-orbit Diviner observation sequences around the terminator with ~5-min local time resolution will isolate the properties of small rocks and the top few centimeters of regolith.

LROC data characterizes lunar geology with two narrow-angle cameras and a seven-color wide-angle camera.



7-band UV-Vis filters ~100-m pixel scale



50-cm pixel scale 5-km combined swath

LROC NAC Oblique ⑥

Highly oblique images acquired with large spacecraft slews will allow stratigraphic relationships to be more readily distinguished.

LROC NAC Stereo ⑥

Stereo image pairs acquired by slewing the spacecraft on adjacent orbits will enable derivation of high-res local topography of features of interest.

LROC Featured Mosaic ⑥

Mosaics of many NAC images acquired with uniform illumination over several consecutive orbits will enable consistent geologic analyses of complex sites larger than a single NAC pair.

LROC temporal pair ⑥

Repeat nadir imaging with near-identical illumination will make it possible to identify surface changes that occur in the intervening time (years).

LROC Photometric ⑥

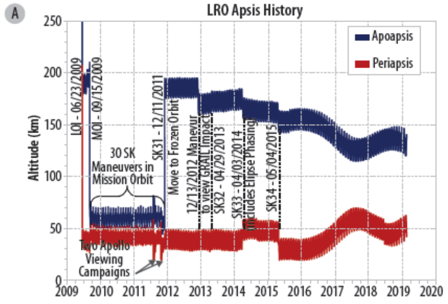
Repeat imaging of a site under a wide range of illumination and viewing geometries will provide critical information about its surface properties.

The LRO team will use these instruments to address new science questions in the ESM4

Scientific Objectives	Instrument Contribution	Ref. Section
Volatiles		
Diurnal Variation of Hydrogen How does hydration (OH, H_2O) vary on the surface and near-surface as a function of latitude and local time as well as geochemistry (mafic vs feldspathic)?	1 2	3.1.1
Lunar Exosphere What are the abundances of argon, oxygen, and H_2 in the lunar exosphere?	2	3.1.1
Space Environment What influence does the solar cycle exert on the exosphere, lunar water cycle, and radiation environment of the Moon?	1 2	3.1.1
Polar Craters and Surrounding Areas – Targeted Observations of Cabeus and Amundsen What controls the distribution of volatiles laterally and with depth within lunar polar crater permanently shadowed regions and surrounding regions?	2 4 5 6	3.1.2
Volcanism, Tectonism, and the Interior		
Rock Diversity and Mafic Rocks in the Moon's Primary Crust What is the distribution of mafic rock types of the primary crust? How do they vary in composition and with depth, and what is their context and association with "purest anorthosite"?	1 6	3.2.1
Investigating Non-Mare Magmatism and Volcanism What are the origins of domes, massifs, and ejecta of unusual evolved silicic compositions; and are the occurrences locally or regionally heterogeneous?	5 6	3.2.2
Refining the Source and Stratigraphy of Basaltic Flows within the Youngest Regions of Maria How were the final mare eruptions distributed in space and time? What is their compositional range and their implications for magma evolution?	4 6	3.2.3
Physical Properties and Composition of Pyroclastic Deposits: Do pyroclastic deposits preserve evidence of mantle heterogeneities as well as local, near-surface magmatic processes? How does regolith development differ for glassy pyroclastic deposits compared to typical mare basalt?	2 3 4 5 6	3.2.4
Detect Recent Tectonic Activity Is the Moon tectonically active in the present day? Is there detectable evidence of change induced by coseismic slip events on or in proximity to lobate thrust fault scarps? Are boulder fields associated with wrinkle ridges evidence of recent or ongoing tectonic activity in the maria?	4 5 6	3.2.5
Regolith and Impacts		
Quantify the Extent and Distribution of Impact Melt What is the abundance of impact melt in proximal and distal ejecta deposits of impact craters at all scales? What is the nature of putative basin melt and antipodal deposits?	4 5 6	3.3.1
Variations in the Recent Impact Flux How has the impact flux varied over the past billion years, and what are the implications for lunar chronology and for solar system dynamics?	4 5 6	3.3.2
Regolith Evolution and Space Weathering in the Late Copernican How, and how fast, are the albedo and texture of newly exposed materials altered at late Copernican craters?	2 3 5 6	3.3.3
The Reflected, Scattered, and Emitted Photometric Properties of the Lunar Regolith How does the small-scale structure of the lunar surface affect the photometric and thermal properties we observe? How do variations in the surface texture and thermophysical properties produce anomalous features, such as swirls and distal ejecta deposits?	2 3 4 5 6	3.3.4

1 CRaTER 2 LAMP 3 LOLA 4 Mini-RF 5 Diviner 6 LROC

A



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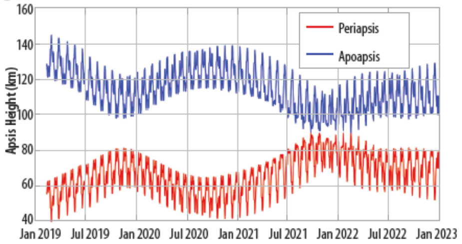

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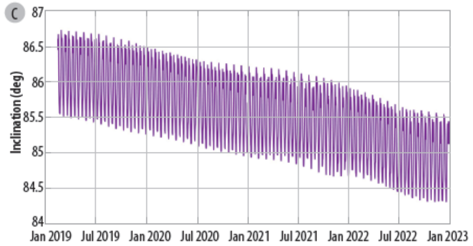

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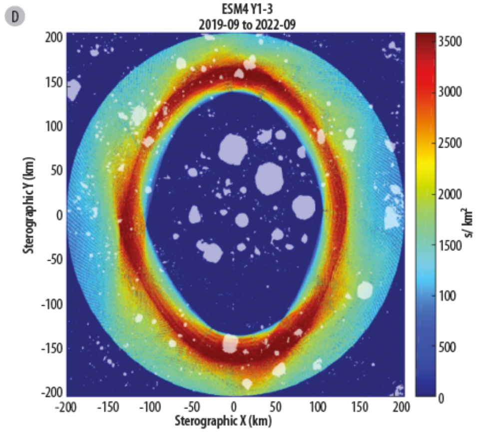


Quad Chart Template for ESM5

- (see separate file)

Title

Key Figure(s)

High Level Science Question(s)

- Point to Decadal/SCEM/Artemis SDT report

Investigation Science Question(s)

- What is/are the questions being answered

Instrument Observations (and how much data is required)

- Instrument 1: Observation/data needed
- Instrument 2: Observation/data needed (if necessary)

Anticipated Outcome(s)

Additional Information

Additional details:

Additional figures:

Additional references:

Draft Quad Chart Examples from ESM4

- Quads get turned into text for the proposal, each objective gets a short amount of page space (couple of paragraphs and maybe 1 figure)
- Similar objectives may be combined or grouped
- Weaker objectives will probably not make it to the final draft, each theme has room for 3 or 4 objectives (depending on length of each)
- Bibliographic notes are very helpful!
- Identify a quad chart POC (or lead) to help with follow up questions and writing & editing of proposal text.

Recent Tectonic Activity – Wrinkle Ridge Boulder Fields

ESM4

Science Questions:

- Are boulder fields associated with wrinkle ridges in mare basalts evidence of recent tectonic activity?

Pictures:

Mare ridge in Procellarum with boulder fields on its western flank

Integrated Measurements:

- LROC – Target wrinkle ridges with boulder fields and derive high resolution NAC DTMs
- Mini-RF – Target wrinkle ridges with boulder fields at S-band wavelengths using the Arecibo Observatory
- Earth-based radar – High resolution P-band images of boulder field wrinkle ridges

Anticipated Outcome:

- Determine if boulder fields are being exposed by down-slope movement of regolith on slopes of wrinkle ridges or if boulders being generated and exposed by recent, continued deformation of the mare basalts.

Investigating (Regional?) Subsurface Silicic Magmatism

ESM4

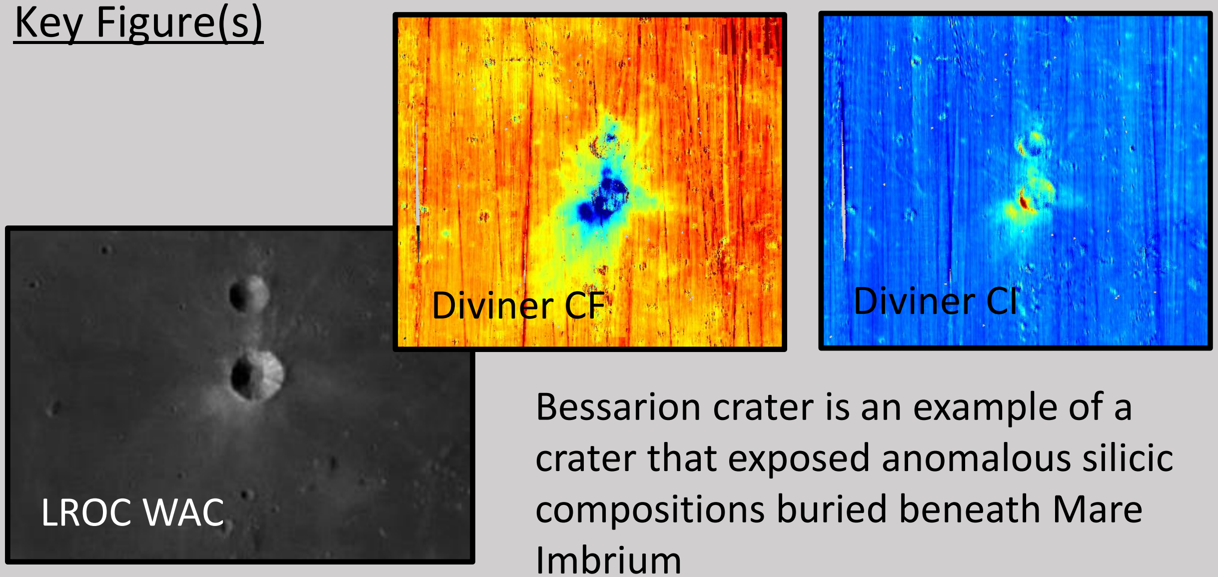
High Level Science Question(s)

- SCEM 3a, SCEM 3b & SCEM 3d
- SCEM 4a, 5d

Investigation Science Question(s)

- How are the compositions and morphologies of deposits in and around silicic anomaly craters (SACs) related to subsurface compositional variability?
- Is the the occurrence(s) locally or regionally heterogeneous?

Key Figure(s)



Bessarion crater is an example of a crater that exposed anomalous silicic compositions buried beneath Mare Imbrium

Instrument Observations

- LROC NAC Featured Mosaics and DTMS for prioritized subset of SACs; Measure photometric properties of SACs using NAC; Measure single scattering albedo using NAC
- Diviner: Targeted observations of under-sampled SACs under best lighting conditions (i.e. midday); targeted EPF observations of type-examples
- Mini-RF? LAMP? WAC Color?

Anticipated Outcome(s)

- Refined catalog of SACs
- Classification of SACs by geomorphology and regional context
- Shape files of SACs by classification
- Identification of depth of origin for SAC materials
- Improved understanding of possible regional structures related to subsurface silicic magmatism

Investigating Intermediate Silicic Massifs and Domes

ESM4

High Level Science Question(s)

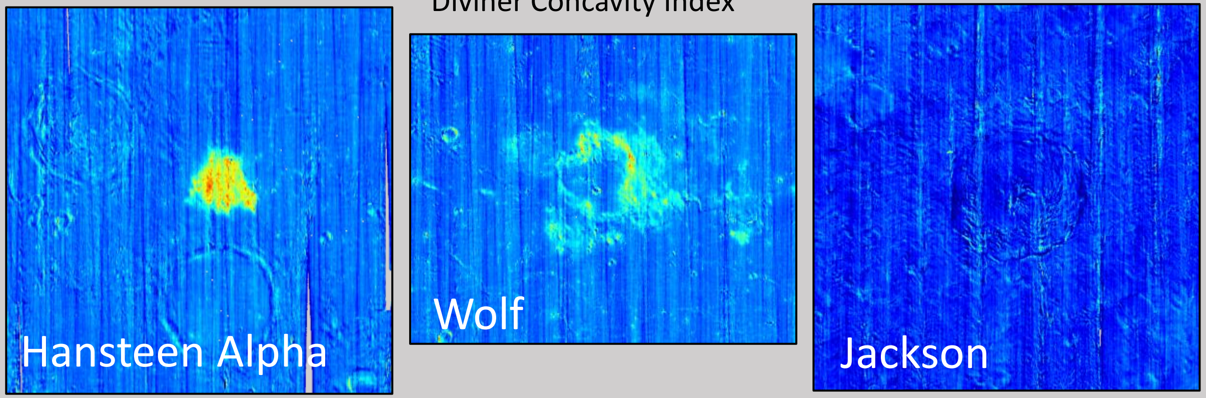
- SCEM 3a, SCEM 3b & SCEM 3d
- SCEM 4a, 5d

Investigation Science Question(s)

- How is the composition and morphology of intermediate silicic composition massifs and domes related to highly silicic features, subsurface plutonic deposits, and other lunar terranes?
- Is the the occurrence(s) locally or regionally heterogeneous?

Key Figure(s)

Diviner Concavity Index



The light toned massifs around Wolf crater appear to be an intermediate composition to highly silicic Hansteen Alpha and the highland crater Jackson

Instrument Observations

- LROC NAC Featured Mosaics and DTMS for identified intermediate silicic features; Measure photometric properties of using NAC; Measure single scattering albedo using NAC
- Diviner: Targeted observations of under-sampled intermediate silicic featrues under best lighting conditions (i.e. midday); targeted EPF observations of type-examples
- Mini-RF? LAMP? WAC Color?

Anticipated Outcome(s)

- Refined catalog of intermediate silicic massifs and domes
- Classification of intermediate silicic features by geomorphology and regional context
- Shape files of intermediate silicic features by classification
- Improved understanding of relationship with possible regional structures, highly silicic features, lunar terranes, and Apollo sampled sites

Pyroclastic deposits

ESM4

High Level Science Question(s)

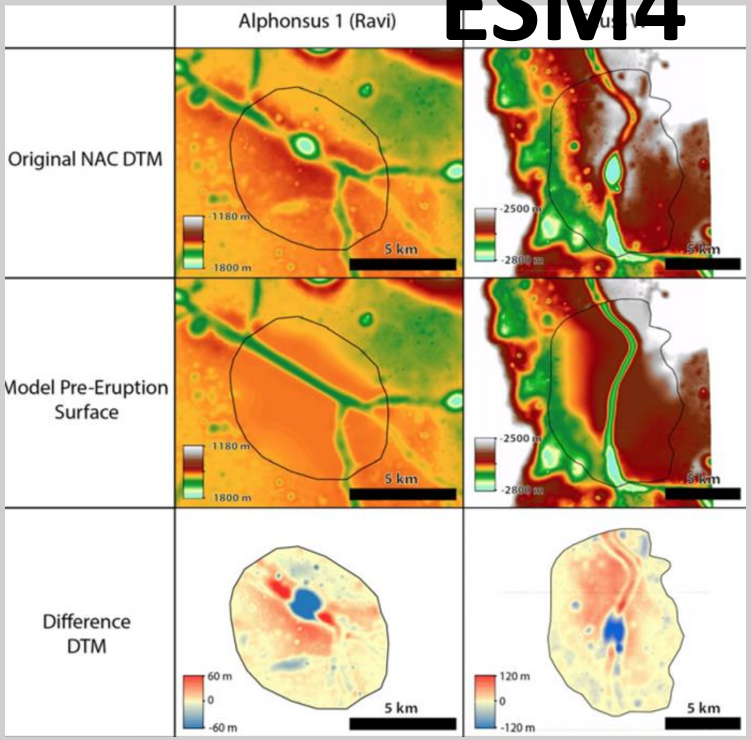
- SCEM 5c, 5d

Investigation Science Question(s)

- Investigate the range of pyroclastic deposit composition, eruption style, and material properties
- spatial distribution of pyro (use H parameter map/radar data to identify low TI areas that are likely pyro)

Key Figure(s)

LROC derived volume estimates of localized pyroclastic deposits



Instrument Observations

- LROC DTMS: DTMs of selected pyroclastic deposits to constrain their volume (target select endmember composition/glass abundance)
- LROC photometric observations: target the Miliken and Li volatile-rich deposits
- Diviner: increased Diviner temporal coverage [check if we need more coverage anywhere?]
- Mini-RF: radar variability between deposits?
- LAMP: no spectral inversion

Anticipated Outcome(s)

- Volume estimates of localized pyroclastic deposits, which can be compared to composition/glass/rock abundance/juvenile content estimates to constrain eruption style
- Estimates of Hapke parameters (function of grain size/shape, albedo) that would support other mission data products and models
- Thermophysical properties of pyroclastic fines
- Compositional information and thickness from Mini-RF

Additional Information

ESM4

Additional details

Undertake consistent measurements of each potential pyroclastic deposit identified in the literature. This includes expanding upon deposits listed within Gaddis [2003]. Constrain the full range of physical/compositional variations expressed in these deposits. Dating phyroclastics would be brilliant – but obviously very challenging!

Additional figures

References
Gaddis 2003

Maths

Exploring Crustal Rock Diversity

ESM4

High Level Science Question(s)

- SCEM 3a, 3b, 3c, & 3d

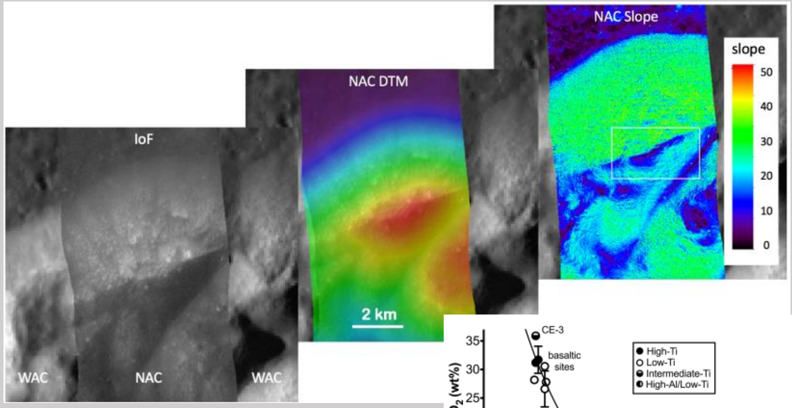
Investigation Science Question(s)

- ESM3 focused on PAN (Purest Anorthosite) for LROC NAC photometry investigations.
- For ESM4, focus on **mafic rocks** of the primary lunar crust (other than PAN).
- Where do mafic rocks occur, what is their context and with what other rock types do they occur? Specific focus on SPA. How vary with crustal thickness/depth?

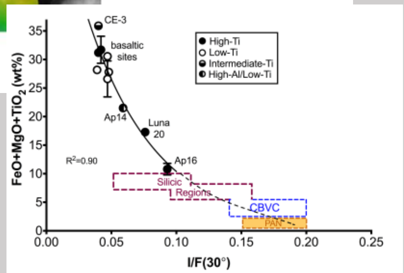
Key Figure(s)

New PAN site DTM and photometric pair (single scattering albedo) – mapping out PAN vs. more mafic exposures. Korolev (or Hertzsprung, pending availability of NAC DTM)

Partially complete non-PAN site



Isolate compositional effects on NAC albedo using NAC DTM data; compare to Diviner CF data, M^3 data, etc.



Instrument Observations

- LROC – NAC Geometric Stereo, Photometric Sequences (requiring slews) and NAC DTMs to characterize occurrences of mafic rocks based on spectral observations, e.g., Lemelin et al. (2015) JGR.
- LROC: Investigate variations in albedo derived from NAC photometry to investigate PAN occurrences at NAC (outcrop) scale.
- DIVINER – measure CF parameters of same locations investigated with NAC photometry.

Anticipated Outcome(s)

- Investigate the full variety of mafic crustal rocks (Px- and Olv-bearing) in key locations that juxtapose various rock types (central peaks, crater walls, basin ring uplift structures).
- By combining NAC-scale resolution images, terrain, and photometric data with Diviner and other spectral data (e.g., M^3), we will gain a better understanding of the occurrence and role of the more mafic rock types in the lunar highlands and the primordial lunar crust.

What does current global crustal elemental composition tell us about key lunar evolutionary processes? Developing next generation consolidated LRO Neutron/Proton/Gamma maps

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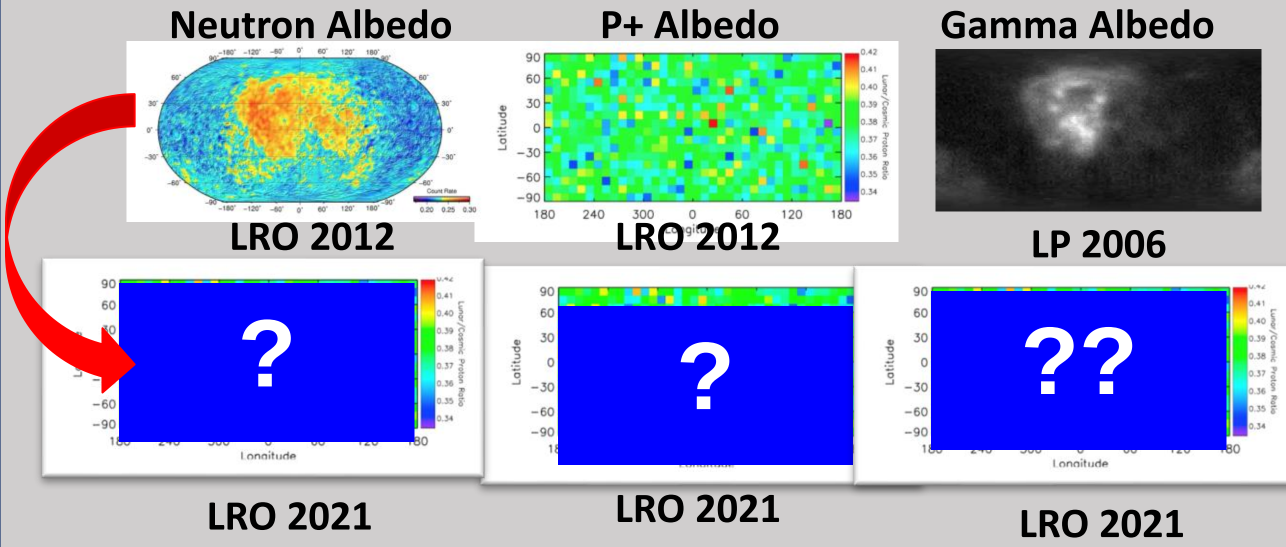
High Level Science Question(s)

- SCEM 3, ASM-SAT Concept 3 – Key Planetary Processes (Goal 3a – Determine the extent and composition of the primary feldspathic crust, KREEP layer, and other products of planetary differentiation)

Investigation Science Question(s)

- What is spatial distribution, on a global scale, of elemental composition of lunar crust?
- TBD…



Instrument Observations

- CRaTER: Proton albedo and potential for identifying gamma rays of geochemical interest; potential for refined modes during the elevated rates associated with solar proton events
- LEND: Neutron albedo (thermal, epithermal); Does LEND have possibility for gamma detection, too?
- All Others: Maps of crustal properties produced by all other LRO instruments

Anticipated Outcome(s)

- TBD improved spectral resolution of gamma rays at 150 km (TBD) spatial resolution, co-registered with complementary next-generation neutron and proton albedo maps
- Potential for contributing to a better understanding of the Mg value
- Potential for gamma rays to be used to identify hydrated regions (OH), to clarify contemporary neutron (“ring of fire”) and proton albedo signatures

ESM4

Additional Information

- Increase spectral resolution Maybe 50km/pixel
- How is this data better than LP
- Contribute to understanding the Mg number
- Could gamma rays be used to identify OH? Clarify the LEND data – use elemental data
- Elevated solar proton events – “new mode” to collect more data

What makes a good objective?

- Need new observations
- Don’t overpromise (considering operational limitations, timeframe, orbits, or aging hardware)
- Timely and compelling
- Supported by multiple instruments

LRO-wide theme meeting

May 20 (Thurs) at noon to 2 pm EDT
- **11 am - 1 pm CDT**
- **10 am to noon MDT**
- **9 am to 11 am PDT (MST)**

Objectives of the meeting:
- What new observations are needed in ESM5?
- Are there any earlier objectives or discoveries that need follow ups in ESM5?
- Bring any Quad Chart drafts or ideas
- Look for any cross-instrument investigations or synergies
- Begin refining towards a solid set of ESM5 objectives that will carry forward

(there will likely be an additional follow up PSWG meeting to identify/discuss and refine the quads)

(also, in the writing phase, some quads may not be included in the proposal text because there are just too many objectives and not enough space to include them all)

What you can start to do now to prepare

- Evaluate ESM4 progress, document bibliographic notes (goes into a summary section of proposal)
- Quantify why, where, & what type of new observations are needed (e.g., coverage maps, SNR, etc.)
- Consider limitations of operations, fuel usage, orbits, etc.
- Brainstorming, draft quad charts
  - Noah: Targeted observations of key mare flows for chronology?
  - Noah: Polar plains deposits? Polar volcanism or a record of impact basins?
  - Follow up on ESM4 (or earlier) progress?
  - New opportunities or discoveries at large (e.g., landed missions)?