Program
New Views of the Moon 2

May 24–26, 2016 • Houston, Texas

Institutional Support

Universities Space Research Association (USRA)
Lunar and Planetary Institute (LPI)

Conveners

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*University of Notre Dame*

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Abstracts for this workshop are available in electronic format via the workshop website at www.hou.usra.edu/meetings/newviews2016/ and can be cited as Author A. B. and Author C. D. (2016) Title of abstract. In *New Views of the Moon 2*, Abstract #XXXX.

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Lunar and Planetary Institute 3600 Bay Area Boulevard Houston TX 77058-1113
Technical Guide to Sessions

**Tuesday, May 24, 2016**

8:20 a.m.  Lecture Hall  New Views of the Moon 2 Plenary: Chapter Topic Summaries
1:30 p.m.  Lecture Hall  Endogenous and Surface Volatiles
1:30 p.m.  Hess Room  Origin of the Earth Moon System and Primordial Differentiation
1:30 p.m.  Berkners  Impact Chronology and the Cratering Process

**Wednesday, May 25, 2016**

8:30 a.m.  Lecture Hall  Magmatic Evolution, Volcanism, Lunar Crust, and Lunar Meteorites
8:30 a.m.  Hess Room  Lunar Magnetism and Surface Processes
1:30 p.m.  Lecture Hall  Lunar Exosphere and Space Weathering
1:30 p.m.  Hess Room  Lunar Interior and Tectonics
3:15 p.m.  Hess Room  Development of the Moon and Cislunar Space
5:30 p.m.  Great Room  Poster Session

**Thursday, May 26, 2016**

8:30 a.m.  Lecture Hall  Workshop Session Summaries
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Tuesday, May 24, 2016

NEW VIEWS OF THE MOON 2 PLENARY: CHAPTER TOPIC SUMMARIES
8:20 a.m. Lecture Hall

Chairs: Clive Neal
Charles “Chip” Shearer

8:20 a.m. Neal C. *
Welcome, Logistics, Opening Remarks, Goals of the Workshop

8:30 a.m. Canup R. Righter K. *
Topic Summary: Origin of the Moon and Earth System

8:40 a.m. Gaffney A. * Warren P.
Topic Summary: Magmatic Evolution I - Lunar Magma Ocean

8:50 a.m. Neal C. Shearer C. *
Topic Summary: Magmatic Evolution II - Subsequent Magmatism

9:00 a.m. Head J. W. * Hiesinger H.
Topic Summary: Volcanic Features and Processes

9:10 a.m. Bottke W. Cohen B. *
Topic Summary: Impact Chronology

9:20 a.m. Melosh J. * Osinski G.
Topic Summary: Cratering Processes

9:30 a.m. Weber R. * Andrews-Hanna J.
Topic Summary: Constitution and Structure of the Lunar Interior

9:40 a.m. Korotev R. Zeigler R. *
Topic Summary: The Contribution of Lunar Meteorites

9:50 a.m. Pieters C. * Elardo S.
Topic Summary: Evolution of the Lunar Crust

10:00 a.m. Break

10:15 a.m. Wieczorek M. Weiss B. *
Topic Summary: Lunar Magnetism

10:25 a.m. Nahm A. *
Topic Summary: Lunar Tectonics

10:35 a.m. McCubbin F. Liu Y. *
Topic Summary: Endogenous Lunar Volatiles

10:45 a.m. Hurley D. * Siegler M.
Topic Summary: Surface Lunar Volatiles

10:55 a.m. Farrell W. * Halekas J.
Topic Summary: Lunar Exosphere
11:05 a.m. Noble S. * Denevi B.
Topic Summary: Space Weathering and Exosphere-Surface Interactions

11:15 a.m. Plescia J. * Robinson M.
Topic Summary: Lunar Surface Processes

11:25 a.m. Sanders G. * Spudis P.
Topic Summary: Development of the Moon

11:35 a.m. Lawrence S. *
Topic Summary: Recent Lunar Missions
ENDOGENOUS AND SURFACE VOLATILES
1:30 p.m. Lecture Hall

Chairs: Dana Hurley
        Yang Liu

1:30 p.m. Hurley D. M. * Siegler M. A.
Lunar Surface Volatiles [#6046]
This is a broad draft outline for the surface volatiles chapter that we can use to identify holes, overlaps, and contributors.

1:45 p.m. McCubbin F. M. *
Endogenous Lunar Volatiles: Insights Into the Abundances of Volatiles in the Moon from Lunar Apatite [#6090]
This abstract briefly summarizes the utility of lunar apatite in understanding abundances of volatiles (F, Cl, H) in the Moon.

2:00 p.m. Robinson K. L. * Barnes J. J. Anand M. Taylor G. J. Franchi I. A.
Volatiles in Evolved Lunar Rocks: Connecting Water and Chlorine [#6081]
Apollo 15 quartz monzodiorites have the lowest D/H ratios reported thus far in lunar apatite. New Cl isotope data suggests they obtained H and Cl from different sources.

2:15 p.m. Treiman A. H. * Boyce J. W. Greenwood J. P. Eiler J. M. Gross J. Guan Y. Ma C. Stolper E. M.
D-Poor Hydrogen in Lunar Mare Basalts Assimilated from Lunar Regolith [#6041]
D/H in apatites in mare basalts decreases with Fe-Mg homogenization of their pyroxenes. This suggests that the low D/H represents hydrogen from lunar regolith, which masquerading as an igneous component.

2:30 p.m. Liu Y. * Guan Y. Chen Y. Taylor L. A.
Impact Melt (Agglutinitic Glass) of Lunar Regolith: A “Volatile Recorder” of the Lunar Surface [#6010]
We report volatiles in impact melts of lunar soils and ancient regolith breccias.

2:45 p.m. Siegler M. A. * Miller E. Lucey P. G. Hayne P. O. Neumann G. A. Paige D. A. Greenhagen B. T.
Evidence for Surface Volatiles on the Moon and Mercury: A Planetary Comparison [#6089]
We evaluate evidence from UV and near infrared reflectance data for surface volatiles on the Moon and Mercury. Comparison of these planetary bodies leads to new understanding (and questions) regarding water in the inner solar system.

3:00 p.m. Break

The LCROSS Plume as Observed by LRO/LAMP [#6071]
The LCROSS impact on the Moon revealed much about the composition of the volatiles in lunar PSRs.
LRO Lyman Alpha Mapping Project (LAMP) Far-UV Maps: A New View of the Moon

The LRO-LAMP investigation has provided a unique view at far-UV wavelengths, and uses an innovative way to measure surface reflectance within permanently shaded regions in order to constrain the water frost abundance at the surface.

The Lunar Far-UV Albedo: Indicator of Hydration and Space Weathering

The ultraviolet, and particularly the far-ultraviolet as studied using LRO LAMP, is useful for understanding dayside, non-polar hydration as well as space-weathering effects. The depths sensed are complementary to those studied at longer wavelengths.

Mini-RF bistatic observations of the Moon show an opposition surge for portions of the floor of Cabeus that are not in permanent shadow. The unique nature of the response may indicate the presence of near-surface deposits of water ice.


4:15 p.m. Monitored by Session Chairs

3-Minute Lightning Round of New Data and Perspectives

4:30 p.m. DISCUSSION
Chairs: Kevin Righter
Paul Warren

1:30 p.m. Righter K. * Canup R. M.
Testing and Resilience of the Impact Origin of the Moon [#6080]
We summarize the geochemical and physical aspects of the Earth and Moon and discuss the implications for lunar origin models.

1:45 p.m. Warren P. H. * Siegler M. A. Greenwood J. P. Kohl I. E. Young E. D.
The Bulk Composition of the Moon: Merely Earth-Like, or Earth-Lite? [#6079]
New heat flow, isotopic and other data constrain the bulk composition of the Moon to be closely similar to that of the bulk silicate Earth.

2:00 p.m. Draper D. S. * Rapp J. F. Elardo S. M. Shearer C. K. Jr. Neal C. R.
Experimental Simulations of Lunar Magma Ocean Crystallization: The Plot (But Not the Crust) Thickens [#6020]
If we think we know/How lunar magma ocean worked/We must think again.

2:15 p.m. Steenstra E. S. * van Westrenen W.
Review of Geochemical Constraints on the Formation and Composition of the Lunar Core [#6039]
Siderophile element depletions in the lunar mantle are an important tool to investigate the PT conditions during lunar core formation. Here, we summarize recent work that studied the PT conditions during core formation and lunar core composition.

Mare Frigoris: Window Into the Evolution of the Lunar Mantle [#6024]
Mare Frigoris sat on a crack. Mare Frigoris got covered in KREEP. All the king’s horses and all the king’s men couldn’t make Frigoris erupt anything besides high-Al basalts.

2:45 p.m. Klima R. L. *
Assessing the Compositional Diversity of Intrusive Rocks on the Moon Using Near-Infrared Spectroscopic Data [#6077]
Near-infrared, gamma-ray and neutron, and thermal-infrared observations have advanced our understanding of the compositional diversity, including minor components such as thorium and hydroxyl, of intrusive lithologies exposed on the lunar surface.

3:00 p.m. Break

3:15 p.m. Prissel T. C. *
On the Provenance and Distribution of the Lunar Highlands Magnesian-Suite [#6011]
The distribution and petrogenesis of the lunar highlands magnesian-suite is discussed in light of recent experimental and orbital data.

3:30 p.m. Monitored by Session Chairs
3-Minute Lightning Round of New Data and Perspectives

3:45 p.m. DISCUSSION
IMPACT CHRONOLOGY AND THE CRATERING PROCESS

1:30 p.m. Berkners

**Chairs:**
- Harald Hiesinger
- Barbara Cohen

**1:30 p.m.**

*Remote Sensing Constraints on Lunar Chronology [#6040]*

Moon rocks breaking down, indicating impact flux. Faster than we thought.

**1:45 p.m.**
Hiesinger H. * van der Bogert C. H. Pasckert J. H. Plescia J. B. Robinson M. S.

*Impact Chronology of the Moon — Results from the Lunar Reconnaissance Orbiter Camera (LROC) [#6036]*

We present absolute model ages (AMAs) based on crater size-frequency distribution (CSFD) measurements for Copernicus, Tycho, North Ray, Cone, and Autolycus craters to test and possibly improve the lunar cratering chronology.

**2:00 p.m.**
Dhingra D. *

*Remote Mineralogical Assessment of Impact Melt Deposits: Their Role in Crustal Compositional Diversity and Evolution [#6095]*

Mineralogical diversity of the lunar crust has been extensively studied using samples and through remote sensing.

**2:15 p.m.**
Zellner N. E. B. * Delano J. W.

*Lunar Impact Glasses as Clues to the Moon’s Bombardment History [#6045]*

Specific lunar impact glasses can elucidate details of the Moon’s bombardment history.

**2:30 p.m.**

*Factors Affecting Crater Size-Frequency Distribution Measurements: Insights Supported by the LRO Mission [#6015]*

CSFD measurements are affected by illumination angle, count area size/slope, secondary cratering, target property effects, and differential degradation. Investigations using LRO data have made progress characterizing and quantifying these factors.

**2:45 p.m.**
Zanetti M. * Jolliff B. van der Bogert C. H. Hiesinger H. Plescia J. Artemieva N.

*Self-Secondary Crater Populations on Copernican Continuous Ejecta Blankets [#6019]*

Self-secondary craters (a population of craters formed on continuous ejecta deposits by fragments from the parent crater) may account for melt/ejecta CSFD discrepancies, and may imply inner Solar System cratering flux estimates are overestimated.

**3:00 p.m.**
Break

**3:15 p.m.**
Stickle A. M. * Patterson G. W. Cahill J. T. S. Bussey D. B. J.

*Radar Scattering Properties of Young Lunar Crater Ejecta Blankets Using Mini-RF [#6058]*

Mini-Rf data provides a powerful way to examine young lunar crater ejecta. Radial profiles of radar returns outward from the crater rim provide insights into ejecta emplacement, crater degradation, and near surface stratigraphy.

**3:30 p.m.**
Mahanti P. * Robinson M. S.

*On the Small Depth-Diameter Ratios of Small Lunar Craters [#6088]*

Small lunar craters (SLC; D<250 m) have simple shapes but much lower d/D value compared to larger (D > 1 km) simple craters - target strength properties dictate their shapes.
The Moon as an Archive of Small Body Migration in the Solar System [6086]
We discuss how lunar samples provide evidence of different impactor species striking the Moon through time, and implications for understanding small body migration in the inner solar system.

4:00 p.m. Kring D. A. *
A Summary of Geological, Geochemical, Petrological, and Isotopic Evidence of Impactor Sources [6068]
A diverse array of impactor signatures suggests asteroids have always dominated comets during the evolution of the Moon.

4:15 p.m. Jolliff B. L. * Petro N. E. Shearer C. K. Pieters C. M. Head J. W.
Recent Mission Datasets Shed New Light on the Character and Fate of the South Pole-Aitken Basin Impact Melt Sheet [6054]
Characterizing and accessing impact melt rocks of the South Pole-Aitken basin is of high priority for understanding the history of the Moon, the giant basin forming process, and establishing the chronology of giant impacts in the early solar system.

4:30 p.m. Monitored by Session Chair
3-Minute Lightning Round of New Data and Perspectives

4:45 p.m. DISCUSSION
Wednesday, May 25, 2016
MAGMATIC EVOLUTION, VOLCANISM, LUNAR CRUST, AND LUNAR METEORITES
8:30 a.m. Lecture Hall

Chairs: Carle Pieters
        James Head III

8:30 a.m. Shearer C. K. * Neal C. R. Gaddis L. R. Jolliff B. L. Bell A. S.

Magmatic Evolution 2. A New View of Post-Differentiation Magmatism [#6003]
Numerous missions, new state-of-the-art sample measurements, new lunar samples (meteorites), and sophisticated modeling have provided a new perspective on lunar magmatism. We use these new observations to expand our understanding of lunar magmatism.

8:45 a.m. Head J. W. III * Wilson L.

Mare Basalt Volcanism: Generation, Ascent, Eruption, and History of Emplacement of Secondary Crust on the Moon [#6007]
Theoretical analyses of the generation, ascent, intrusion and eruption of basaltic magma provides new insight into magma source depths, supply processes, transport and emplacement mechanisms (dike intrusions, effusive and explosive eruptions).

9:00 a.m. Morota T. Haruyama J. * Ohtake M. Ishihara Y. Cho Y. Kato S.

Hiesinger H. LISM Working Group
Timing and Characteristics of Mare Volcanism on the Farside and in the Central Region of the PKT Revealed by Kaguya [#6044]
Unraveling the timing of mare volcanism on the Moon is essential for understanding its thermal evolution. Using Kaguya data, we have performed crater counting on mare basalts on the farside and in the PKT. Here we review our findings.


Silicic Volcanism Identified by the Diviner Lunar Radiometer Experiment [#6043]
The Diviner Lunar Radiometer Experiment on the Lunar Reconnaissance Orbiter has mapped and characterized a number of silicic volcanic constructs on the lunar surface. Here, we summarize Diviner's contributions to our understanding of these features.


Felsic Volcanics on the Moon [#6051]
LRO data sets have been used to characterize sites of red-spot volcanism on the Moon, confirming that they are composed of silica-rich materials and establishing key morphometric parameters including shape, slopes, boulder contents, and photometry.

9:45 a.m. Pieters C. M. * Elardo S.

Lunar Crustal Evolution: What Do We See? [#6018]
Topics are provided for discussion of lunar crustal evolution.

10:00 a.m. Break

10:15 a.m. Elardo S. M. * Pieters C. M.

The Evolution of the Lunar Crust: The View from Samples, Experiments, and Geochemistry [#6074]
This abstract presents a very brief summary of some of the major areas of research regarding the lunar crust from a laboratory-based science perspective in order to fuel discussion and planning for the evolution of the lunar crust chapter.
10:30 a.m. Ohtake M. * Yamamoto S. Uemoto K.
*Composition of the Lunar Highland Crust and Mantle and Its Implications* [#6038]
Recent remote sensing data suggest that extremely pure anorthosite (PAN) layer is a main component of the lunar highland crust and presence of crustal material with higher Mg# on the farside than the nearside.

10:45 a.m. Magna T. * Neal C. R.
*Non-Traditional Stable Isotope Constraints on the Evolution of Moon* [#6035]
Non-traditional stable isotope systems provide constraints on the origin and evolution of the Moon. They have gained importance in disentangling the processes of the lunar differentiation, volatile loss, and hydrous vs. anhydrous nature of the Moon.

11:00 a.m. Joy K. H. * Curran N. A. Pernet-Fisher J. F. Arai T.
*Lunar Meteorites: New Insights into the Geological History of the Moon* [#6047]
We outline how studies of lunar meteorites have brought new insights to the Moon’s lithological diversity and geological history.

11:15 a.m. Monitored by Session Chairs
*3-Minute Lightning Round of New Data and Perspectives*

11:30 a.m. DISCUSSION
LUNAR MAGNETISM AND SURFACE PROCESSES

Wednesday, May 25, 2016

Chairs: Georgiana Kramer
        Jeff Plescia

8:30 a.m. Kramer G. Y. *

*The Formation of Lunar Swirls: International Investigations Reach Consensus [#6025]*

The man in the moon looked out of the moon and this is what he said, “Tis time that, we all agree, swirls are regions that are protected from solar wind weathering by the magnetic anomalies.”

8:45 a.m. Fa W. *

*The Moon’s Regolith: Stratigraphy and Evolution [#6013]*

New results about regolith thickness and accumulation rate are estimated from new data sets from recent lunar missions.

9:00 a.m. Denevi B. W. * Robinson M. S. Sato H. Boyd A. K.

*LROC Wide Angle Camera Ultraviolet-Visible Images of the Moon [#6064]*

LROC WAC ultraviolet through visible 7-band observations of the lunar surface have provided insights into space weathering and the distribution and nature of lunar swirls.


*New Global Observations of Lunar Regolith Maturity in the Far-Ultraviolet [#6060]*

Examination of lunar swirls, photometric anomalies, and maturity with global Lyman-alpha albedo data.

9:30 a.m. Paige D. A. *

*New Infrared Views of the Moon from Diviner [#6094]*

The Diviner Lunar Radiometer Experiment has mapped the lunar surface for almost seven years, acquiring a dataset of unprecedented quality, detail, and coverage, providing many new infrared views of the Moon and its history.

9:45 a.m. Plescia J. B. *

*Characteristics and Evolution of the Lunar Regolith [#6083]*

Our understanding of the properties of the lunar regolith, its formation, and the role it plays in the production, transport and storage of volatiles has changed dramatically over the last decade.

10:00 a.m. Break

10:15 a.m. Clegg-Watkins R. N. * Jolliff B. L.

*New Insights on Lunar Surface Properties from the Perspective of LRO NAC Photometry [#6028]*

The use of NAC photometry has allowed us to gain new insights into physical changes of regolith at spacecraft landing sites, and to determine correlations between composition and reflectance that can be applied to areas of unusual composition.

10:30 a.m. Needham D. H. * Bleacher J. E. Garry W. B. Petro N. E. Whelley P. L. Young K. E.

*Lava Flow Emplacement and Related Surface Features on the Moon [#6048]*

Observations of new volcanic features and of finer-scaled details of known features have shown the Moon to be more complex than previously considered; thus, these features should be incorporated into a volcanism chapter in New Views of the Moon 2.
10:45 a.m. Speyerer E. J. * Povilaitis R. Z. Robinson M. S. Thomas P. C. Wagner R. V.
*Dynamic Moon: New Impacts and Contemporary Surface Changes [6082]*
Before and after image pairs acquired by the Lunar Reconnaissance Orbiter Camera enable the identification of new impact craters and secondary surface changes revealing new insight into the cratering process and regolith gardening.

11:00 a.m. Monitored by Session Chairs
*3-Minute Lightning Round of New Data and Perspectives*

11:15 a.m. DISCUSSION
LUNAR EXOSPHERE AND SPACE WEATHERING
1:30 p.m. Lecture Hall

**Chairs:** Brett Denevi
William Farrell

1:30 p.m. Horanyi M. * Szalay J. Gruen E. Glenar D. Wang X. Zakharov A.
The Dust Environment of the Moon [6005]
We will briefly review the history of the observations of the lunar dust environment, but mainly focus on the results of the LADEE mission, and the recent laboratory results on the charging and mobilization of dust particles on regolith surfaces.

The Lunar Gas and Dust Exosphere as Revealed by the LADEE Mission [6022]
The Lunar Atmosphere and Dust Environment Explorer mission acquired unprecedented coverage of the composition, structure and variability of the Moon’s gas and dust exosphere.

2:00 p.m. Farrell W. M. * Halekas J. S. Killen R. M. Collier M. R. Hurley D. H. Colaprete A. Elphic R. C. Mahaffy P. R. Benna M.
Astounding New Aspects to the Lunar Exosphere [6052]
We describe very exciting advances in exospheric research since the last NVM book in 2006.

2:15 p.m. Sarants M. * Colaprete A. Szalay J. McLain J. L. Wooden D. H. Poppe A.
How Exospheric Sodium and Potassium Migrate on the Moon: The View from LADEE [6053]
LADEE data and models enable us to quantify in unprecedented detail how Na and K gases are generated and how they migrate on the surface of the Moon.

2:30 p.m. Fatemi S. Poppe A. R. Halekas J. S. Delory G. T. Holmstrom M. Farrell W. M. *
Kinetic Modeling of the Moon-Solar Wind Plasma Interaction [6072]
We use a three-dimensional self-consistent hybrid model of plasma (kinetic ions, fluid electrons) to study solar wind plasma interaction with the Moon. We have studied lunar wake, interaction with crustal fields, and lunar interior with our model.

2:45 p.m. Kramer G. Y. *
Space Weathering Dominated by Solar Wind at Earth-Moon Distance [6026]
Micrometeorites and solar wind ions are largely responsible for weathering the surfaces of airless bodies. But which dominates? The lunar swirls demonstrate the dominance of the solar wind on space weathering, at least at the Earth-Moon distance.

3:00 p.m. Break

3:15 p.m. Keller L. P. * Zhang S.
Space Weathering Rates in Lunar Soils [6030]
We use solar flare track densities in individual lunar soil grains to constrain the rate of space weathering.

Space Weathering in the Thermal Infrared: Lessons from LRO Diviner [6063]
Before LRO, it was suggested that TIR spectroscopy would be less susceptible to the effects of space weathering. Diviner has shown the TIR is affected by space weathering. We will discuss this unanticipated space weathering dependence.
3:45 p.m. Cahill J. T. S. * Lawrence D. J. Delen O.  Stickle A. M.  Raney R. K.  Patterson G. W.  Greenhagen B. T.  
*Examining Lunar Regolith Maturation at a Deeper Level [#6076]*  
Taking a look at lunar non-polar regolith maturation across data sets.

4:00 p.m. Monitored by Session Chairs  
*3-Minute Lightning Round of New Data and Perspectives*

4:15 p.m. DISCUSSION
The GRAIL mission provided new constraints on the Moon’s thermal evolution, including the abundance of radioactive elements, the extent of early lunar radius change, volume of early cryptomagmatism, and thickness of a low conductivity megaregolith.

We infer the likely lunar interior structures by solving the inverse problem using the observed mass, moment of inertia, and tidal Love numbers $k_2$ and $h_2$ as constraints.

Geophysical evidence does not support the existence of a Procellarum basin. The thin crust is a result of primordial long-wavelength variations. Topography data reveals no evidence for a basin rim. Gravity reveals magmatic-tectonic structures.

This is review of the studies based on subsurface radar sounding of the Moon by SELENE (Kaguya) Lunar Radar Sounder (LRS). This is review of the studies based on subsurface radar sounding of the Moon by SELENE. The paleoregolith layers found by SELENE indicates the subsurface lava boundaries, and enable us to perform studies on the volcanism and tectonics in the maria.

New Insights into Lunar True Polar Wander

Relative ages of graben and wrinkle ridges on the nearside of the Moon reveal contradictory relationships.

Relative ages of graben and wrinkle ridges on the nearside of the Moon reveal contradictory relationships.
The New View of the Moon: Redefining Future Surface Exploration Using the Lunar Reconnaissance Orbiter

The profound importance of LRO past and future observations to future Exploration is discussed, as well as the best destinations for surface exploration to achieve core planetary science and human exploration goals.

Lunar Holes and Their Associating Subsurface Caverns: From SELENE (Kaguya) to UZUME

We present a summary of lunar holes and associated caverns. Furthermore, we also introduce the project Unprecedented Zipangu Underworld of the Moon/Mars Exploration (UZUME) to explore the holes and caverns.

A Review of Terrestrial Analogs for the Moon

The purpose of this review will be to describe terrestrial geologic analogs that have been used to study lunar geologic processes including: volcanism, impact cratering, structural, and surface processes.

The Use of Field Portable Instrumentation in Preparing for the Next Generation of Lunar Surface Exploration

While Apollo sample collection was enabled by basic sampling tools, in situ analytical instrumentation is now being developed for fieldwork. It is critical that the lunar community develop this technology for the future of lunar surface exploration.

Preparing Human Explorers for Surface Science Operations on the Moon

If the Moon becomes a destination for human operations it is critical that the developing architecture and training programs evolve along with our scientific knowledge.

3-Minute Lightning Round of New Data and Perspectives

DISCUSSION

Global Assessment of Pure Crystalline Plagioclase Across the Moon: Implications for the Evolution of the Primary Crust [#6017]
Global characterization of pure crystalline plagioclase across the Moon using Moon Mineralogy Mapper (M^3) and Diviner Lunar Radiometer observations.

Ling Z. C. Jolliff B. L.

New Views of Lunar Compositions and Rock Types Revealed by Spectroscopic Data from Chang’è-1 and Chang’è-3 Missions [#6057]
Global hyperspectral imaging datasets of Chang’e-1 IIM have brought new science returns of lunar surface compositions and rock types. The in-situ spectroscopic measurements by Yutu yielded compositional constraints of a new type of basaltic rock.

Pernet-Fisher J. F. Joy K. H.

Developments in Our Understanding of Lunar Crustal Formation and Evolution [#6049]
Our recent understanding of lunar crustal formation has developed through the combination of analytical advances, and the increased availability of anorthositic material sampled as clasts within meteorite regolith breccias.

Weber R. C. Nahm A. L. Yanites B. Schmerr N.

Mass Wasting on the Moon: Implications for Seismicity [#6009]
Here we investigate the regional effects of lunar seismicity with the goal of determining whether surface features such as landslides and boulder trails on the Moon are triggered by fault motion.

Yamamoto S. Nakamura R. Matsunaga T. Ishihara Y. Ohtake M. Haruyama J.

Global Distributions of Large Exposed Areas of Lunar Major Minerals and Its Implications [#6034]
We review the global distributions of large exposure areas of the various lunar major minerals revealed by the recent remote-sensing hyperspectral observations, and discuss possible implications for lunar crust and mantle.

Matsumoto K. Harada Y. Ishihara Y. Haruyama J.

Low-Velocity and Low-Viscosity Zone at the Lowermost Mantle of the Moon [#6037]
Tidal response of the Moon indicates the existence of a low-velocity/viscosity zone at the base of the mantle which needs to be thicker than 170 km to fit observation. The inferred density of the layer suggests lunar magmas with high TiO2 content.

Lemelin M. Lucey P. G. Gaddis L. R. Miljković K. Ohtake M.

The Composition of the Lunar Crust: An In-Depth Remote Sensing View [#6055]
We conduct a quantitative survey of the mineralogy of the innermost ring of 13 impact basins, constrain the depth of origin of the material exposed on these rings, and study the composition of the lunar crust with depth.

Fa W. Cai Y.

Mini-RF PSR Observations: Water Ice or Rocks? [#6014]
The enhanced CPRs in the interior of anomalous craters in Mini-RF images are most probably caused by meter-scale rocks, suggesting that ice deposits, if present, are not the only physical agent causing the enhanced CPR.

Barnes J. J. Tartese R. Anand M. McCubbin F. M. Neal C. R. Franchi I. A.

The Chlorine Isotopic Composition of Lunar urKREEP [#6091]
We have measured the Cl isotopic composition of apatite in a range of lunar rocks using NanoSIMS. We find a correlation between Cl isotopes and bulk rock chemistry which strongly suggesting urKREEP was characterized by heavy Cl.
Recent Radar Imaging Observations of the Moon: New Views of Pyrocastics, Mare Basalts, Impact Crater Deposits, and the Lunar Subsurface

In the last decade, radars with different wavelengths have provided polarimetric imaging of the lunar surface. These data sets have yielded new information about topics such as pyroclastics, mare basalts, cryptomare, and impact ejecta and melt flows.

Global Regolith Properties from Diviner Thermal Infrared Measurements

We used Diviner infrared data to map regolith properties globally. These maps reveal a variety of interesting features with distinct thermophysical properties, opening a fruitful area for future study.

Impacts Large and Small: Modification of the Lunar Regolith Observed by LRO Diviner

Diviner reflectance and infrared observations reveal how impact craters from meter-scale to basin-scale modify the thermophysical and radiative properties of the regolith globally.

The NWA 773 Clan: A Unique Group of Lunar Meteorites

The NWA 773 Clan is a unique group of lunar meteorites that represents an intrusive and extrusive magmatic system on the Moon, spanning from early, magnesian lithologies, to late, ferroan lithologies.

Lunar Atmospheric Campaigns of the UV Spectrograph LAMP on Board of the Lunar Reconnaissance Orbiter

We present a summary of the LAMP atmospheric campaigns performed so far, to study the composition and the properties of the lunar atmosphere, as well as its temporal variations.

New Views of Southern Nearside Lunar Highland Composition from the Chandrayaan-1 X-ray Spectrometer (C1XS)

Lunar surface elemental abundances - Results from Chandrayaan-1 X-ray Spectrometer (C1XS) on-board Chandrayaan-1 and goals for the upcoming Chandrayaan-2 Large Area Soft X-ray Spectrometer (CLASS) experiment on-board Chandrayaan-2.
Thursday, May 26, 2016
WORKSHOP SESSION SUMMARIES
8:30 a.m. Lecture Hall

Chairs: Clive Neal
       Lisa Gaddis

8:30 a.m. Liu Y. * Hurley D. *
          Volatiles

8:45 a.m. Warren P. * Righter K. *
          Origin and Differentiation

9:00 a.m. Hiesinger H. * Cohen B. *
          Impacts and Cratering

9:15 a.m. Head J. * Pieters C. *
          Magmatic Evolution, Volcanism, Lunar Crust, and Lunar Meteorites

9:30 a.m. Kramer G. * Plescia J. *
          Lunar Magnetism and Surface Processes

9:45 a.m. Denevi B. * Farrell W. *
          Lunar Exosphere and Space Weathering

10:00 a.m. Weber R. * Nahm A. *
           Lunar Interior and Tectonics

10:15 a.m. Break

10:30 a.m. DISCUSSION: Adjustment of Chapters Based on Workshop Results

11:45 a.m. Shearer C. * Jolliff B. *
           Closing Remarks
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**Introduction:** The lunar Procellarum region has been proposed to be a mega-basin on the basis of its composition, low topography, thin crust, and possible basin rings [1,2]. However, the evidence for and against the Procellarum basin is equivocal [3]. Here the geophysical evidence for the Procellarum basin is re-evaluated using gravity [4] and topography [5] data.

**Gravity and crustal thickness:** GRAIL gravity data revealed a quasi-rectangular pattern of magmatic-tectonic structures surrounding Procellarum [6]. These structures are incompatible with an interpretation as the rim of an ancient basin, but do not rule out the possibility of such a basin. The thin crust in Procellarum appears consistent with a basin [7]. However, the long-wavelength variations in crustal thickness are dominated by the nearside-farside asymmetry (degree 1), with superposed bulges on the nearside and farside (degree 2). The symmetry of these low degree patterns favor simple models that make *a priori* predictions of degree 1 and 2 variations [8–12]. Although a giant impact might be invoked to explain the asymmetry, the degree 1 pattern is centered on a point that is far from the center of Procellarum. After removal of degrees 1 and 2, the crust in Procellarum is no thinner than that in the surroundings. The remaining crustal thickness signature of Procellarum is noteworthy only for the buried rift valleys previously identified in GRAIL data [6].

**Topography and slopes:** Although the preservation of a rim scarp is unlikely for a structure of such great antiquity, the long-wavelength signature of the topographic transition at the edge of the basin may still be expected to be preserved. To test for the signature of the basin rim, slopes were calculated from spherical harmonic topography with a low-pass cosine taper between degrees 20 and 30 (corresponding to a spatial wavelength of 440 km). This filter highlights the rim of the ancient SPA basin. In contrast, the proposed Procellarum basin is noteworthy only for the very low slopes over the maria contained within the region, with slopes along the proposed basin rim rarely rising above the mean farside slope.

**Summary:** The observed crustal thinning in Procellarum is entirely explained degree 1 and 2 variations in crustal thickness that are likely a result of early asymmetries in crustal formation. The proposed basin is not surrounded by a topographic transition that can be interpreted as a basin rim. Structures observed in gravity data trace out a polygonal pattern and are a result of early magmatic and tectonic processes. Geophysical evidence does not support the existence of the Procellarum basin.

**References:**

**Figure 1.** Crustal thickness [7] for all degrees (top; centered on nearside) and after removing degrees 1 and 2 (bottom).

**Figure 2.** Topography (left) and slope (right) for the SPA basin (a,b) and Procellarum region (c,d). Black and white contour lines indicate the +1σ and +2σ slopes of the farside.
NEW VIEWS OF SOUTHERN NEARSIDE LUNAR HIGHLAND COMPOSITION FROM THE CHANDRAYAAN-1 X-RAY SPECTROMETER (C1XS). C1XS team, athray@gmail.com, Manipal Centre for Natural Sciences, Manipal University, Manipal – 576 104. India.

Introduction: Lunar missions over the last decade have revealed the complexity of the compositional, mineralogical, geomorphological and geophysical structure of the lunar crust and the near surface environment of the Moon. These new insights are helping to test models of lunar evolution from understanding the formation of the lunar ancient anorthositic highlands, to the chemical diversity and temporal history of volcanic and magmatic rocks.

The C1XS instrument: Chandrayaan-1, India’s first lunar mission was launched on 22nd Oct. 2008 and was in operation until Aug. 2009. The primary scientific objective of the Chandrayaan-1 X-ray Spectrometer (C1XS) was to produce elemental maps using the X-ray Fluorescence (XRF) technique [1], with a spatial resolution of ~25 km on the lunar surface.

The instrument was the first well calibrated remote-sensing experiment to measure the characteristic XRF emission lines from all major rock-forming elements including Mg, Al, Si, Ca, Ti, Fe and Na with a good on-board spectral resolution (~ 153 eV peak width at 6 keV ref. Fig 2). C1XS was accompanied by X-ray Solar Monitor (XSM) which simultaneously measured the incident solar X-ray spectra, essential to derive the surface elemental chemistry. Systematic data reduction and spectral analysis was made adopted using detailed instrument calibration [2]. Elemental abundances with uncertainties are determined using well-established inversion algorithm [3].

Observations and Analysis: The majority of observations made during solar flare events coincided with ground tracks in the lunar near-side southern highland regions, including the relatively young impact crater Tycho and its ejecta crater rays (Fig. 1).

Results: The lunar southern highlands results (Fig. 2) from the 6th July 2009 flare are consistent with regoliths dominated by the mineral plagioclase (i.e., anorthositic-rich rocks), with a slight mafic mineral content. Interestingly, these results suggest that the mapped regoliths have Ca/Al ratios significantly lower than measured in lunar returned samples[4]. One of the major findings of C1XS is the demonstration of first direct detection and quantification of the moderately volatile element Na from these nearside highland areas [5].

Discussion: The lunar crustal highlands on the central nearside of the Moon are interpreted to be produced from primary crust ferroan anorthositic bedrock, mainly composed of plagioclase feldspar with anorthite content > An95, as observed in lunar samples and remote sensing IR observations [6]. The C1XS XRF results imply that some of these areas may also have enhanced levels of sodium, which may equate to the presence of more sodic (albitic) plagioclase. Albitic plagioclase (~An40) are typically found in rocks form the magmatic high alkali suite, although are rare in the Apollo and lunar meteorite sample collections.

One of the plausible explanations for this sodic rock-type being located in lunar highlands [7] could be the signature of evolved magmatism. Global elemental mapping of Na distribution and concentration is essential for further detailed scientific interpretation of these observations, and to identify outcrops of alkali-rich lithologies across the lunar surface.

Future perspectives: The upcoming Chandrayaan-2 Large Area Soft x-ray Spectrometer (CLASS) [8] to be flown on the second Indian lunar mission Chandrayaan-2 will continue global elemental mapping with greater sensitivity and better spatial resolution.

THE CHLORINE ISOTOPIC COMPOSITION OF LUNAR URKREEP. J. J. Barnes¹,², R. Tartèse¹,², M. Anand¹,³, F. M. McCubbin², C. R. Neal³, and I. A. Franchi¹. ¹Planetary and Space Sciences, The Open University, Milton Keynes, MK7 6AA, UK, ²Department of Earth Sciences, Natural History Museum, London, SW7 5BD, UK, ³NASA Johnson Space Center, Mailcode XI2, 2101 NASA Parkway, Houston, Texas 77058, USA.

Introduction: Since the long standing paradigm of an anhydrous Moon [1] was challenged there has been a renewed focus on investigating volatiles in a variety of lunar samples (e.g., [2-9]). However, the current models for the Moon’s formation have yet to fully account for its thermal evolution in the presence of H₂O and other volatiles [10-11]. When compared to chondritic meteorites and terrestrial rocks (e.g., [12-13]), lunar samples have exotic chlorine isotope compositions [7, 14-17], which are difficult to explain in light of the abundance and isotopic composition of other volatile species, especially H, and the current estimates for chlorine and H₂O in the bulk silicate Moon [2, 18].

In order to better understand the processes involved in giving rise to the heavy chlorine isotope compositions of lunar samples, we have performed a comprehensive in situ high precision study of chlorine isotopes, using NanoSIMS, of lunarapatite from a suite of Apollo samples covering a range of geochemical characteristics and petrologic types.

Results and discussion: We show that the Cl isotopic composition of apatite from low- and high-Ti mare basalts are consistent with previous studies [7, 14], with δ³⁵Cl values from 12 to 18‰. In contrast, apatite from KREEP-rich basalts such as KREEP basalt 72275 [14] and very high potassium (VHK) basalt 14304 have distinctly heavier Cl isotopic compositions than apatite found in mare basalts. Similarly, apatite from highland samples display very heavy Cl isotopic compositions (+20‰).

We investigated whether the heavy δ³⁵Cl values of lunar rocks could be related to the proportion of KREEP component they contain, by comparing the Cl isotope compositions of apatite with bulk-rock incompatible trace element data. Our results strongly indicate mixing between a mantle source with low Cl isotopic composition (~0‰) and a KREEP-rich component characterized by a δ³⁵Cl value +30‰.

The internal differentiation of the Moon via a LMO predicts a volatile-rich urKREEP layer dominated by CI [19], containing at least 1350 ppm CI [2]. Boyce et al. [7] proposed that degassing of CI from the LMO would account for the fractionation of CI isotopes and δ³⁷Cl values +30‰ in the residual urKREEP layer. Whilst the LMO model provides an elegant mechanism for concentrating CI in the Moon, the solubility of CI in basaltic silicate liquids is high (e.g., [20]) and the confining pressure beneath the 30-40 km of lunar crust [21] would be sufficient to prevent the loss of CI by degassing.

Therefore, in order to explain the fractionated Cl isotopic composition of urKREEP, we envisage a scenario in which, during the latter stages of LMO crystallization (>95%), a large bolide(s) punctured the lunar crust [22] to a depth sufficient to bring KREEP-rich material to lower pressures, drastically decreasing the solubility of CI in the residual LMO magmatic liquids and enabled degassing of metal chlorides [14, 23], leading to the fractionation of CI isotopes. If such an event was restricted to the nearside of the Moon, i.e., the Procellarum KREEP Terrane, then one would expect rocks from outside of this region to have relatively unfractionated Cl isotope compositions.


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PREPARING HUMAN EXPLORERS FOR SURFACE SCIENCE OPERATIONS ON THE MOON.
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Introduction: Successful Lunar surface geological exploration will be dependent on a number of different elements, including mission class, mobility capabilities, crew makeup and training, field tools and IT assets that enable efficient data collection, sharing and archiving. These key elements are not independent; when developed together they become the foundation of successful and integrated mission operations. To achieve the best possible lunar surface geological exploration, integration of these elements should start at the beginning of a mission concept, to include the development of mission hardware, crew training and operational concepts.

Mission Class and Transportation: Different geological problems call for different solutions, and in order to solve these problems, operational approaches must be matched to the appropriate solution. We use the idea of mission class to define the operational approaches that can be matched to a given solution.

A Class I mission involves simple sample return for geochemical and radiometric age determination and can be conducted robotically without requirements for extensive mobility. Class II missions involve more detailed robotic exploration and sample return from a complex geological area over time periods greater than one day with requirements for increased mobility and dexterity for the robotic asset. A Class III mission would resemble an Apollo J-mission with as many as 4 crewmembers, a 3-7 day duration, mobility assets to allow 10-20 km radius of exploration and up to 150 kg of sample return capability. A class III mission could be sent to a site previously investigated by a Class II robot, or could be a site where it is clear that human crewmembers will result in the best science return. A Class IV mission involves advanced exploration capability, with durations longer than a Class III mission and exploring around a semi-permanent outpost or on long (100s of km) surface roves, and involving multiple small pressurized rovers (MMSEV-class) that can, if necessary, robotically pre-positioned into a potential exploration area prior to human crew arrival.

Crew Composition and Training: Geologic exploration requires exceptional training in geological observations in procedures, an insight not lost on Apollo trainers. Once engineering missions (AS-11, -12 & -14) were complete, attention turned to conducting extensive geological exploration of the lunar surface. The J-mission crews received in excess of 1000 hours of science training prior to flight, with over 500 hours spent in field geologic training. Future missions will require a similar training commitment, particularly in the lead up to flight. Further, in order to conduct competent science operations, crew selection will be critical. The AS-17 experience of pilot/engineer Cernan paired with a geologist Schmitt proved exceptional and should form the base training model for future human exploration of the lunar surface. Similar crew mixes have been tested on Desert RATS 2010, and have proven the validity of the Apollo 17 experiences.

Conclusions: Current geology training for the astronauts can be generally divided among three main approaches, including: 1) class room teaching and field exercises during the Candidacy training, 2) a subsequent field assistant program, and 3) integrated analog field tests. Classroom and field exercises incorporate an “outcrop to orbit” perspective. Whether the subject is structural geology, volcanology, or other planetary processes, the topical training integrates orbital observations. The field component of geology training is also integrated with a Crew Office requirement to routinely provide expeditionary training and team building experiences. Today, crew training is motivated by the flight opportunities and training required for missions aboard the International Space Station. This focus will evolve as new opportunities for missions beyond Earth orbit mature, and may once again include the Moon as a target for human exploration for NASA, or NASA support of international efforts to explore the Moon with humans. This includes the Moon either as a target for human surface science operations or as a destination for astronaut operated assets.

The 2010 joint CAPTEM-LEAG study, Lunar Sample Acquisition and Curation Review cited a need to develop a Lunar Exploration Science PI and Science Team well ahead of human landings on the lunar surface. Such a team could support ongoing astronaut training with specific links to lunar exploration. This would involve identification of analog sites relevant to the science topics identified in the New Views of the Moon 2 report. Training would integrate knowledge of mission class, science goals and development of field tools and communications assets that will be necessary for successful human exploration of the Moon.

Introduction: The Lunar Reconnaissance Orbiter (LRO) Lyman Alpha Mapping Project (LAMP) is providing insights into the upper ~100 nm of the regolith, specifically detecting surface frost and estimating porosity of lunar polar regions in the far-ultraviolet (FUV) [1-3]. LAMP also routinely collects both day and nighttime data of polar and equatorial regions of the Moon. Efforts to examine these non-polar data have studied latitudinal variations in hydration, the examination of swirl and swirl-like photometric anomalies, and cratering deposits [4-6]. These studies are providing a unique new view of the Moon.

Data Set: LAMP is a FUV push-broom photon-counting imaging spectrograph collecting data in the 57-196 nm spectral range [1]. Here, global nighttime Lyman-α (Ly-α; 121.6 nm) normal albedo data are examined for low-albedo features as they are related to lunar regolith maturity (Fig. 1). This data set is unique in that it collects naturally reflected light at night from surfaces theoretically diffusely lit by solar Ly-α scattered off of interplanetary H atoms from all directions. This is a simplification, of course, as the Ly-α sky glow intensity varies with respect to the motion of the solar system and point sources from UV-bright stars, which are more plentiful in the southern hemisphere owing to the Galactic plane [1, 8]. Thus, the signal-to-noise of the LAMP nighttime data varies with latitude, increasing from north to south.

A New FUV View of Surface Maturation: Many of the interesting new perspectives in the FUV include crater rays, pyroclastic deposits, and swirls (Fig. 1), all of which have a low Ly-α albedo relative to their surroundings, contrasting with high NUV and VIS albedos of these deposits. This is because regolith particles are not transparent in the FUV and particle reflections dominate [9, 10]. Particularly near 120 nm where transition metals no longer dominate the reflectance properties. This provides a unique view of maturity nearly devoid of compositional effects that make quantifying maturation difficult in the VIS and NIR [11, 12]. In stark contrast, young craters show high Ly-α albedo relative to their rays and surroundings.

Two examinations of swirls have been performed in the FUV [5, 6] and provide insight regarding lunar surface maturation. Hendrix et al. [5] detailed examinations of the Reiner Gamma and Gerasimovich swirls using LAMP wavelengths >130 nm noting swirls to be characterized by reddened FUV albedos and noting that immature regolith becomes brighter (i.e., bluer) and flattened with exposure. Cahill et al. [6] concentrated their examination on Lyman-α signatures of more enigmatic lunar features including swirls, normally associated with magnetic anomalies.


Fig. 1: Lunar global non-polar nighttime Ly-α observations (30 ppd). (Black boxes) Enigmatic low Ly-α albedo features. (Yellow boxes) Observed lunar swirls. (Orange boxes) Discernable pyroclastic deposits. (Red boxes) Craters with high Ly-α albedo proximal ejecta and contrasting low Ly-α albedo rays [7]. When constructing these preliminary albedo maps, the number of Δλ bins was divided, lowering the color bar values by a factor of three.
EXAMINING LUNAR REGOLITH MATURATION AT A DEEPER LEVEL. J. T. S. Cahill\textsuperscript{1}, D. J. Lawrence\textsuperscript{1}, O. Delen\textsuperscript{1}, A.M. Stickle\textsuperscript{1}, R.K. Raney\textsuperscript{2}, G.W. Patterson\textsuperscript{1}, and B.T. Greenhagen\textsuperscript{1}. \textsuperscript{1}The Johns Hopkins University Applied Physics Laboratory (Joshua.Cahill@jhuapl.edu), \textsuperscript{2}Unaffiliated.

Introduction: Lunar surface maturity is consistently examined using the NIR optical maturity parameter (OMAT) \cite{1}. However, the NIR only provides a perspective of the upper microns of the lunar surface. Recent studies of Lunar Prospector (LP) and Lunar Reconnaissance Orbiter data sets are now demonstrating additional measures of maturity with sensitivities to greater depths (~2 m) in the regolith. These include thermal infrared, S-band radar, and epithermal neutron data sets \cite{2-4}.

Previous Work: Interestingly, each of these data sets measured parameters or abundances is directly comparable to OMAT despite each measuring different aspects of the regolith. This is demonstrated by Lawrence et al. \cite{3} where LP-measured non-polar highlands epithermal neutrons trend well with albedo, OMAT, and the Christensen Feature (CF). Lawrence et al. \cite{3} used these data to derive and map highlands hydrogen (H) which is dominantly a function of H-implantation. With this in mind, areas of enriched-H are mature, while areas of depleted H are immature.

Lunar Maturation from Additional Perspectives: Surface roughness measured by S-band radar \cite{4}, also provides a measure of maturity. In this case, the circular polarization ratio (CPR) is high when rough and immature, and low when smooth and mature. Knowing this, one can recognize areas in the non-polar lunar highlands that show contradictory measures of maturity. For example, while many lunar localities show consistently immature albedo, OMAT, CF, CPR, and H concentrations (e.g., Tycho), others do not. Orientale basin is the most prominent example, shown to have immature CPR, CF, and H concentrations despite a relatively mature albedo and OMAT values as well as an old age determination (~3.8 Ga; Figure 1).

Summary: To better understand how the lunar regolith is weathering in the upper 1-2 m of regolith with time we examine the Orientale basin relative to other non-polar highlands regions (~35 localities).


Figure 1: Orientale impact basin in (a) LROC WAC monochrome, (b) Lunar Prospector derived Hydrogen, and (c) Mini-RF derived CPR maps at 2 ppd.
Recent Radar Imaging Observations of the Moon: New Views of Pyrocastics, Mare Basalts, Impact Crater Deposits, and the Lunar Subsurface. L. M. Carter, B. A. Campbell, G. A Morgan, R. R. Ghent, and C. D. Neish. NASA Goddard Space Flight Center (lynn.m.carter@nasa.gov), Smithsonian Institution, University of Toronto, Western University.

**Introduction:** Recent radar data sets have provided new information about a wide variety of lunar science topics. Radar waves are capable of penetrating into the surface and imaging buried rocks and buried structures. Longer wavelength radar waves are capable of traveling farther into the regolith, and they are also less sensitive to smaller rocks. Radar is also sensitive to the density and composition of the surface and near-subsurface through the dielectric permittivity.

In the last decade radars have provided polarimetric imaging of the lunar surface at multiple wavelengths: Arecibo and the Green Bank Telescope at 70 cm and 12.6 cm wavelength [1,2], and Mini-SAR on Chandrayaan-1 and Mini-RF on the Lunar Reconnaissance Orbiter at 12.6 cm and 4.2 cm [3]. The use of polarimetry data, such as the Circular Polarization Ratio (CPR), has provided a means to investigate the roughness of volcanic deposits and crater ejecta.

**Lunar Pyroclastics:** Fine-grained pyroclastic deposits are typically dark in radar images due to their smooth surface and lack of embedded rocks. They also often have very low CPR values. Radar data of pyroclastics at both 12.6 and 70 cm wavelength have led to new mapping of deposit extent, and to the identification of new deposits, including some associated with domes and rilles [4]. On the Aristarchus plateau, radar penetrates through the pyroclastic ash to reveal shallow buried flows; low-CPR, radar-dark regions of the pyroclastic deposit are deeper, rock-poor regions [5].

**Mare Basalts and Cryptomare:** The lunar Mare consist of layered basalt flows of varying age and composition. Radar is very sensitive to the TiO2 content of the mare basalts, due to an increased loss tangent that attenuates the radar wave. Radar backscatter at 70 cm exhibits strong variations with minor changes in flow TiO2 content when the fractional abundance of ilmenite is less (< 4%–5%) and the radar can penetrate to the substrate [6]. Mapping changes in radar brightness across Mare Serenitatis clarified boundaries between major buried lava flow complexes, and revealed linear features inferred to be collapsed lava tubes [7]. The improved delineation of units also helped to reconcile inconsistencies between regional stratigraphic relationships and crater-count age dating.

Cryptomare units – mare basalts covered by highlands material – represent an additional component of the early volcanic record of the Moon. The deep probing allowed by the 70 cm wavelength radar has added significantly to our understanding of these ancient lava flows. For example, areas east of the Orientale basin where highland material was mapped at the surface from multi-spectral methods had much lower 70 cm radar echoes than expected [8]. These areas are connected with mare-contaminated highland material mapped by [9] near the edge of Oceanus Procellarum, showing that the cryptomare units must extend a long distance beneath the Orientale ejecta.

**Impact Cratering and Age Dating:** The age of the regolith affects the radar backscatter and polarization properties, because comminution of rocky ejecta over time reduces the average block size and smooths the surface. The effects of aging are particularly apparent in radar images of impact ejecta. Lunar craters of Early Imbrian age or younger typically have radar dark haloes that appear farther from the rim than the blocky continuous ejecta, which appear bright in radar images [10]. Radar and infrared comparisons have revealed that large surface rocks break down faster than expected, but that shallowly-buried rocky ejecta can remain undisturbed for long periods [11,12]. The radar properties of ejecta blankets offer a new means of dating lunar craters [12].

Recent observations have also revealed previously unrecognized buried impact melt flows [1,13,14]. A survey of Mini-RF data led to a significant reassessment of how melt is emplaced; a larger number of small craters have melt flows than was expected and pre-existing topography appears to play a dominant role in the emplacement of melts [14]. Impact melts are also some of the roughest features on the Moon, despite appearing smooth in optical images [1,14].

NEW INSIGHTS ON LUNAR SURFACE PROPERTIES FROM THE PERSPECTIVE OF LRO NAC PHOTOMETRY. R. N. Clegg-Watkins and B. L. Jolliff, Department of Earth & Planetary Sciences and the McDonnell Center for the Space Sciences, Washington University in St. Louis, 1 Brookings Dr., St. Louis, MO 63130, Planetary Science Institute, Tucson, AZ. (rclegg@levee.wustl.edu)

Introduction: Reflectance properties of the lunar surface are strongly related to physical and compositional properties of the regolith. Factors such as grain size, composition and mineralogy, regolith structure, surface roughness, space weathering, and glass and Fe\(^0\) contents affect how the surface of an airless silicate body reflects light [1,2]. Photometry is a powerful tool for determining differences in composition and regolith structure, and photometric data from Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) images has the potential to greatly enhance our understanding of the regolith properties of the Moon. Here we discuss how photometry of NAC images, coupled with photometric models and soil sample data, has been used to determine physical changes in regolith at spacecraft landing sites and to determine correlations between reflectance and mineralogy.

Landing Site Alterations: Rocket exhaust from the Apollo, Luna, and Surveyor descent engines disturbed the regolith at their landing sites, causing the soil to become more reflective. These surface alterations, “blast zones” (BZs), are still visible in NAC images. Typically the reflectance is higher than background in an approximately annular region surrounding the landers, and lower than background beneath the landers [3]. NAC photometry and Hapke modeling have shown that the high reflectance BZs are less backscattering and smoother than undisturbed areas. Surface smoothing, destruction of fine-scale surface structure (i.e., “fairy-castle” structure), and possibly redistribution of fine particles are the most likely causes of the increased reflectance around the landers [3-5].

Change-3: Chang’e-3 (CE-3) landed in December 2013 [6], providing an opportunity to compare reflectance changes at a recent site to those of the significantly older Surveyor, Apollo, and Luna landing sites. The similarities in magnitude of increased reflectance, as revealed through NAC photometry, between the CE-3 landing site and the historic sites suggest that lunar soil reflectance changes caused by interaction with rocket exhaust are not significantly altered over a period of 40 to 50 years [4]. Longer-term space-weathering processes should eventually “reset” the reflectance.

Composition and Reflectance: Comparing landing site reflectance \((I/F)\) at a common phase angle (30°) with known soil compositions [7,8] reveals a strong correlation between \(I/F(30°)\) and mineralogy [9] (Fig. 1). There is a strong anticorrelation between \(I/F(30°)\) and the FeO+MgO+TiO\(_2\) contents of Apollo, Luna, and CE-3 soils. The CE-3 site has the lowest reflectance of all the landing sites, consistent with the high concentration of FeO+MgO+TiO\(_2\) measured for that landing site [8]. This correlation has also been used to interpret NAC reflectance and to make compositional inferences at sites of silicic volcanism across the lunar surface.

Silicic Volcanics: Regions of silicic volcanism on the Moon correlate with thorium anomalies, have low (<5 wt%) FeO content, and are highly reflective. NAC images of these regions reveal unique morphologic and reflectance characteristics that suggest a volcanic origin and mineralogy that differs from mare basalts [11-15]. Using the relationship between \(I/F(30°)\) and mafic content derived from landing-site studies, we found that silicic regions plot along the extrapolation to low (<5-10 wt%) FeO+MgO+TiO\(_2\) contents, consistent with interpretations of felsic rock types (Fig. 1) [7,11,15]. Areas of pure anorthosite (PAN) also fall well beyond this extrapolation, consistent with the interpretation that there is very little, or no, mafic mineral exposure in PAN areas.

LROC WIDE ANGLE CAMERA ULTRAVIOLET–VISIBLE IMAGES OF THE MOON. Brett W. Denevi1, Mark S. Robinson2, Hiroyluki Sato2, and Aaron K. Boyd2. 1Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA (brett.denevi@jhuapl.edu), 2School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85251, USA.

The Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) provides a global dataset to assess differences in ultraviolet (UV, 321 nm and 360 nm) through visible (415, 566, 604, 643, 689 nm) reflectance across the lunar surface. The WAC is a push-frame imager, with filter strips mounted on the CCD, and acquires near-global coverage each month [1]. This repeat coverage over a wide variation of illumination and viewing conditions allowed for the calculation of Hapke-based model parameters for 0.5°×0.5° tiles, providing detailed knowledge of photometric variations [2], and enabling the production of seamless, photometrically normalized mosaics [3]. WAC color mosaics were also produced by compiling many months of observations and taking each photometrically normalized reflectance value as the median of all observations at that point (typically >100), which greatly increases the signal-to-noise ratio of the mosaic and minimizes any residual errors in calibration or photometric normalization [3].

Composition has a strong control on reflectance at WAC UV–visible wavelengths, particularly the abundance of ilmenite, which is highly correlated to 321/415 nm ratio [4]. However, this result only holds for sub-mature to mature soils [5], as maturity has a strong effect on spectral slope in this wavelength region [6]. In contrast to ilmenite, silicate minerals typically have a steep spectral slope at wavelengths below ~450 nm due to strong absorptions shortward of 300 nm [7]. Spectra of laboratory samples suggest that space weathering decreases this slope [8]; LROC WAC observations of fresh craters generally confirm these results, with an important exception [6].

Changes in UV slope are explored with a ratio of 321/415 nm, where a low value is consistent with a steeper slope. Low ratio values are observed in association with the ejecta and rays of Copernican craters throughout the mare. However, in the highlands, the picture is more complicated. Instead of a simple relationship between maturity and 321/415 nm ratio as seen in the mare, fresh ejecta at highland craters has ratio values both lower (within ~one crater radius) and higher (distal ejecta and rays) than for mature soils. Laboratory spectra of powdered lunar rocks (no space weathering) and soils of varying degrees of space weathering (as measured by Iq/FeO [9]) show that for materials with less than ~5 wt% FeO, little change is observed in the 321/415 nm ratio except for an increase at the lowest levels of maturity (Iq/FeO ~< 20).

However, relatively modest shock pressures result in the solid-state transformation of plagioclase to a diaplectic glass, maskelynite [10]. Rather than a minimal downturn toward short wavelengths at ~360 nm, maskelynite and low-iron glass has a strong downturn at ~415 nm, likely the result of broadening of the plagioclase UV absorption due to vitrification [6]. Thus the low 321/415 nm ratio values near to crater rims are likely due to the effects of shock [6].

Swirls are also found to be distinct in LROC WAC UV data [11], as well as at far-UV wavelengths observed by the Lyman Alpha Mapping Project (LAMP) instrument on LRO [12]. Similar to fresh craters, swirls have low 321/415 nm ratios and elevated reflectance, and this distinguishing characteristic allowed for the creation of a comprehensive map of their global distribution [11]. Swirls generally have high optical maturity (OMAT) parameter values, stronger 1-μm bands, and shallower normalized continuum slopes than their surroundings, consistent with a surface that has experienced less space weathering. However, some swirls cannot be discerned in OMAT or band-depth images. Areas of swirls with low 321/415 nm ratios but non-distinct visible–near-infrared properties could be related to the presence of fresh silicates or a glassy component that does not have a substantial abundance of embedded large submicroscopic iron grains (i.e., a difference in the agglutinate fraction of the soil). Swirl color properties vary with distance from Copernican and some Eratosthenian craters; their association with Eratosthenian craters suggests fresh material may be preserved longer in swirls than in non-swirl regions.

REMOTE MINERALOGICAL ASSESSMENT OF IMPACT MELT DEPOSITS: THEIR ROLE IN CRUSTAL COMPOSITIONAL DIVERSITY AND EVOLUTION

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Introduction: Mineralogical diversity of the lunar crust has been extensively studied using samples and through remote sensing [e.g.,1,2]. Recent lunar missions have provided wealth of new insights in this context [e.g., 3-7], leading to new hypotheses about the origin of the observed crustal mineralogical variations. Here, we highlight some results on impact melt deposits based on an integrated analysis of high spectral and spatial resolution data from recent lunar missions.

Impact Melt Mineralogy: Lunar sample analyses of impact melts have highlighted their diverse mineralogical and textural character that ranges from glassy impact melt spherules [e.g., 8], melt-bearing breccia [e.g., 9] to completely crystalline impact melt [10]. The latter observation has led to debates about the possible differentiation of the enormous melt sheets within the impact basins [e.g., 11-13].

Insights from Remote Mineralogical Character of Impact Melt Deposits: Recent availability of high spatial and spectral resolution data has enabled detailed assessment of the mineralogical character of impact melt deposits in different geological settings and comparison of their mineralogical character with the predictions [12,13]. Our work has focused on the mineralogy of impact melt deposits at complex craters, especially in the context of their crystallinity and degree of mixing. We wish to highlight two important findings:

1. Large Scale Mineralogical Heterogeneity in Impact Melt Deposits: Copernicus crater exhibits the presence of a mineralogically distinct, low-calcium-pyroxene-bearing sinuous melt feature juxtaposed next to a high-calcium pyroxene-bearing impact melt on the crater floor [6]. The sinuous melt feature is >30 km long (extending from the northern crater wall onto the floor) and is 0.5 - 5 km wide, highlighting its enormous spatial extent and also the extent of mineralogical heterogeneity. The sinuous melt feature is almost devoid of any topographic expression making it hard to detect in albedo images. It is distinctively detectable only in the spectral data. These properties make the mineralogically distinctive impact melt feature quite unique. We have identified and characterized mineralogically heterogeneous impact melt, at different spatial scales, at other craters including Tycho and Jackson.

2. Multiple Origins of Lithologies with Similar Spectral Character: The well-known olivine-bearing central peaks and the northern wall olivine exposure at Copernicus crater had been proposed [14] to originate from a common source at depth. However, detailed spectral and morphological analysis has suggested an impact melt (modified primary source) origin for the wall exposure, distinct from the primary (subsurface exposure) origin of the central peaks [7].

Implications for crustal mineralogical evolution:

The prevalence of impact melt in the lunar crust along with its well-defined, diverse spectral signatures at numerous locations, strongly suggests its role in the observed crustal mineralogical diversity (i.e. all is not primary in nature) and its evolution through time. It is also important to note that spectrally similar lithologies within a geological setting may have different origins thereby directly affecting the interpretations (viz. spatial extent of the lithology and its origin).


Figure 1 Moon Mineralogy Mapper (M3) based color composite of Copernicus crater highlights (a) The sinuous melt feature (green color, low-calcium pyroxene) in contrast to the floor impact melt nearby (the two fresh craters in magenta color indicate the presence of high-calcium pyroxene) (b) Spectrally similar character of olivine-bearing central peaks and the northern wall exposure (shown to be of different origin).
GLOBAL ASSESSMENT OF PURE CRYSTALLINE PLAGIOCLASE ACROSS THE MOON: IMPLICATIONS FOR THE EVOLUTION OF THE PRIMARY CRUST. K. L. Donaldson Hanna1, L. C. Cheek2, C. M. Pieters3, J. F. Mustard2, B. T. Greenhagen1 and N. E. Bowles1, 1Atmospheric, Oceanic and Planetary Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford, UK (Kerri.DonaldsonHanna@physics.ox.ac.uk), 2Dept. of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, USA, and 3Applied Physics Laboratory Johns Hopkins University, Laurel, MD, USA.

Introduction: The formation of the Moon’s primary anorthositic crust is still an outstanding science question as two major hypotheses have been suggested. The impetus for the hypothesis of a lunar magma ocean came from the analyses of pristine Apollo samples [e.g. 1-2] and suggests that the lunar primary crust was formed by the crystallization and flotation of plagioclase in the late stages of a magma ocean. Serial magmatism models have also been suggested in which plagioclase crystallizes from several different plagioclase-rich diapirs and these models are based on the analyses of terrestrial anorthosites and lunar breccias and feldspathic meteorites[e.g. 3-5]. Thus, examining the local and global distribution of crystalline plagioclase across the lunar surface and estimating its compositional variations is significant for constraining the crustal formation processes. In this work we combine the strength of identifying Fe-bearing minerals in near infrared (NIR) remote sensing data with the strength of determining plagioclase composition using remote thermal infrared observations [6] to characterize the distribution of pure crystalline anorthosite and determine its composition in those anorthosites.

Results: Analysis of M3 NIR observations confirmed that pure, crystalline plagioclase is widely distributed across the lunar surface. We identified spectrally pure, crystalline plagioclase in the walls and ejecta of simple craters and in the walls, floors, central peaks, and ejecta of complex craters; most in association with near- and far-side impact basins. All of these identifications are associated with regions of the highest crustal values (as modeled by Wieczorek et al. [7]) surrounding each impact basin.

To better understand the compositional variability of plagioclase globally distributed across the lunar highlands, estimated Diviner Christensen Feature (CF) values were analyzed. A single distribution of CF values is observed with a mean CF value of 7.91 ± 0.05 µm suggesting that the average composition of plagioclase identified in all of the highlands craters is similar. The mean Diviner CF value can be compared to the wavelength position (7.84 µm) of the CF of anorthite (An90) measured under simulated lunar conditions to estimate the An# for the observed pure plagioclase units. The mean CF value measured by Diviner suggest the plagioclase composition across the highlands is relatively uniform in composition, highly calcic (An50), and is consistent with plagioclase compositions found in the ferroan anorthosites (An94-98) in the Apollo sample collection.

Conclusions: Our results confirm that spectrally pure anorthosite is widely distributed across the lunar surface and most exposures of the primary anorthositic crust are concentrated in regions of thicker crust surrounding impact basins on the lunar near- and far-sides. In addition, the scale of the impact basins and the global nature and distribution of pure plagioclase requires a coherent zone of anorthosite of similar composition in the lunar crust, thus supporting its formation from a single differentiation event like a magma ocean.


Figure 1. Red circles highlight M3 identifications of pure crystalline plagioclase. The background image is the Lunar Orbiter Laser Altimeter (LOLA) topography overlain on a Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) global mosaic.

**Introduction:** Numerical models of differentiation of a global-scale lunar magma ocean (LMO) [1-3] have raised as many questions as they have answered. Recent orbital missions and sample studies have provided new context for a large range of lithologies, from the comparatively magnesian “purest anorthosite” reported by [4] to Si-rich domes [5] and spinel-rich clasts [6, 7] with widespread areal distributions. In addition, the GRAIL mission provided strong constraints on lunar crustal density and average thickness [8]. Can this increasingly complex geology be accounted for via the formation and evolution of the LMO? We have in recent years been conducting extensive sets of petrologic experiments designed to fully simulate LMO crystallization [9-13], which had not been attempted previously. Here we review the key results from these experiments, which show that LMO differentiation is more complex than initial models suggested. Several important features expected from LMO crystallization models have yet to be reproduced experimentally; combined modelling and experimental work by our group is ongoing.

**Experimental Approach:** We have simulated both equilibrium [9] and fractional crystallization [10-13] of two proposed LMO compositions, Taylor Whole Moon [TWM; 14] and Lunar Primitive Upper Mantle [LPUM; 15], under nominally anhydrous conditions. Relative to bulk Earth, these compositions have, respectively, either a ~50% refractory-element enrichment or no such enrichment. Equilibrium crystallization is duplicated by taking each bulk composition directly to successively shallower conditions, whereas fractional crystallization is simulated by iteratively synthesizing new starting materials with the composition of the prior run’s liquid phase, mimicking removal of crystals.

**Results and Inferences:** Fig. 1 compares model results to those from our fractional experiments. Equilibrium runs (not shown) extending to 50% solidified produced ol + opx-dominated cumulate piles. Fractional runs produced greater volumes of monomineralic olivine and smaller volumes of orthopyroxene. Cr-spinel in TWM suppresses the onset of plagioclase, paradoxically producing more plag in the less aluminous LPUM and hence a thicker anorthositic crust of ~60 km. Both produce thicker crust than the 34-43 km implied by GRAIL results. Sequestration of Al in pyroxene, aluminous phases, and/or in interstitial trapped liquid [2], could result in less plagioclase, resulting in crustal thickness closer to that implied by the GRAIL results.

**The Path Forward:** Our work indicates that LMO solidification is more complicated than anticipated. Reconciling these complexities may require some combination of a) better understanding of the role of trapped liquid; b) a hybrid process of equilibrium followed by fractional crystallization [1]; or c) that the LMO is shallower than “whole Moon,” although the latter may lead to even more plag crystallization, hence even thicker crust, owing to its enhanced stability at low pressures.


**Fig. 1.** Comparison of LMO cumulate lithologies from numerical models [1, 2] (left two columns) and from fractional crystallization of TWM and LPUM LMO bulk compositions (our work; white area = work ongoing). Width of mineral fields = modal abundance. Note significant mismatches between modelled and experimentally-derived LMO cumulate piles. Plagioclase in LPUM corresponds to ~60 km thick lunar crust. See text for discussion.
**THE EVOLUTION OF THE LUNAR CRUST: THE VIEW FROM SAMPLES, EXPERIMENTS AND GEOCHEMISTRY.** S. M. Elardo$^1$ and C. M. Pieters$^2$. $^1$Geophysical Laboratory, Carnegie Institution of Washington, Washington, DC 20015, USA. $^2$Geological Sciences, Brown University, Providence, RI 02912, USA.

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**Introduction:** The origin and evolution of the lunar crust is a particularly difficult aspect of lunar geology to study. The extreme antiquity of the primary and most secondary lithologies in the crust means they potentially record crucial information about geologic processes operating on the early Moon. However, they have also been subject to up to 4.3 billion years of impacts, cosmic rays, and other forms of geologic processing and alteration. More recent endogenous geologic activity affecting the lunar crust appears to be either poorly sampled, less abundant, or both. Nevertheless, recent efforts have demonstrated that an enormous amount of primary information about the geologic processes that were shaping the Moon very soon after its formation is still recorded in the diverse samples of the lunar crust.

**Areas of Recent Advances:** Laboratory-based studies of the lunar crust, which include geochemical analyses of lunar samples and analog experimental studies, have focused on a number of areas of interest in recent years. Below is a brief and undoubtedly incomplete summary of some of the major advances made since publication of New Views of the Moon (NVM) and areas of ongoing research related to the evolution of the lunar crust.

**Age Relationships Among Ancient Lunar Crustal Lithologies:** The chronology of the lunar crust has been an area of tremendous advances in recent years. The apparent age overlap in early lunar crustal lithologies, specifically the ferroan anorthosites (FANs) and the Mg-suite, was known at the time of writing for NVM. However, more recent efforts have greatly improved the precision of radiogenic systems used to date these lithologies [e.g., 1-3]. These new, high-precision ages for FANs and Mg-suite samples have shown that the age overlap is not an artifact, but rather records rapid differentiation of the Moon and complex relationships between magmatic events.

**Alteration of Lunar Crustal Lithologies, Elemental Mobility, and Crustal Volatiles:** The discovery of abundances of magmatic volatiles in lunar samples that far exceeded previous estimates and the renewed focus on crustal chronology has led to new studies of the alteration of crustal samples. These studies have proposed alteration processes that had not been extensively considered in the past. These processes include metasomatism by basaltic melts [4], halogen-rich fluids [5], and sulfur-rich vapors [6]. These advances have increased our understanding of the processes that can alter pristine lunar crustal samples and transport volatile elements throughout the crust. Additionally, the quantification of magmatic volatile abundances in lunar crustal rocks [7] and determinations of isotopic compositions of volatile elements [e.g., 5, 8] have provided an entirely new window into magmatic processes contributing to crust formation in the lunar magma ocean and during subsequent magmatism.

**Lithologic Diversity in Lunar Crustal Rocks:** Our understanding of the geologic diversity in the lunar crust has significantly advanced since NVM and is an area of lunar science that has brought together new remote and sample observations in a meaningful way. Advances from laboratory observations have largely come from the plethora of lunar meteorites that have been discovered and studied since NVM. New analyses of lunar meteorites have challenged the concept of a clear compositional distinction between the FANs and the Mg-suite [e.g., 8, 9] and provided a sample-based context in which to interpret remote observations of spinel-rich lithologies [e.g., 10] that has been complemented by laboratory experiments [11].

The Youngest Known Mare Basalts: Lunar meteorites have provided the lunar science community with samples of mare basalts that are younger than any of those sampled by Apollo/Luna [12-15]. These (relatively) recent additions to the lunar crust have opened up a new period in lunar history to detailed sample-based study and have led to the refinement of models for lunar magmatic and crustal evolution.


NASA’s Lunar Atmosphere and Dust Environment Explorer, LADEE, performed a fully successful investigation of the Moon’s tenuous gas and dust atmosphere. LADEE hosted three science instruments to address atmospheric and dust objectives: an ultraviolet-visible spectrometer (UVS), a neutral mass spectrometer (NMS), and a lunar dust experiment (LDEX) are available [1,2,3,4]. In its low-altitude, retrograde lunar orbit, LADEE carried out observations over a wide range of local times and altitudes. Here we describe some of the initial results.

**Lunar Exospheric Dust:** LDEX measured a tenuous but persistent “cloud” of small dust grains, from ~0.3 to >0.7 μm in radius [5]. The number density of these grains maximizes over the morning side of the Moon, the hemisphere on the “upstream” side of the Moon’s motion about the Sun. The cloud, with observed densities ranging between 0.4 – 4 x 10^3 m^-3, is made up of ballistic ejecta from micrometeoroidal impacts on the lunar surface. The cloud density increases as the Earth-Moon system passes through known meteoroid streams, such as the Geminids, which are derived from cometary debris trails. LDEX data found no evidence for electrostatically lofted dust down to altitudes of a few kilometers [6].

**Lunar Exospheric Structure and Composition:** LADEE’s NMS instrument measured exospheric helium (³He), neon (²⁰Ne) and argon (⁴⁰Ar), revealing systematic variations in density and scale height for these three noble gas species [7]. The diurnal variation of helium, neon and argon are largely controlled by surface temperature. Helium density closely tracks the input of He⁺ from the solar wind; loss is by way of thermal escape. ²⁰Ne is a minor solar wind constituent, but it has a long lifetime at the Moon and builds up to significant densities in the lunar atmosphere. These three are the most abundant species in the lunar exosphere. ⁴⁰Ar density maximizes over the western maria, in particular the KREEP-rich Mare Imbrium and Oceanus Procellarum areas, part of the PKT [7,8]. There is also an overall, many-lunation variation in argon density, perhaps reflecting changes in the rate of release out of the subsurface, either the interior diffusive source or impacts.

NMS’s ion mode revealed multiple species that are ionized by solar EUV and accelerated by the solar wind electric field, as measured in the lunar neighborhood by ARTEMIS [9]. These species include H₂⁺, He⁺, ²⁰Ne⁺, Na⁺, K⁺ and ⁴⁰Ar⁺, as might be expected, but include ¹²C⁺, ¹⁴N⁺ and mass 28, which could be Si⁺ or most likely CO⁺. Masses 17 and 18 (OH⁻ and H₂O⁻), also observed in ion mode, are probable outgasing artifacts in the local spacecraft “coma”.

**Remote Sensing of Na and K:** LADEE’s UVS measured the sodium and potassium exospheres. The former exhibits a systematic variation with lunar phase, peaking near Full Moon, but with temporal structure in the density that suggests solar wind sputtering (absent in the geomagnetic tail) is an important process. Meanwhile, mobile Na atoms that are not lost to photoionization can be trapped on the cold nightside, and recycled into the atmosphere after sunrise. As the Moon leaves the geomagnetic tail, sputtering resumes and the abundance rises with newly-released Na atoms. There is a long-term trend to the sodium, with an overall decline similar to ⁴⁰Ar [10]. Shower-generated sodium enhancements (eg., Geminids) may persist for many lunations.

The potassium exosphere is similar to that of sodium but there is less evidence for magnetotail-related drops in density. There are indications of regional enhancements related to surface composition, with higher values of K over the PKT.

Introduction: The primary product of the continuous impacts of large and small meteoroids on the lunar surface is a global fragmented layer, termed as the regolith [1]. Regolith stratigraphy preserves vital clues about the geology and impact history of the Moon, and is also critical for quantifying potential resources for future lunar exploration and engineering constraints for human outposts. Regolith thickness can be estimated from geophysical experiments at the lunar surface, morphology and size-frequency distributions of impact craters, and radar and microwave remote sensing techniques [2]. The first approach has been applied only to a few regions at the Apollo landing sites, whereas applications of the last two approaches are relatively limited due to lacking of high-resolution optical images and microwave remote sensing data.

Recently, with a renewed interest in lunar explorations, it is possible to estimate regolith thickness over large regions using newly acquired data sets based on old methods. Based on results from new data sets, regolith stratigraphy and evolution can be investigated.

New Regolith Thickness from New Data Sets:
Using brightness temperature data acquired from Chang’E-1 (CE-1) microwave radiometer and a three-layer thermal emission model, mean regolith thickness of the maria is estimated to be 4.5 m, and that of the highlands is 7.6 m (Fig. 1) [3]. The thinnest regolith layers occurs in Mare Imbrium (mean value 3.6 m), and the thickest regolith occurs over Mare Fecunditatis and Mare Nectaris (7.8 m and 7.7 m).

The inversion of regolith thickness over lunar nearside is studied using newly acquired Earth-based 70-cm Arecibo radar data and a quantitative radar scattering model [2]. With several assumptions on size and abundance of buried rocks and surface roughness, results show that regolith thickness is ~3.5 m over Oceanus Procellarum and ~5.1 m over Mare Crisium, and regolith thickness over the highlands is ~7–8 m.

Using Lunar Reconnaissance Orbiter Camera optical images, 378,556 small impact craters over Sinus Iridum region were counted and their morphologies were identified. Results show that median regolith thickness is 8.0 m, and that 50% of the region has a regolith thickness between 5.1 m and 10.7 m [4].

The lunar penetrating radar at the Chang’E-3 landing site reveals four stratigraphic zones from the surface to a depth of ~20 m: a surface regolith (<1 m), an ejecta layer (~2–6 m), a paleoregolith (~4–11 m), and the underlying mare basalts (Fig. 2) [5]. Thicknesses of the surface regolith and the paleoregolith are consistent with estimations based on crater morphology (Fig. 3). With model surface ages, mean regolith accumulation rate at the CE-3 landing site is ~5–10 m/Ga for the surface regolith, and is ~1.3–3.7 m/Ga for the paleoregolith [5].

Conclusions: With new datasets from recent lunar missions, regolith thicknesses over large regions can be estimated, and cross-validation of regolith thickness between different methods is also available. The estimated regolith thickness, when combined with lunar surface age, can provide valuable information on the formation and evolution of lunar surface.


**Figure 1.** Regolith thickness estimated from China’s CE-1 microwave radiometer observations [3].

**Figure 2.** Regolith stratigraphy at the CE-3 landing site revealed by the lunar penetrating radar [5].

**Figure 3.** Counted craters (left) and cumulative distribution of regolith thickness (right) over the CE-3 landing region [5].
MINI-RF PSR OBSERVATIONS: WATER ICE OR ROCKS? Wenzhe Fa, and Yuzhen Cai, Institute of Remote Sensing and Geographical Information System, Peking University, Beijing 100871, China (wzfa@pku.edu.cn).

**Introduction:** Potential water ice in the permanently shadowed regions (PSRs) over the lunar poles is regarded as one of the most valuable resources in the solar system, and it also contains information concerning significant questions about the Moon [1]. Radar is regarded as an effective tool for detecting water ice, because under certain conditions, ice deposits produce a unique backscatter signature. Recently, NASA’s and India’s Miniature Radio Frequency (Mini-RF) radars found a class of anomalous craters with high circular polarization ratio (CPR) only in their interior regions, but not exterior to their rims. Most of these craters are located in the permanently shadowed regions, and their CPR characteristics are different from those of fresh craters. Based on the correlation with Lunar Prospector neutron data and thermal conditions, these anomalous craters were interpreted as potential sites for water ice deposits [2, 3].

**New Results:** We conducted an exhaustive search in the LRO Mini-RF CPR images and found 84 and 34 anomalous craters over the north and south polar regions (Fig. 1) [4]. In addition, we also found a large number of anomalous craters over the non-polar regions, where water ice cannot exist. A recent study showed that, for anomalous craters, CPR varies with position relative to the crater center [5].

Using a quantitative radar scattering model [6], we found that surface slope, roughness, dielectric permittivity, and regolith thickness cannot explain the elevated CPR in the interior of anomalous craters. Examinations in high-resolution optical images from Lunar Reconnaissance Orbiter Camera (LROC) show that there are abundant surface rocks within the interior region of anomalous craters, whereas no rocks outside of their crater rims (Fig. 2).

To study the effect of surface rocks, a two-component (single scattering from a rock-free surface and double scattering from rocks) mixed model is proposed to simulate lunar surface CPR. From this model, CPR difference between the interior and exterior regions of a crater correlates directly with the difference in rock abundance. Results for 8 typical craters showed that there is a strong correlation between CPR difference and the difference in rock abundance, which matches well with model prediction (Fig. 3). This indicates that surface rocks are the key factor for the elevated CPR in the interior of anomalous craters, instead of ice deposits as pointed out in previous studies [2, 3].

**Conclusions and Future Work:** The enhanced CPRs in the interior of anomalous craters are most probably caused by meter-scale rocks either perched on the lunar surface or buried in the regolith, suggesting that ice deposits, if present, are not the only physical agent causing the enhanced CPR. Future study is required to verify whether polar anomalous craters are overabundant or not. If so, does this represent the signature of water ice?


![Figure 1. Distribution of permanently shadowed craters, anomalous craters, and fresh craters over the lunar surface.](Image 322x133 to 391x332)

![Figure 2. (a) A LROC NAC mosaic for Hermite B. (b) A LROC image showing a rocky region (box 1) in the northern crater wall. (c) A LROC image for a rock free region in the south of outer wall (box 2).](Image 464x267 to 537x476)

![Figure 3. CPR difference between the interior and exterior regions versus the difference in rock abundance from model prediction (black line) and observations (dots).](Image 6014)
ASTOUNDING NEW ASPECTS TO THE LUNAR EXOSPHERE. W. M. Farrell\textsuperscript{1}, J. S. Halekas\textsuperscript{2}, R. M. Killen\textsuperscript{1}, M. R. Collier\textsuperscript{1}, D. H. Hurley\textsuperscript{3}, A. Colaprete\textsuperscript{4}, R. C. Elphic\textsuperscript{5}, P. R. Mahaffey\textsuperscript{1}, M. Benna\textsuperscript{1}\textsuperscript{,2}; 1. NASA Goddard SFC, 2. University of Iowa, 3. JHU\textit{}/Applied Physics Laboratory, 4. NASA Ames RC, 5. Univ. Of Maryland, Baltimore County (william.m.farrell@nasa.gov)

Motivation for an Update. When the first ‘New Views’ perspective was present in 2006, it is difficult to imagine the authors could have predicted the numerous new findings made over the next 10 year. This is especially true in the area of lunar exospheric research - which made extraordinary strides including: 1) The discovery of a number of new exospheric components (including impact-generated dust) by the LADEE mission, 2) the LRO/LAMP instrument’s inventory of the exospheric content made via FUV fluorescence [Cook et al., 2013], 3) the entry into lunar orbit of the twin ARTEMIS spacecraft and the observation of exo-ions, and 4) the unique 2009 LCROSS plume (transient dusty exosphere) experiment which exposed lunar water in polar cold traps [Colaprete et al., 2009].

A review chapter updating new activity has to incorporate these outstanding new findings from these missions along with tying the observations into some of the new concepts on the lunar system.

The Bigger Picture. While each of these spectacular missions contributed their own unique observational set and new discoveries, it is actually the merging across missions of the various findings that has lead to an entirely new view of the exosphere.

Specifically, its is becoming clear that a tenuous lunar water cycle may exist – hinted at in earlier works like Butler, 1999; Crider and Vondrak, 2000. Figure 1 shows 4 sources of OH and water on any given mid-latitude stretch of lunar regolith. Specifically, modeling suggests that the polar reservoirs are themselves exospheric sources with water liberated by impact vaporization and plasma sputtering process. Volatile-rich micrometeoroids also deliver water and OH to the lunar surface. Hydrogen infused minerals can contribute to the H in the exosphere via plasma sputtering from these surfaces.

Finally, there is clear observational evidence to indicate that much of the incoming solar wind is not retained in the surface, but converted and re-emitted to neutral H (from thermal to high energies), H\textsubscript{2}, and reflected protons; all channels constituting branches of a lunar hydrogen sub-cycle. Some fraction of the neutral H atoms may be retained in the cooler surface regions, possibly accounting for the diurnal effect reported in the surface 3 micron IR observations [Sunshine et al., 2009].

Such exciting new perspectives could be incorporated in any new chapter that is updating views of the Moon.

Other System-Level Topics For Consideration. Other topics that could be considered in an update of the latest research include the full assessment of oxygen in the exosphere – has it been fully measured and do we know where it goes? After LADEE, consideration could be given to the redefined role of impactors in releasing surface vapor into the exosphere. Given our new understanding of the solar wind plasma flow near the surface in polar regions, we can assess how such plasma ions might alter the surface of polar crater floors, including possibly releasing trapped volatiles via sputtering.

An update can address these new system-level topics, and in this workshop we will consider these and other suggested topics for inclusion into the chapter review.

Over the next ten years, we anticipate an even greater understanding of these processes and the discovery of new aspects not even possible to consider now – which will likely make the NVM II exosphere chapter outdated in its perspective. We look forward to such exciting activity.


KINETIC MODELING OF THE MOON-SOLAR WIND PLASMA INTERACTION. S. Fatemi\textsuperscript{1,5}, A. R. Poppe\textsuperscript{1,5}, J. S. Halekas\textsuperscript{2,5}, G. T. Delory\textsuperscript{1,5}, M. Holmström\textsuperscript{1}, and W. M. Farrell\textsuperscript{4,5}.\textsuperscript{1} Univ. of California at Berkeley, \textsuperscript{2} Univ. Of Iowa, \textsuperscript{3}IRF-Kiruna, Sweden, \textsuperscript{4}NASA Goddard SFC, \textsuperscript{5}NASA SSERVI. (shahab@ssl.berkeley.edu)

Introduction: A renewed interest in lunar exploration in the last two decades and proposed manned missions to near-earth asteroids demand deep understanding of the plasma environment around these objects. The physics of the solar wind plasma interaction with the Moon is very dynamic and complex [1]. In addition to in-situ plasma and field measurements at the Moon (i.e., ARTEMIS), a three-dimensional kinetic model of the lunar plasma environment is a necessary and complementary tool for understanding this complex interaction. We have used a three-dimensional self-consistent hybrid model of plasma (kinetic ions, fluid electrons) to understand the details of the Moon-solar wind plasma interaction. Our model has been extensively used for this context and validated through comparison with WIND, Lunar Prospector, and ARTEMIS observations [2,3,4].

Lunar plasma wake: Due to the lack of a global intrinsic magnetic field and dense atmosphere most of the solar wind ions impacting the lunar surface are absorbed by the Moon. This forms a wake structure downstream and leaves a plasma cavity behind the Moon [1,5]. Our hybrid simulations have provided detailed structures of the lunar wake [2]. Consistent with observations, we showed that the structure of the wake is highly controlled by the direction of the interplanetary magnetic field (IMF), plasma thermal pressure, and solar wind beta [2,4]. We also modeled the lunar wake current systems and examined the effects of IMF changes on the topology of the wake currents [6].

Plasma interaction with magnetic anomalies: Lunar crustal fields are extensively spread over the entire lunar surface with various field intensities [1]. We have used our hybrid model to understand the physics of plasma interaction with lunar magnetic anomalies on global and local scales [7,8,9]. Consistent with observations we showed that the lunar crustal fields are, for typical solar wind conditions, not strong enough to form a bow-shock upstream but rather reflect plasma and drive compressive interactions [7]. Compressed magnetic fields form upstream above strong crustal fields and convect downstream in the vicinity of the lunar wake, forming limb compressions [7]. We also examined the effects of solar wind dynamic pressure on plasma interaction with localized crustal fields near the Gerasimovich crater [8]. Our simulations suggested that Gerasimovich mostly deflects solar wind plasma during low dynamic pressure, while a large reflection (over 20% as shown in Figure 1) is expected during high dynamic pressure. This is due to the different electrostatic potentials built up under various dynamic pressure [8]. In addition, we used our hybrid model to examine different source magnetizations for the Reiner Gamma magnetic anomaly [9]. We characterized the plasma interaction with these fields and compared plasma precipitation flux to the surface with optical albedo measurements of Reiner Gamma. The model results constrained the proposed source magnetizations for Reiner Gamma and suggested that vertical crustal magnetic fields are required to produce the observed albedo patterns for Reiner Gamma [9].

![Figure 1. A snapshot of solar wind plasma reflected from the Gerasimovich magnetic anomaly (From [8]).](image)

LUNAR SWIRLS, SPACE WEATHERING, AND LATITUDINAL SPECTRAL TRENDS. I. Garrick-Bethell1,2, 1Department of Earth and Planetary Sciences, University of California, Santa Cruz (igarrick@ucsc.edu), 2School of Space Research, Kyung Hee University, South Korea.

Introduction: Lunar swirls are high-albedo features correlated with crustal magnetic anomalies [1, 2]. Swirls exhibit low amounts of space weathering and low relative abundances of hydroxyl/water molecules [3]. Therefore, swirls are at the intersection of several important fields in lunar and planetary science. Here I highlight some of the recent work on the formation and properties of these features, and show how they have provided fundamental insights into space weathering.

Formation theories: The dominant theory for swirl formation has been that the magnetic field is able to stand off the solar wind, a weathering agent, from the lunar surface [1]. Lesser attention has been given to the comet impact model [4], largely due to difficulties producing remanent magnetism in the crust, but the idea has been revived [5]. The newest ideas have focused on processes that modify the structure of the regolith, either by lofted dust due to electrostatic fields generated by magnetic field-plasma interactions [6], or due to modifications of the putative “fairy castle” structure of the regolith [7]. To date, however, radar observations [8], thermal inertia studies [9], and considerations of magnetic field geometry [10] have failed to support such theories. Photometric anomalies that have been reported at swirls remain a puzzle that helps keeps the soil modification theories alive.

Optical properties and space weathering implications: One of the most recent insights is that while swirl soils are optically immature, they are distinct from classically immature soils [6]. Interestingly, their spectral properties mimic the spectral properties found at high latitudes [11] (Fig. 1). This suggests that the solar wind flux, rather than the accumulated dose, controls how space weathering manifests itself – a fundamental result. This discovery has been supported by differences found between the pole and equator facing slopes of high latitude craters [12] (each have different angles of attack with respect to the solar wind), and has implications for interpreting spectra in polar regions.

Other latitude-dependent spectral trends: Supporting evidence for latitude-dependent space weathering effects has recently been reported by Jeong et al. [13], who finds that regolith grain size increases at high latitudes. This has been interpreted to be due to the roughly ecliptic population of micrometeoroids, and their reduced flux and weathering efficiency at high latitudes (Fig. 2). Other latitude-dependent spectral trends have also been reported [14].

THE LONG WAVELENGTH STRUCTURE OF THE LUNAR CRUST: TIDAL-ROTATIONAL ORIGINS AND TRUE POLAR WANDER. I. Garrick-Bethell1,2, 1Department of Earth and Planetary Sciences, University of California, Santa Cruz (igarrick@ucsc.edu), 2School of Space Research, Kyung Hee University, South Korea.

**Introduction:** The shape of the Moon and the structure of its crust at long wavelengths has long been a puzzle in lunar science. Understanding the origins of these features would have implications for the thermal history of the Moon, its orbital evolution, and its history of true polar wander. Here I review some of the historical and recent work in this area.

**Background:** Unlike the shape of the Earth, which is dominantly controlled by its spin, the shape of the Moon is not in hydrostatic equilibrium. That is, the Moon’s shape is more distorted than would be expected if it was entirely controlled by tidal forces from the Earth and the Moon’s own spin. Laplace was the first to notice this effect, when he inferred the Moon’s moment of inertia differences from its precession rate. Historically, these moment of inertia differences have been used to represent the distortions of the Earth and the Moon’s own spin. Laplace offered an explanation for these moment of inertia differences: because the Moon was once closer to the Earth, it could have frozen in its shape during an epoch of stronger tidal and rotational deformation [1]. In particular, Sedgwick inferred that the freeze-in occurred at a semi-major axis between about 15 and 30 Earth radii. This idea became known as the fossil bulge hypothesis. However, a number of issues eventually arose with this idea. In particular, the ratios of the moment differences did not match those expected from theory, e.g. [2]. In the last few decades, proposals for reconciling the discrepancy suggested that some component of the lunar shape might be due to random geologic “noise” [3, 4].

**New tidal-rotational models:** A more recent proposal to reconcile the moment of inertia differences with a tidal-rotational shape model came about when it was realized that higher eccentricity orbits and spin-orbit resonances other than 1:1 would affect the moments of inertia differently during freeze-in [5]. The viability of this idea was subsequently deemed unlikely based on orbital evolution models [6].

A further limitation of the above study was that it only used the moments of inertia as a measure of the shape, when in fact the modern era of lunar observations has made available global maps of topography and gravity. The moment of inertia differences can be represented by the degree-2 spherical harmonic gravity coefficients. Garrick-Bethell et al. analyzed the Moon’s topography and gravity together, outside of the largest basins, to infer that the Moon’s shape was the sum of two tidal-rotational effects: a frozen fossil bulge, plus tidal heating in the crust [7]. The idea that the lunar crust could be tidally heated had been previously proposed [8], and was borrowed from work on Europa. Keane and Matsuyama studied the Moon’s gravity after removing the effects of the basins, but did not analyze the Moon’s topography. They inferred that the moments of inertia were consistent with freeze-in during a synchronous orbit with eccentricity of ~0.2 [9], still a high and likely implausible value.

**Other models:** Other early evolution models have been proposed to explain the structure of the crust without relying on tidal-rotational effects, e.g. [10].

**True polar wander:** The history of true polar wander is important for constraining the history of polar volatiles and density changes inside the Moon. The two studies above ([7, 9]) both inferred various degrees of polar wander, based on the orientation of the reference frame that contains the Moon’s primordial tidal axis. However, the two inferred polar wander histories disagree with each other, and are in further disagreement with a variety of studies based on lunar magnetic anomalies. Runcorn provided one of the earliest examinations of lunar magnetic paleopoles [11], but modern spacecraft data have provided more recent studies that have increased the scatter [12, 13].

Interestingly, there is some degree of agreement between a recently reported “hydrogen paleopole” [14], and the topography paleopole of [7]: a great circle between them passes through the present poles and the center of the Procellarum KREEP Terrane. Further modeling and data interpretation are required to reconcile the diverse paleopoles of the Moon to better understand its orbital history and thermal evolution.

A REVIEW OF TERRESTRIAL ANALOGS FOR THE MOON. W.B. Garry\(^1\), D.H. Needham\(^1\), K.E. Young\(^1\), P.L. Whelley\(^1\), J.E. Bleacher\(^1\), \(^1\)NASA Goddard Space Flight Center, Greenbelt, MD 20771, brent.garry@nasa.gov

Introduction: Terrestrial analogs have long been used to help us better understand the subtle and complex geology of the lunar surface. The Apollo astronauts took field trips and conducted training exercises at several geologic locations considered analogs for the Moon [1,2] and many of these sites will provide a foundation for the review of this topic. Recent high-resolution data sets from multiple lunar missions have allowed us to analyze lunar features in much greater detail. The advantage of these new data sets is that we can now compare the lunar surface to terrestrial features at similar scales and resolutions. Here, we propose a review of terrestrial analogs as a topic within New Views of the Moon 2.

Old and New Views of Terrestrial Analogs: The purpose of this review will be to describe terrestrial geologic analogs that have been used to study lunar geologic processes including: volcanism, impact cratering, structural, and surface processes. Returning to these classic sites on Earth, given new data from the Moon, continues to provide insights into lunar geology. Furthermore, new analog sites are providing fresh perspectives.

Volcanism. Analogs of lunar volcanic processes have been widely used throughout the literature. Long lava flows in the lunar mare have been compared to terrestrial flood basalts. For example, the flow field in Mare Imbrium has been compared to the Columbia River Basalts (CRB), USA [3]. However, a new understanding of the formation of the CRB [4] and analyses of the recent lunar data have led to investigations of different terrestrial flows (e.g. Askja volcano in Iceland) [5] as analogs. Lunar sinuous rilles have been compared to lava channels and lava tubes in Hawai`i [6,7,8] and Lava Beds National Monument in California [9]. More recent studies have considered lava tubes that formed from breach scoria cone (e.g. Bandera crater, New Mexico) as an analog for Vallis Schröteri [10] and Kiluaea Iki and the Roza member of the CRB have been compared to observations of Lunar Reconnaissance Orbiter Camera (LROC) images of Rima Prinz [11]. The numerous cones and domes on the Moon have long drawn comparisons to terrestrial cinder cones and low-shields [12] including SP crater in Arizona [13]. New details revealed from LROC images and terrain models [14] allow more rigorous comparisons of flow features with field observations of terrestrial analogs. Plains-style volcanism has been identified in Mare Orientale and surrounding lacus [15]. Entire field guides have been devoted to plains volcanism in Idaho and their comparison to lunar features [16]. Recent investigations continue the study of these small shields in Craters of the Moon National Monument (Idaho) comparing high resolution topographic data and field observations to LROC images and terrain models [17]. Enigmatic volcanic features, like Ina, have been compared to domes and drain out features in Iceland [18]. Recent field investigations of inflated lava flows in New Mexico and Hawai`i were compared to LROC data to explain the formation of Ina [19]. The discovery of pits on the lunar surface [20] have reinvigorated studies of various types of pits on Earth, including lava-rise pits [21] and collapse pits in lava tubes.

Impact craters. Terrestrial impact structures, most notably Meteor Crater [22,23], are used to understand lunar impact processes. The Sudbury impact structure in Canada [24] and the Ries impact crater in Germany [25,26] are considered analogs for understanding melt deposits and the structure of impact basins. The Mis- tastin Lake impact structure in Canada [27] has been studied as a lunar analog due to its impact into an anorthosite-rich target. In a cross comparison, terrestrial lava flows serve as analogs to explain the flow processes of impact melt flows on the Moon [28].

Summary: This section will include the following subtopics: 1) Background of terrestrial analog studies conducted before and during the Apollo era; 2) Detailed case-studies of select sites considered key analogs for lunar geologic processes; 3) Review of recent studies that compare new lunar data sets to terrestrial analogs; and 4) Discussion about the limitations for making direct comparisons.

**REMOTE SENSING CONSTRAINTS ON LUNAR CHRONOLOGY.**

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**Introduction:** A critical and underconstrained element of the effort to understand fundamental physical processes operating on the Moon is the rate at which these processes occur. Establishing rates, or absolute ages planetary features or terrains is difficult. For example, absolute ages on the Moon are generally determined by analyzing the statistical distribution of small craters superimposed on the feature or terrain of interest, and relating the relative ages thus derived to the absolute timescale via returned samples [e.g., 1]. This methodology requires significant labor resources and uncertainty over identification of secondary craters and the effects of variations in physical properties of the target material [2] further complicate crater counting.

Here, we present an alternative method for the derivation of surface ages using observations of impact craters and two datasets: 1) thermal infrared data from the LRO Diviner thermal radiometer and 2) Earth-based S- and P-band radar. We show that remote sensing observations can shed light on the rates of geological processes, and on the fundamental underpinnings of lunar chronology.

**Data:** Rock abundance (the fraction of each pixel covered by exposed rocks larger than the diurnal thermal skin depth, or ~0.5 m) is derived from Diviner nighttime thermal infrared temperatures [3]. Lunar regolith fines are highly insulating; therefore, rocks covered by even a small thickness of regolith are not detectable in this dataset. Thus, the rock abundance dataset provides a reliable inventory of surface rocks. Radar data, by contrast, senses rocks anywhere within the sensing depth, or up to ~10 wavelengths. Comparison of Diviner rock abundance with radar data of multiple wavelengths allows us to estimate the relative abundance of surface vs. subsurface rocks.

**Surface rock breakdown and survival time:** Using Diviner rock abundance data for the ejecta blankets of 9 large craters with published model ages derived from ejecta blanket crater counts, we have previously established a relationship between crater age and ejecta rock content [4]. To characterize the rock distribution, we measured the 95th percentile values of rock abundance for each crater's ejecta. We found that as craters age, this value decreases from >10% toward the background value of ~0.5% as a power-law function of time. Craters older than ~1.5 Gyr show surface rock populations indistinguishable from the background. We conclude that the survival time for rocks larger than ~0.5 m is on the order of 1.5 billion years. This places a new observational constraint on the rate of rock breakdown.; if micrometeorite bombardment is the dominant process, this rate should match that predicted by the micrometeorite flux. Alternatively, if thermally induced stresses are sufficiently high to break down rocks [e.g., 5-7], our result should constrain the relative importance of this process.

**Subsurface rock survival time:** Earth-based radar observations at 70 and 12.6 cm wavelengths show that craters older than 1.5 Gyr, whose ejecta are free of surface rocks, maintain their rocky ejecta signatures [8]. In fact, most nearside impact craters show rocky ejecta in radar images. We interpret this as evidence that the majority of surviving impact ejecta on the Moon reside in the shallow subsurface: too deeply buried by fine regolith to be visible to Diviner, but within the radar penetration depth of 1-10 meters (depending on wavelength). We observe no correlation between degree of subsurface rockiness, measured using radar circular polarization ratio, and crater age. This ultimately places a constraint on the rate of regolith overturn by bolides large enough to penetrate the regolith to meter scales to break down buried rocks.

**Variations in impact flux:** Using the results of [4], we have calculated absolute ages for ~500 craters with diameter ≥5 km between 80S and 80N [9]. We find evidence for a factor of 2-3 increase in impactor flux at all sizes (that is, impactors that create craters ≥5 km in diameter) at ~388 Ma. This finding supports other lines of evidence for an increase, e.g., from the occurrence of lunar impact spherules [10]. This result has profound implications for work that depends on the recent flux for age dating.

SILICIC VOLCANISM IDENTIFIED BY THE DIVINER LUNAR RADIOMETER EXPERIMENT. T. D. Glotch¹, B. T. Greenhagen², J. J. Hagerty³, B. L. Jolliff⁴, J. W. Ashley⁵, J.-P. Williams⁶, and N. E. Petro⁷;¹Department of Geosciences, Stony Brook University, Stony Brook NY 11794-2100 (timothy.glotch@stonybrook.edu), ²Applied Physics Laboratory, ³United States Geological Survey, ⁴Washington University in St. Louis, ⁵Jet Propulsion Laboratory, ⁶University of California Los Angeles, ⁷NASA Goddard Space Flight Center

Introduction: The Lunar Reconnaissance Orbiter Diviner Lunar Radiometer Experiment (Diviner) has been used to detect and characterize a number of silicic volcanic constructs on the Moon [1-6]. These regions include Hansteen Alpha, the Gruthuisen domes, the Mairan domes, the Compton-Belkovich volcanic complex, and the Lassell Massif. An additional detection of silicic material in the Aristarchus central peak and ejecta suggests the excavation of a silicic pluton. Non-mare volcanism had long been suspected at several locations on the Moon based on unique reddening in visible/near-infrared (VNIR) spectra, and geomorphic consistency with viscous lava flows [7-10]. Additional evidence for the unique composition of these regions includes their association with high Th abundances and low FeO contents mapped by the Lunar Prospector Gamma Ray Spectrometer [4, 11-12]. Here, we review the contributions made by Diviner to the understanding of these important features.

Diviner Conavity Index: Diviner is an infrared radiometer that includes three narrow band channels centered at 7.8, 8.25, and 8.55 µm that are used to characterize the silicate Christiansen feature (CF), an emissivity maximum that is indicative of bulk silicate composition [2, 13-14]. The emissivities of these three “8 µm channels” are used to model the emissivity maximum as a parabola, the maximum of which is taken to be the CF position. Materials with high silica contents including SiO₂ polymorphs and alkali feldspars have CF positions outside of the region that can be characterized by the Diviner CF channels. Instead of defining a concave down parabola, the 8 µm channels display a concave-up spectral shape. Because the concave-up spectral shape is unique to highly silicic materials (with the notable exception of fayalitic olivine), we have defined an index to map the concavity of the Diviner 8 µm channels [1, 4-6] (Figure 1).

Implications for Lunar Volcanism and Future Exploration: Global mapping of Diviner data at 32 pixels per degree has not indicated the presence of evolved silicic lavas beyond those discussed by [1-6]. Nevertheless, it is clear that silicic magmas are volumetrically more important than suggested by the Apollo sample suite. Granitic clasts exist among the Apollo samples and exhibit textures consistent with formation via silicate liquid immiscibility [15]. The relatively large volumes of magma required to form the features observed by Diviner have led others to suggest a basaltic underplating mechanism [1, 11, 16]. Studies of silicic clasts in the Apollo sample suite have identified quartz as the only SiO₂ phase [17], although these likely initially formed as tridymite or cristobalite [18], the high temperature SiO₂ polymorphs commonly seen in extrusive silicic rocks. This suggests that the Apollo suite may have sampled the class of silicic volcanic deposits identified by Diviner. One or more of these sites should be considered high priority targets for future exploration and sample return.

LUNAR ATMOSPHERIC CAMPAIGNS OF THE UV SPECTROGRAPH LAMP ON BOARD OF THE LUNAR RECONNAISSANCE ORBITER. C. Grava1, D. M. Hurley2, J. C. Cook2, K. D. Retherford1, G. R. Gladstone1, T. K. Greathouse1, S. A. Stern3, P. D. Feldman4, and the LRO/LAMP Team. 1Southwest Research Institute, 6220 Culebra Road, San Antonio, TX, 78238 USA, 2Johns Hopkins University, Applied Physics Laboratory, Laurel, MD, USA, 3Southwest Research Institute, Boulder, CO, USA, 4Johns Hopkins University, Baltimore, MD, USA.

Introduction: The Lunar Reconnaissance Orbiter (LRO) [1] has been studying the Moon since its orbit insertion in late 2009. Among its seven instruments, which provided an unprecedented understanding of the complex lunar environment, is the UV spectrograph LAMP (Lyman-Alpha Mapping Project) [2]. It proved to be a great remote sensing tool to study not only the properties of the lunar upper regolith such as porosity [3] and hydration [4], but also of the tenuous lunar exosphere, whose atoms and molecules resonantly scatter sunlight. Here we summarize the results of LAMP’s atmospheric campaigns performed so far to study the composition and properties of the lunar atmosphere, as well as its temporal variations.

Geometry: Being pointed at the nadir most of the time to map the lunar surface, LAMP can detect resonantly scattering atoms and molecules in the lunar atmosphere when the latter is illuminated, and the instrument is pointing at the lunar nightside surface. Due to the polar orbit of LRO, such occurrences occur when the spacecraft is poleward of ~75° latitude, or ~2 hours nightwards of either dusk or dawn terminators (“twilight observations”). Because of the faintness of the emission lines, LAMP needs to accumulate photons over a long period of time to obtain a decent signal-to-noise ratio (SNR). During dedicated campaigns, to increase the illuminated path along its line-of-sight and hence the SNR, LRO was also pitched along the direction of motion and rolled sideways.

Helium: The emission line of HeI at 58.4 nm is by far the brightest exospheric emission line within the LAMP bandpass (57.5 – 196.5 nm). Therefore, helium is the only element of the lunar atmosphere detectable by LAMP on a single orbit. It was detected during the first atmospheric campaign of LAMP, in 2011, looking at the sky [5]. The second atmospheric campaign was performed with LRO close to the terminator, and showed no variation of helium with latitude, but variation with time [6]. In particular, LAMP detected a decrease of a factor of 2 in the helium surface density in a 5-day period when the Moon was in the Earth’s magnetotail, confirming that lunar helium has its main source in the neutralization of solar wind alpha particles upon impinging on the lunar surface [7]. However, subsequent observations with LAMP revealed sporadic enhancements of helium, uncorrelated with either solar alpha particles flux or meteor showers [8]. A plausible explanation for these “flares” is the release, by shallow moonquakes, of trapped lunar endogenic He formed from the radioactive decay of $^{232}$Th and $^{238}$U within the crust. Subsequent observations with LAMP [9, 10] are consistent with ~40 % of lunar helium being endogenic.

Molecular Hydrogen: LAMP detected H$_2$ in the vapor plume from the Lunar Crater Observation and Sensing Satellite impact [11]. Later, accumulating photons during the first 4 years, LAMP detected for the first time in the ambient exosphere the Lyman and Werner emission bands of molecular hydrogen [12]. Interestingly, the inferred surface density of H$_2$ was several times lower than previous upper limits inferred by the Apollo 17 Ultraviolet Spectrometer, and showed a dawn/dusk asymmetry, with surface density at dawn being 1.4x higher than at dusk.

Other species: In addition to these detections, more than 3 years of LAMP’s “twilight observations” placed stringent upper limits on several other species [13], some of them (O, Mg, Al, and Ca) in agreement with models in which sputtering is the dominant source process. As the mission progresses and LAMP accumulates photons, improved upper limits are warranted in the future.


Introduction: Before the launch of the Lunar Reconnaissance Orbiter (LRO), it was suggested that thermal infrared spectroscopy would be a unique tool for lunar compositional remote sensing in part because evidence indicated this technique was less susceptible to the known optical effects of lunar surface exposure to space [1] than the more widely used visible and near-infrared wavelengths [e.g. 2, 3]. However, with global data from the LRO Diviner Lunar Radiometer (Diviner), it quickly became evident that the Christiansen Feature (CF; a mid-infrared compositional indicator) measured from the lunar surface was affected by space weathering [4, 5]. We will present and discuss hypotheses for the unanticipated space weathering dependence revealed by Diviner.

Observable thermal infrared spectroscopic space weathering effects are most likely caused by variations in the epiregolith thermal gradient due to differences in visible albedo and not composition or bulk thermophysical properties. Young features such as interiors, ejecta and ray deposits of the craters Tycho and Jackson show CF positions at systematically shorter wavelengths than their more space weathered surroundings, as do deposits of the other young rayed craters. Lunar swirls, commonly thought to form as a result of inhibition of the space weathering process, also show shorter CF positions than their surrounding terrains [6]. Diviner and ground-based telescopic data indicate that temperatures observed on- and off-swirl during nighttime and lunar eclipse are consistent with differences in albedo and not thermal inertia [6, 7].

In addition to characterizing and quantifying the degree to which space weathering affects the CF, this presentation presents techniques for the normalization of space weathering effects to enable examination of the underlying composition (Figure 1).

Datasets: We used calibrated radiances from Diviner’s three 8 μm-region channels to calculate effective emissivity and then fit the three emissivity values with a parabola. The wavelength maximum of the parabola is the estimated CF wavelength [5]. Our data were “photometrically” corrected by projecting the data onto a topographic grid, calculating photometric geometry, and applying an empirical correction methodology [after 5]. Global Diviner data were binned at 32 pixels per degree to produce maps of CF values for latitudes below 60 degrees. We compare the CF to the Clementine-derived optical maturity (OMAT) parameter [8]. For specific regions of interest, Diviner data were binned at 128 pixels per degree and compared to OMAT derived from Kaguya Multiband Imager data.

Conclusions: Diviner CF data have a clear dependence on optical maturity owing to differences in visible albedo. While the near-IR derived OMAT parameter can be used to grossly correct the CF data for the space weathering effect, residual signals remain. Comparisons of CF and OMAT at highest resolution suggest that in the least weathered areas the two parameters diverge in their response to space weathering and the proposed correction is less effective in the lunar maria. Therefore it is likely that Diviner CF contains unique information regarding space weathering [9, 10].

Figure 1. Demonstrating the use of OMAT to correct space weathering effects from Diviner CF data.

WATER AND VOLATILES IN APOLLO ROCKS: THE VIEW FROM SAPPORO AND CONNECTICUT.
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Introduction: Since the discovery of water in lunar soil samples [1], there has been an explosion in research on the new field of lunar water. We have been analyzing water, D/H, and other volatile elements in Apollo rock samples since 2009, and have now conducted thousands of analyses, using SIMS spot analyses, SCAPS ion image analyses, FEG-EPMA, FEG WDS Kα mapping, FEG-EDS, and micro-Raman spectroscopy in high titanium mare basalts, low titanium mare basalts, AI-basalts, KREEP basalts and highland rocks. This extensive analysis of Apollo rock samples allows us to understand the history and distribution of volatiles in lunar samples that cannot be attained by studying lunar soil samples alone.

High Titanium Basalts: We have now found abundant evidence for volatile-rich and water-rich glasses and melt inclusions in high-titanium basalts [2-4]. We have also found evidence for a change to more oxidizing conditions in the high-titanium basalts upon emplacement near the lunar surface, wherein we find Fe metal becoming oxidized to form hycynite (Fe₅Al₂O₄). We have also found a new lunar volatile mineral, with the preliminary name of Ce-Chlor-Britholite, that crystallizes after apatite in slowly-cooled high titanium basalts. That this mineral crystallizes after apatite, and is F-,Cl-rich, shows that apatite crystallization did not deplete the melt in fluorine, as predicted by the Lunar Apatite Paradox model [5]. We predict that all high-titanium basalts were similarly enriched in volatile elements. We will present results that demonstrate that some high-titanium basalts have only an order of magnitude depletion in H₂O relative to terrestrial magmas. If high-titanium magmas underwent significant degassing [6], then this would predict at least earth-like levels of water, and possibly higher.

Low Titanium Basalts: The low-titanium basalts have proven especially fruitful for disentangling the D/H history of lunar magmas. We will present the results of a comprehensive and cohesive model to explain D/H systematics of the Moon. This model indicates a high D/H for the lunar mantle, as originally found by [7].

According to the Lunar Apatite Paradox model, OH-richapatites are due to low overall volatile element contents of lunar magmas. OH-richapatites are only found in low-titanium basalts, suggesting overall lower volatile contents for low-titanium basalts relative to high-titanium basalts. Conversely, chromite-hosted melt inclusions have high F and Cl abundances [8], suggesting that water behavior may be decoupled from F and Cl in these magmas, and especially during their subsolidus history [9].

KREEP basalts: We have found the most Cl-rich extraterrestrial glasses in KREEP basalts 15382 and 15386, with up to 1000 ppm Cl [10]. Comparison of volatile/refractory elements such as F/Nd and Cl/Nb of KREEP basalts, shows an order of magnitude depletion in F and double that in chlorine relative to the Earth (Fig. 1). All lunar samples analyzed for F and Cl thus far, including 74220 water-rich olivine hosted melt inclusions, show a similar relationship (Fig. 1).

Summary: Comprehensive analyses of volatile element distributions in Apollo rock samples since 2009 have finally unveiled the history of lunar volatiles and the origins of the Moon’s water. High D/H of the lunar mantle is still best explained as delivery of cometary water to the Moon after the Giant Impact.

Figure 1. Cl/Nb vs. F/Nd of the Moon, Earth, and CI.

LUNAR HOLES AND THEIR ASSOCIATED SUBSURFACE CAVERNS: FROM SELENE (KAGUYA) TO UZUME. Junichi Haruyama 1), Isao Kawano 1), Toshiyuki Nishibori 1), Takahiro Iwata 1), Yukio Yamamoto 1), Kazuhiro Shimada 1), Keiko Yamamoto 1), Toshiaki Hasenaka 2), Tomokatsu Morota 3), Masaki N. Nishino 3), Ko Hashizume 4), Motomaro Shirao 5), Goro Komatsu 6), Nobuyuki Hasebe 7), Hisayoshi Shimizu 8), Kensei Kobayashi 9), Shinichi Yokobori 10), Yohei Miyake 12), Takeshi Tsuji 12), Reina Shinoda 12), 1)JAXA, Japan, 2)Kumamoto University, Japan, 3)Nagoya University, Japan, 4)Osaka University, Japan, 5)Planetary Geology Institute, Japan, 6)Università d’Annunzio, Italy, 7)Waseda University, Japan, 8)University of Tokyo, Japan, 9)Yokohama National University, Japan, 10)Tokyo University of Pharmacy and Life Sciences, Japan, 11)Kobe University, Japan, 12)National Institute for Environmental Studies, Japan, E-mail: haruyama.junichi_at_jaxa.jp.

In 2009, three deep pits, gigantic vertical holes, that have aperture diameters and depths of several tens of meters to one hundred meters were discovered in the data of Terrain Camera (TC) onboard Selenological and ENgineering Explore (SELENE, nicknamed KAGUYA)[1,2](Fig.1). These holes are located in Marius Hills, Mare Tranquillitatis, and Mare Ingenii. They are possibly “skylights” opened on subsurface caverns such as lava tubes. Similar hole structures are also found on Mars [3,4].

![Fig.1 A hole, possible possible skylight of a undersurface cavern, discovered in Mairus Hills on the Moon.](image)

The United States Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) which resolution is ten times better than that of TC later identified more pits on the Moon [2,5-7], including three holes that SELENE TC had discovered. Wagner et al. (2014) [7] classified the pits into three types based on their locations: floors of large craters, mare, and highlands. The pits on the crater floors were possibly formed by depression and/or degassing of cooling impact-melt lavas. Most are smaller than a few tens of meters in diameter and are not skylights of subsurface caverns. Eight pits including that SELENE TC discovered were identified in mare regions.

“Pit” is a general term for depression structures. However, vertical holes that SELENE TC discovered are apparently unique, different from other smaller and shallower depressions [8]. Thus, we adopt the term “hole” to refer to possible skylights of subsurface caverns, such as the Marius Hills Hole (MHH), Mare Tranquillitatis Hole (MTH), and Mare Ingenii Hole (MIH).

Subsurface caverns are quite safe shelters for long-term manned/unmanned activity on the Moon; humans/machines can escape from impacts of numerous meteorites, constantly showering radiation, and widely oscillating temperature in the caverns. They are the best places for constructing lunar bases. Lunar holes are possible entrances to the caverns. The discovery of lunar holes has opened a new era for humans to explore the Moon and go beyond it.

Lunar holes and their associated subsurface caverns could be regarded as resources for lunar science[9]. They are places where (1) fresh materials are easily observed and sampled in the holes and caverns and (2) are entrances to caverns that provide a safe, quiet environment. Furthermore, exploring the lunar caverns through the deep vertical holes will provide good lessons for exploring Martian holes where we will be able to acquire information of the Martian geologic history and to establish bases and where extraterrestrial life may survive.

We present a summary of lunar holes and associated caverns. Furthermore, we also introduce the project Unprecedented Zipangu Underworld of the Moon/Mars Exploration (UZUME) [9] to explore the holes and caverns.

GLOBAL REGOLITH PROPERTIES FROM DIVINER THERMAL INFRARED MEASUREMENTS. P. O. Hayne1, J. L. Bandfield2, A. R. Vasavada3, R. R. Ghen1,4, M. A. Siegler1, J-P. Williams3, B. T. Greenhagen4, C. M. Elder1, D. A. Paige5 1NASA-Jet Propulsion Laboratory, California Institute of Technology (Paul.O.Hayne@jpl.nasa.gov), 2Space Science Institute, 3University of Toronto, 4Planetary Science Institute, 5University of California, Los Angeles, 6Applied Physics Laboratory, Johns Hopkins University.

Introduction: The Moon’s regolith records the history of fragmentation and overturn by meteorite impacts, which are the dominant geologic processes shaping the lunar surface [1]. Because the impact flux is dominated by the smallest bolides, the upper layers of the lunar surface are overturned and pulverized most frequently [2][3]. Apollo core samples showed depth-dependent density and thermal conductivity profiles, presumably caused by this gradient in overturn timescale [4] and compaction. Local and regional differences in regolith properties may also reveal overturn histories important for understanding cosmic ray exposure ages of individual samples [5].

New Dataset: We used thermal infrared data from the Diviner instrument onboard the Lunar Reconnaissance Orbiter (LRO) to probe the properties of the upper part of the regolith, and map their variations. Diviner is a multi-spectral push-broom imaging radiometer [6], enabling separation of emission from rocks and regolith [7]. Using derived regolith temperatures, we performed least-squares fits to nighttime cooling curves with a numerical heat diffusion model [8][9]. Given the uniformity of the upper regolith structure on the scale of the Diviner measurements [10], we chose to fit the “H-parameter”: the vertical e-folding scale of the thermal inertia profile.

Results: Global maps of regolith properties were produced from latitude -70 to +70 at a resolution of 128 pixels per degree (~250 m at the equator). Figure 1 shows the resulting map of the H-parameter. Many notable features appear in the H-parameter map, on a range of spatial scales; here we describe only a few of them.

Global Scale Patterns: At the largest spatial scales, the most prominent patterns are high thermal inertia materials concentrated in crater rays, and a broad low thermal inertia region correlated with the South Pole Aitken Basin (SPA). We also find a latitude gradient, with lower thermal inertia (higher porosity) at higher latitudes.

Regional Scale Patterns: At scales of ~10 – 100 km, we note the presence of very high thermal inertia regolith within and surrounding large impact craters, as well as the Tycho crater antipode [11]. Low-thermal inertia regolith is found surrounding some fresh impact features, known as “cold spots” [12]. Finally, some low-thermal inertia features on this scale correlate with pyroclastic deposits, though not all pyroclastic deposits exhibit this behavior.

Local Scale Patterns: Regolith properties show distinct variations down to the ~250-m scale of the measurements. Many of these variations are caused by impact processes, and we note an age relationship similar to that identified by [13]. Volcanic features such as irregular mare patches (IMP) also exhibit sometimes strong thermal anomalies, which may be used to constrain their formation mechanisms.


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MARE BASALT VOLCANISM: GENERATION, ASCENT, ERUPTION AND HISTORY OF EMPLACEMENT OF SECONDARY CRUST ON THE MOON. James W. Head¹ and Lionel Wilson¹².
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Numerous advances have been made in the understanding of mare basalt volcanism and secondary crustal emplacement on the Moon in the last decade since NVM-1. We utilize a theoretical analysis of the generation, ascent, intrusion and eruption of basaltic magma on the Moon [1-7] to develop new insights into magma source depths, supply processes, transport and emplacement mechanisms via dike intrusions, and effusive and explosive eruptions (Fig. 1, 2).

Generation: Density contrasts between the bulk mantle and regions with a greater abundance of heat sources will cause larger heated regions to rise as buoyant melt-rich diapirs that generate partial melts that can undergo collection into magma source regions; diapirs could rise to the base of the anorthositic crustal density trap (when the crust is thicker than the elastic lithosphere) or, later in history, to the base of the lithospheric rheological trap.

Ascent: Residual diapiric buoyancy, and continued production and arrival of diapiric material, enhances melt volume and overpressurizes the source regions, producing sufficient stress to cause brittle deformation of the elastic part of the overlying lithosphere; a magma-filled crack (dike) initiates and propagates toward the surface as a convex upward, blade-shaped dike. The volume of magma released in a single event is likely to lie in the range 10² km³ to 10³ km³, corresponding to dikes with widths of 40-100 m and both vertical and horizontal extents of 60-100 km, favoring eruption on the nearside. As the Moon cools with time, the lithosphere thickens, source regions become less abundant and rheological traps become increasingly deep; the state of stress in the lithosphere becomes increasingly contractional, inhibiting dike emplacement and surface eruptions.

Effusive Eruptions: Relatively low effusion rate, cooling-limited flows lead to small shield volcanoes (e.g., Tobias Mayer, Milicius); higher effusion rate, cooling-limited flows lead to compound flow fields (e.g., most mare basins) and even higher effusion rate, long-duration flows lead to thermal erosion of the vent, effusion rate enhancement, and thermal erosion of the substrate to produce sinuous rilles (e.g., Rimae Prinz). Extremely high effusion rate flows on slopes lead to volume-limited flow with lengths of many hundreds of kilometers (e.g., young Imbrium basin flows).

Explosive Eruptions: Dikes penetrating to the surface produce a wide range of explosive eruption types whose manifestations are modulated by lunar environmental conditions: 1) terrestrial strombolian-style eruptions map to cinder/spatter cone-like constructs (e.g., Isis and Orient); 2) hawaiian-style eruptions map to broad flat pyroclastic blankets (e.g., Taurus-Littrow Apollo 17 dark mantle deposits); 3) gas-rich ultraplinian-like venting can cause Moon-wide dispersal of gas and foam droplets (e.g., many isolated glass beads in lunar soils); 4) vulcanian-like eruptions caused by solidification of magma in the dike tip, buildup of gas pressure and explosive disruption, can form dark-halo craters with admixed country rock (e.g., Alphonsus Crater floor); 5) ionian-like eruptions can be caused by artificial gas buildup in wide dikes, energetic explosive eruption and formation of a dark pyroclastic ring (e.g., Orientale dark ring); 6) multiple eruptions from gas-rich fissures can form regional dark mantle deposits (e.g., Rima Bode).

Summary: Early high-Ti, middle low-Ti lavas suggest heterogeneity of mantle source regions in space and time; we see no evidence for asymmetrical (e.g., nearside/farside) distribution of source regions. The total volume of lunar extrusive secondary crust is miniscule compared with primary crust. This improved paradigm for the generation, ascent, intrusion and eruption of basaltic magma provides the basis for a more detailed understanding of lunar thermal evolution.

Fig. 1. Maria (purple), cryptomaria (green) [5-6] and pyroclastic deposits (red dots; [7]).

Fig. 2. Chronology of lunar magmatic-volcanic events.

THE LUNAR FAR-UV ALBEDO: INDICATOR OF HYDRATION AND SPACE WEATHERING.
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The ultraviolet is an ideal region of the spectrum in which to study both hydration and space weathering processes and effects because a strong H$_2$O absorption exists in this spectral regime, and because the UV senses largely surface scattering, proportional to Fresnel reflectance, rather than volume scattering. That is, the measured reflectance is directly related to the index of refraction [1]. The index of refraction of many materials increases with decreasing wavelength, so that they become brighter at shorter wavelengths. In the surface scattering regime, absorption (high k) can produce a reflectance maximum. Furthermore, since UV radiation is less penetrating than visible radiation, short wavelengths are more sensitive to thin coatings on grains that may be the result of weathering processes. UV wavelengths are also sensitive to the topmost grains of the lunar regolith, which experience different thermal variations than grains deeper in the regolith.

**Hydration.** The presence of a strong water absorption edge in the far-UV (near 165 nm) allows the study of lunar hydration by the Lyman Alpha Mapping Project (LAMP) onboard the Lunar Reconnaissance Orbiter (LRO). To map the presence and strength of the water feature in the LAMP data, Hendrix et al. [2] made a straight line fit to each reflectance spectrum in the 164-173 nm range, where the presence of any water is expected to most strongly affect the slope and determined the slope of that line, after photometrically correcting using the Lommel Seeliger term $\mu_0/(\mu+\mu_0)$. For comparison, Hendrix et al. [2] also studied the slopes in the 175-190 nm range, where the slope is not expected to change due to hydration effects. Hendrix et al. [2] found a relationship between the 164-173 nm slope and time-of-day, with steeper (redder) slopes (consistent with increased hydration) earlier and later in the day, and at higher latitudes. Near noon, the slopes were the bluest. The slopes in the 175-190 nm range showed no relationship with time-of-day. These spectral slope changes are consistent with small abundances (~1%) of hydration, with the abundance varying over the course of a day. Far-UV wavelengths are sensitive to the uppermost ~100 nm of the lunar regolith, suggesting that the hydration sensed by LAMP on the lunar dayside is surficial and transient.

**Space Weathering.** Our work has shown that the UV bluing effects associated with weathering and first discovered at near-UV wavelengths [2][3][4] extend into the far-UV (100-200 nm), as confirmed using data from LRO LAMP. The ‘bluing’ of the spectrum (i.e., a negatively-sloped spectrum) is in contrast with the spectral reddening (with a positively-sloped spectrum) that is seen at visible to near-infrared wavelengths (VNIR) with weathering. The bluing is related to the spectral behavior of iron (modeled as inclusions in grains); the addition of sub-microscopic iron (SMFe), likely specifically in the grain rims, tends to mask the typical Fe$^{+3}$ UV/blue IVCT (intervalance charge transfer) absorption edge (near 300-400 nm) of silicates. LAMP data show that the Moon in general is FUV blue, consistent with early results from IUE [5]. In the LAMP data, mare regions rise steadily in reflectance from 190 nm down to 130 nm while the highlands regions are spectrally flat between ~160 and 190 nm and rise with a blue slope shortward of 160 nm. Maria are bluer than highlands regions due to greater abundances of opaques such as ilmenite and some pyroxenes.

LAMP data also demonstrate significant spectral differences between mature and immature terrains, particularly in highlands regions. Mature, weathered highlands regions are spectrally blue in the FUV; immature highlands are less blue, especially at wavelengths > ~160 nm.

We have also used LAMP data to study the magnetically-anomalous lunar swirl regions Reiner Gamma and Gerasimovich [6]. The FUV characteristics of both swirls are consistent with lower levels of maturity than the immature lunar terrains that were studied, in accordance with the lower amounts of weathering expected in a solar wind standoff scenario (e.g., [8]). Swirls in both highlands and mare regions are spectrally relatively red (or less blue) than surrounding terrains, consistent with less weathering.

Introduction: Accurate knowledge of the lunar cratering chronology (LCC) is required to derive absolute model ages across the lunar surface and throughout the inner Solar System [e.g., 1]. Unfortunately, there are only a few data points at ages younger than about 3 Ga, and no data points at ages older than 3.9 Ga to constrain the LCC. We systematically performed crater size-frequency distribution (CSFD) measurements for Copernicus, Tycho, North Ray, Cone, and Autolycus craters to test and improve the LCC [2–4].

Results: Cone crater: Although exposure ages of Apollo 14 samples from Cone crater range from ~12 Ma [5] to ~661 Ma [6], several studies agree on a formation age of ~25–26 Ma [e.g., 7–9]. From nine count areas around Cone crater, our absolute model age (AMA) is ~39 Ma, consistent with previous AMAs varying from ~24 Ma [10] to ~73 Ma [11], in addition to the exposure ages.

North Ray crater: Previous studies [12,13] found cosmogenic ray exposure ages of 50.3±0.8 Ma at North Ray, which agree with the cosmic ray exposure results of [14] (48.9±1.7 Ma). [15] reported an 40Ar/37Ar age of 50.6±3.8 Ma, similar to 22Ne ages and particle track ages. Microfracture measurements suggest that North Ray formed more than 20 Ma ago [16]. Coarse fragments give 39Ar/37Ar cosmic-ray exposure ages between 30 and 50 Ma [17]. Thus, [7] concluded that North Ray formed 50.3±0.8 Ma ago. For North Ray, four individual count areas, as specified by [2], were counted independently by two counters, yielding ages of 46 and 47 Ma [7].

Tycho crater: Secondary craters from the Tycho impact event were suggested to have triggered a landslide at the South Massif at the Apollo 17 landing site [17,18]. Samples returned from the landslide and the Central Cluster revealed exposure ages of about ~100 Ma, which were interpreted as the formation age of Tycho crater [e.g., 13, 18–20]. From the exposure ages, [13] concluded that Tycho is 109±4 Ma old. This age is identical to that of [20], and is similar to an exposure age of 96±5 Ma derived by [19]. CSFD measurements on NAC images of four areas on the continuous ejecta blanket (granular material, not impact melt) of Tycho yielded a combined AMA of 85 Ma, identical to our average AMA of three count areas on the landslide, but slightly younger than that derived from CSFD measurements on the ejecta blanket using WAC images (124 Ma). CSFDs of [21] yield an AMA of 75 Ma for the ejecta blanket.

Copernicus crater: A faint ray of Copernicus material crosses the Apollo 12 landing site, which led [22] to propose that KREEPy glass in the samples was ejected by the Copernicus event, and could be used to date the impact. Exposure ages of the glass have an age of 800–850 Ma [23–27]. Radiometric ages also support an age of 800±15 Ma [26,28–29]. Analyses of 21 regolith samples show degassing ages of 700–800 Ma, which give an estimated 782±21 Ma age for the Copernicus impact event [30]. We used NAC images to count 9 areas on the ejecta blanket, which gave an AMA of 797 Ma. CSFD measurements for three ejecta blanket areas on WAC images yielded a similar age of 779 Ma. Our results fit the existing lunar chronology of [3] significantly better than their previous counts [3].

Autolycus crater: Rays from Autolycus and Aristillus craters cross the Apollo 15 landing site and presumably transported material to this location [e.g., 31,32]. Thus, [33,34] proposed that the 39Ar/39Ar age of 2.1 Ga, derived from two petrologically distinct, shocked Apollo 15 KREEP basalt samples, date Autolycus crater. Aristillus crater is younger than Autolycus crater and as a result severely modified Autolycus crater and its ejecta deposits. Thus, a heating event in sample 15405 at 1.29 Ga was interpreted as the age of Aristillus crater [35]. The exact timing of the two impacts, however, remains under debate because [36] interpreted U–Pb ages of zircon and phosphate grains of 1.4 and 1.9 Ga from sample 15405 as the formation ages of Aristillus and Autolycus. If Autolycus crater is indeed the source of the dated exotic material collected at the Apollo 15 landing site, then CSFD measurements on the ejecta blanket of Autolycus crater offer a new calibration point to the lunar chronology, particularly in an age range that was previously poorly constrained. Using NAC images, we extracted CSFD measurements for 6 areas inside and on the ejecta blanket of Autolycus crater, yielding widely variable AMAs. None of our CSFDs yield AMAs that correspond either to the 2.1 Ga [33,34] or 1.9 Ga [36] sample ages. This either implies that the dated samples are not related to Autolycus or that the CSFD measurements are so heavily affected by resurfacing and secondaries from the Aristillus event that they do not represent the formation age of Autolycus crater. In either case, because of these uncertainties Autolycus cannot be used as a calibration point for the LCC.

LUNAR MAGNETISM: PROGRESS AND REMAINING ISSUES. Lon L. Hood, Lunar and Planetary Laboratory, 1629 E. University Blvd., University of Arizona, Tucson, Arizona, 85721 (lon@lpl.arizona.edu).

Introduction: During the last 10 years that have elapsed since publication of New Views of the Moon, major progress has been made in the interpretation of lunar magnetism. Most importantly, it is now generally accepted on the basis of both sample paleointensity analyses and orbital measurements that the Moon once possessed a global magnetic field generated by dynamo processes in its metallic core. In addition, the Japanese Kaguya mission has provided new measurements of the crustal field that complement the dataset acquired by Lunar Prospector. Analyses of the crustal field data for a number of applications (e.g., solar wind interaction with crustal anomalies, origin of the lunar “swirls”; history of the core dynamo, paleomagnetic pole positions) have been conducted and are continuing.

Progress: As summarized in the 2006 chapter by Wieczorek et al. [1], it was unclear at that time whether a core dynamo magnetic field was required to explain the paleomagnetism of the returned samples or the crustal magnetism observed from orbit. The small size of the lunar metallic core (radius < 400 km) combined with paleointensity estimates exceeding 1 Oersted (100 μT) were difficult to explain via conventional dynamo theory for a thermally convecting core. Several aspects of the crustal field observations, including the apparent concentration of anomalies antipodal to the youngest and largest impact basins, suggested that transient magnetic fields associated with impact processes may have been responsible for imparting some or all of the crustal magnetization.

During the last 10 years, laboratory paleomagnetic analyses of returned samples have improved substantially, leading to two main conclusions: (a) at least some mare and highland igneous samples acquired their primary magnetization via thermoremanence, requiring slow cooling in a steady magnetic field; and (b) the magnetizing field for such samples with ages between ~3.56 and 4.25 Gyr had amplitudes in the range of several tens of μT, up to 60-80 μT [2,3,4].

From an orbital standpoint, the most important new development during the last 10 years has been the gradual realization that at least one class of crustal anomalies almost certainly requires a former core dynamo. These are anomalies within the rims of large impact basins such as Moscovienese and Crisium [5,6]. The sources of these anomalies most probably consist of impact-produced melt that was heated to high temperatures following the impact and required long time periods (up to 1 Myr) to cool through the Curie blocking spectrum. The long cooling timescale requires a steady, long-lived ambient magnetizing field, i.e., a core dynamo field.

Remaining Issues: Several important issues relating to the crustal magnetism are not yet resolved. These include (but are not limited to): Origin of strong anomalies in the lunar highlands; origin of the lunar swirls; reliability of inferred paleomagnetic pole positions; and history of the former core dynamo.

As of 2006, the leading hypothesis for the origin of strong anomalies in the highlands was that the sources consist of impact basin ejecta deposits. This hypothesis stems from surface observations of strong magnetic fields at the Apollo 16 landing site, which is dominated geologically by the Cayley Formation, a smooth plains unit with an impact basin ejecta interpretation [7]. Statistical studies of the Lunar Prospector electron reflectometer data showed that the Cayley Formation is the single geologic unit that correlates best with surface field strength on the near side [8].

Since 2006, alternate hypotheses have been advanced, including that the sources consist of ejecta from an iron-rich asteroid that produced the South Pole-Aitken basin [9] or that they consist of magnetized subsurface dike swarms that fed mare basalt patches emplaced within the SPA rim [10]. On the other hand, further evidence in support of the ejecta model and for the concentration of anomalies antipodal to young impact basins has also been presented [11].

Current work focuses on investigation of paleomagnetic pole positions [12,13] and on providing macroscopic evidence in support of sample data for the history of the former core dynamo [14].

THE DUST ENVIRONMENT OF THE MOON. M. Horányi¹, J. Szalay², E. Grün², D. Glenar³, X. Wang³, A. Zakharev³, ¹Laboratory for Atmospheric and Space Physics, U. of Colorado, Boulder; ² Solar System Exploration Research Virtual Institute (SSERVI) Institute for Modeling Plasmas, Atmospheres, and Comsic Dust (IMPACT), ³Southwest Research Institute, San Antonio, TX; ⁴University of Maryland, Baltimore, MD; ⁵Space Research Institute, Moscow, Russia

Introduction: The dust environment of the Moon remained a controversial subject since the Apollo era. The near surface dust populations are thought to include: a) particles generated by the continual bombardment of interplanetary dust particles; and b) the putative population of electrostatically mobilized particles. We will briefly review the history of the observations by the Surveyor cameras, the Apollo imaging, the Lunar Ejecta and Meteoroid (LEAM) experiment, and the UV observations by Clementine and LRO, but will mainly focus on the results of the Lunar Dust Experiment (LDEX) onboard the Lunar Atmosphere and Dust Environment Mission (LADEE)[1]. The talk will also briefly summarize the recent laboratory experimental results on the charging and mobilization of dust particles on regolith surfaces [2].

The LADEE Mission: LADEE was launched on September 7, 2013, and started its 150 days of science observations in the typical altitude range of 20 - 100 km, following a near-equatorial retrograde orbit, with a characteristic orbital speed of 1.6 km/s. LDEX, an impact ionization dust detector [3], detected a total of ~140,000 dust hits during ~80 days of cumulative observing time by the end of the mission on April 18, 2014.

Summary of the Results: LDEX recorded average impact rates of ~ 1 hit/minute of particles with radii of ~ 0.3 μm (Fig. 1). Using the data taken over many months of operation, LDEX was able to characterize the dust density distribution of the lunar dust cloud as a function of time, altitude, and local-time (LT). LDEX discovered a permanently present, asymmetric dust cloud [4]. The lunar dust cloud was found to be generated by the very same meteoroid fluxes observed at Earth, namely the helion, apex, and anti-helion sources. The ejecta cloud was found to be sensitive to small changes in impactor fluxes and velocities, solidifying that the Moon is an efficient large area dust detector. Its response to the local meteoroid environment provides a valuable resource for understanding the meteoroid population at 1 AU [5]. LDEX measurements were also used to characterize meteoroid showers. Approximately once a week, LDEX observed bursts of 10 to 50 particles in a single minute. By analyzing these bursts during meteoroid showers, the radiants for known showers was extracted from LDEX measurements [6]. LDEX did not find density enhancement over the terminators [7], or any evidence of electrostatic mobilization of very small particles above the surface (h > 1 km).

LDEX measurements can be used to improve our models of the spatial, size, and speed distribution of interplanetary meteoroids. Similar measurements near the moons Phobos and Deimos have been suggested to map the dust flux near Mars. An LDEX type instrument sent to any airless body in the solar system would gather critical information about its local meteoroid environment, and potentially its plasma environment.

**LUNAR SURFACE VOLATILES.** D. M. Hurley¹ and M. A. Siegler²-³, ¹Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, MD 20723 (dana.hurley@jhuapl.edu), ²Planetary Science Institute, Tucson, AZ, ³Southern Methodist University, Dallas, TX

**Introduction:** Since the publication of New Views of the Moon, understanding of surface volatiles on the Moon has increased significantly. In 2000, the existence of water on the Moon was a hypothesized, but not definitively demonstrated. Some tantalizing support for the presence of water existed in neutron observations consistent with the presence of H [1] and radar backscatter consistent with ice [2]; however neither of these observations provided conclusive evidence.

Since that time, an armada of spacecraft including Chandrayaan-1, Deep Impact, Cassini, LRO, LCROSS, and LADEE provided compelling evidence that water is not only present on the Moon, but it also is more prevalent than previously expected [3]. Additional information from Kaguya, ARTEMIS, Chang’è-3, ground-based telescopic observations, lab work, Apollo sample analysis, and modeling have expanded the understanding of the processes involved in the source, distribution, and retention of volatiles on the Moon.

**Quantities of Interest:** For both scientific understanding and for utilization of lunar volatiles as a resource to enable exploration, there are four main quantities of interest: abundance, distribution, composition, and physical form. These quantities have some relevant observations in recent years. Often it is the integration of these data sets that must be used to determine the answers. Scientifically, we would also like to understand the age and origin of these volatiles as they may provide further understanding of the volatiles distribution of the inner solar system. We present the state of knowledge on each of these quantities [4].

**Physical Processes:** Understanding of lunar volatiles is important for the understanding of the physical processes acting on the Moon and on other airless bodies in the solar system. In order to examine, constrain, and compare the physical processes that control the amount and distribution of volatiles on the surface of the Moon, it is important to study it as a system. The system begins with the sources of volatiles. Present day sources, and constraints on past sources, are being quantified by recent and ongoing missions [e.g. 5,6].

Next, the redistribution of the volatiles from the point of delivery is studied. Recent evidence points to a diurnal cycle of OH/H2O adsorbed to the surface [e.g. 7,8]. Volatiles migrating through the exosphere interact with the surface [9]. The LADEE observations of the Chang’e 3 exhaust plume was a controlled experiment of a real vapor release on the Moon that constrained these surface interactions [10]. Migration into the shallow subsurface may also serve as a reservoir for surface derived volatiles [e.g.11]. The migration influences the eventual delivery of volatiles to cold traps.

The stability of volatiles in permanently shadowed regions is the next piece of the system. New data regarding the thermal, illumination, radiation, and regolith properties in the PSRs have increased understanding of the retention and migration of volatiles in PSRs [e.g. 12]. In addition, the processes that remove volatiles from PSRs may not remove them from the system, but instead redistribute the volatiles laterally or with depth. This produces a heterogeneity in the distribution that provides insight into which processes have dominating effects. Understanding the volatiles in the PSRs, especially in comparison to similar regions on the planet Mercury, may provide insights to the age and origin of inner solar system volatiles.

**Conclusion:** Volatiles on the surface of the Moon are a potential resource, and hold a lot of information about important planetary processes.

**THE LCROSS PLUME AS OBSERVED BY LRO/LAMP.** D. M. Hurley¹ G. R. Gladstone², S. A. Stern³, K. D. Retherford², P. D. Feldman³, W. Pryor³, A. F. Egan¹, T. K. Greathouse², D. E. Kaufmann³, M. Davis², M. Versteeg⁶, A. R. Hendrix⁶, ¹Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, MD 20723 (dana.hurley@jhuapl.edu), ²Southwest Research Institute, San Antonio, TX, ³Southwest Research Institute, Boulder, CO, ⁴Johns Hopkins University, Baltimore, MD, ⁵Central Arizona University, ⁶Planetary Science Institute

**Introduction:** The Lyman Alpha Mapping Project (LAMP) onboard the Lunar Reconnaissance Orbiter (LRO) has observed the exosphere of the Moon since its arrival in 2009. The LRO spacecraft was co-manifested with the Lunar Crater Observation and Sensing Satellite (LCROSS). LRO characterized the candidate impact sites enabling the final site selection. LRO participated in the investigation by observing the impact and the evolution of the environment on several subsequent orbits.

**Instrument:** The LAMP far ultraviolet (FUV) imaging spectrograph has a wavelength range of 57-196 nm [1]. Exospheric spectra can be observed when LRO is in the geometry such that the line of sight includes illuminated exosphere but does not include the bright surface of the Moon. In nominal operations, this occurs for a short time while LRO crosses the terminator and the footprint of the field of view falls on the shadowed lunar surface. In addition, LRO performs maneuvers that point off-nadir. This can increase the illuminated column of exosphere and improve the signal to noise for the observation.

**LCROSS impact:** On 9 Oct. 2009, the Lunar Crater Observation and Sensing Satellite (LCROSS) mission performed an intentional impact into the permanently shadowed region (PSR) of Cabeus crater. The impact released vapor into the exosphere. LRO adjusted its phasing such that it would pass the impact site 90 s after the impact. LRO rolled to the side to observe the plume as it rose into sunlight against the background of the dark sky. LAMP detected the plume about 25 s after the impact. The brightness of the plume peaked quickly then decayed. A small hump is observed when the field of view passes the impact site, indicating a lesser slowly subliming source. No signal was detected on any subsequent orbit. Spectral analysis revealed the presence of H₂ and CO. In addition, a feature at 185 nm appears is consistent with the combination of Hg, Ca, and Mg [2].

**Model:** A Monte Carlo model simulated the expansion and propagation of the vapor after released from the surface [3]. The model could reproduce the observed light curves only for a small range of initial conditions. The model assumed the vapor was released as a drifting Maxwellian characterized by a velocity with a thermal distribution is superposed on a constant bulk velocity. The best fit was found for a bulk velocity of ~3.5 km/s. The fits to the 180-190 nm light curve tightly constrained this value, but did not constrain the temperature. The fits to the 130-170 nm spectrum constrained the temperature to ~800 K. Most of the impact vapor escapes the Moon.

**Conclusions:** The LRO LAMP observation of the LCROSS impact identified some of the volatile constituents on the lunar PSRs. The dynamics of the vapor plume were well constrained. The vapor expanded rapidly and dissipated.

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**Figure 1.** LAMP time series showing the light curve of the LCROSS plume in the 180-190 nm range (top) and 130-170 nm range (bottom).

**Figure 2.** Goodness of fit for different modeled temperatures and bulk velocities to the 130-170 nm light curve. They indicate a bulk velocity of < 3.5 km/s and temperature < 1000 K.

FELSIC VOLCANICS ON THE MOON. B. L. Jolliff\textsuperscript{1}, R. N. Clegg-Watkins\textsuperscript{1}, M. R. Zanetti\textsuperscript{2}, S. J. Lawrence\textsuperscript{2}, J. D. Stopar\textsuperscript{3}, K. A. Shirley\textsuperscript{4}, T. D. Glotch\textsuperscript{4}, and B. T. Greenhagen\textsuperscript{5} \textsuperscript{1}Department of Earth & Planetary Sciences, Washington University, St. Louis, MO 63130; \textsuperscript{2}University of Western Ontario, London, Ontario; \textsuperscript{3}Arizona State University, Tempe, AZ 85287; \textsuperscript{4}Stony Brook University, Stony Brook, NY; \textsuperscript{5}Johns Hopkins University Applied Physics Laboratory, Laurel, MD (blj@wustl.edu).

Introduction: Images and data from the Lunar Reconnaissance Orbiter (LRO) have provided a significantly improved view of compositionally evolved felsic volcanics and possibly related intrusive rocks on the Moon [e.g., 1,2,3]. LRO Diviner Lunar Radiometer (Diviner) Christiansen Feature data have revealed felsic compositions [1-4] in several locations previously known as “red spots” such as the Gruithuisen Domes (GD), Mairan Domes (MD), Hansteen Alpha (HA), Lassell Massif (LM), Aristarchus crater ejecta (AE), and the Compton-Belkovich Volcanic Complex (CB). Narrow Angle Camera (NAC) images and digital terrain models (DTMs) derived from NAC geometric stereo images have been used to assess the morphometry of volcanic materials, including relatively steep slopes on volcanic constructs, summit depressions, and caldera-like collapse features [5-9].

These observations provide much needed geologic context for the fragments of compositionally evolved silicic or “felsic” materials known about the Apollo samples for many years, including granite or rhyolite and potentially related alkali-suite monzogabbro and alkali anorthosite [8,10,11]. Such fragments of rock and breccia components are known from all of the Apollo sites, but are most abundant among the Apollo 12, 14, and 15 samples [10]. In every case, these materials have been excavated by impacts and transported from unknown source regions to their sampling locations. The increased resolution of detections and characterization of sites of potential felsic volcanism, however, are leading to a better understanding of possible sites and modes of origin [e.g., 3,5,11,12].

Morphologies: The topographic and morphologic expressions of the inferred silicic volcanic complexes exhibit striking diversity. The Gruithuisen Domes are the largest of the volcanic constructs, with the δ and γ domes each over 10 km across and ~1700-1800 m high [6,13]. The Mairan Domes range in size, with the largest volcanic constructs being the “middle” and “T” domes, on order of 5-8 km base widths and at least 800 m heights, and the T dome has a distinctive summit depression [5,13]. The CB volcanic complex is a broad dome, ~25x35 km across and about half a km height, with an irregular central depression interpreted to be a collapse caldera [3,9,14]. The CB complex has a range of volcanic constructs, with the “alpha” dome being the largest, with a base width of ~4x6.5 km, an elevation ~550 m, and a small summit depression [3,14]. The HA complex is a rough-textured triangular mound ~25 km on a side, the margins of which stand ~700 m above the surrounding mare surface.

Each of these volcanic complexes features relatively steep slopes, up to about 25°, although some of the small topographic features seen in NAC-derived DTMs at HA and CB are little more than low-relief circular bulges. Many of these small bulges also feature distinctive, dense boulder populations. These features suggest formation from relatively silicic and viscous lavas [e.g., 3,5,6,13]. The compositions indicated by remote sensing are consistent with low-FeO felsic materials [15].

Origins: Possible origins put forth for the Apollo granite (felsic) materials include (1) extreme fractional crystallization [3], (2) partial melting of a fertile source, e.g., KREEP-rich materials by basaltic underplating [12], and (3) silicate liquid immiscibility (SLI) associated with late-stage crystallization in either scenario (1) or (2). Although SLI has been demonstrated to have occurred on a small scale [11], it is unclear whether this process could or did occur on a large scale, e.g., to produce the large domes such as GD. Late-stage SLI on a small scale, however, might be involved in the formation of small domes and bulges at HA and CB. A remaining issue is the degree and range of SiO2 enrichment exhibited at the volcanic sites [15].

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**Introduction:** South Pole-Aitken (SPA) basin, the largest and oldest confirmed lunar basin, represents a high-priority science target for current and future lunar and Solar System exploration [1]. The SPA impact event has been interpreted to have generated a huge volume of impact melt that was on order of tens of km to perhaps 50 km thick [2,3] and perhaps 7×10^7 km³ volume [4]. That the age of this huge amount of rock was reset by the SPA event makes the age determination of SPA materials of critical importance for establishing the absolute chronology of giant impacts in the inner Solar System. The SPA basin “chronology,” which includes ages of other basins and large craters within SPA, provides a crucial contrast to the nearside, Imbrium-dominated chronology.

**Recent Results:** The column of rock melted probably included a substantial portion of crust and also upper mantle material. A fraction of the upper crust may have been removed to other parts of the Moon, especially the thick, northern farside highlands [5]. The compositional contribution of relatively mafic deep-seated components contributes today to the mafic interior SPA composition as measured remotely. Recent modeling of the fate of this melt volume suggests differentiation [2,3] to produce the rock types sensed remotely in central peaks, which are dominantly noritic (orthopyroxene- and plagioclase-dominated) in composition [6]. This noritic character does not necessarily reflect mainly crustal materials because a melt sea of tens of km thickness would differentiate, and ultramafic olivine and pyroxene cumulates could form a deep, unsampled keel whereas plagioclase-bearing norite would be expected in the upper parts of the melt sheet [2] or result from more complex interactions with an early, still evolving (overturning) mantle [3] or vigorously convecting impact melt [7]. The detailed composition of the impact melt (and impact-melt breccia) cannot be discerned from orbit, however. Samples of impact melt and entrained clasts are needed to unravel the mixing systematics.

Complicating the surface compositional and mineralogical signature is the mafic contribution from mare and cryptomare volcanics in the basin interior. However, new data are being used to distinguish these deposits and to ascertain their contribution to the basin floor [8-11]. One of the most enigmatic morphological and compositional features is the “Mafic Mound,” near the basin center, for which recent results suggest an ancient volcanic origin possibly associated with the SPA impact-melt sheet [3,12], making this area of the basin interior of special interest. Locations exist where the regolith is expected to contain a mixture of Mafic Mound materials, mare and cryptomare volcanics, and yet still be dominated by SPA substrate [e.g., 13,14]. The chronology of samples from regolith in this part of the basin should contain a rich assortment bearing on the age of SPA, the ages of subsequent large impacts, and the age of volcanism both related to and subsequent to the formation of SPA.

**New Data Sets:** Data on composition, topography and surface roughness [10,11], subsurface density and porosity [15], and relative surface ages by impact crater size-frequency determinations [16] are critical to understanding the geologic history of this key and as yet unsampled terrane of the Moon. Analysis of mission data from Kaguya [17-20], Chandrayaan-1 M³ [21], GRAIL gravity [15], and LRO [e.g., 10,22,23] are providing new insights to these issues and helping in the identification of potential sampling sites.

THE MOON AS AN ARCHIVE OF SMALL BODY MIGRATION IN THE SOLAR SYSTEM. K. H. Joy¹ (katherine.joy@manchester.ac.uk), I. A. Crawford², N. A. Curran², M. E. Zolensky³,4, A. L. Fagan⁴, and D. A. Kring³
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Overview: Constraining the sources and temporal flux of impactors delivered to the Moon helps to address key questions about the causes of impact bombardment in the inner Solar System [1-7]. Some evidence for the lunar impact record comes from surface morphology and geophysical characteristics of craters and basins (e.g., the number, size, and relative ages of structures [1,2]). Additional information is preserved in the lunar sample collection, recording the timing of impact events (i.e., isotopic resetting of rocks and impact melt crystallisation events [3]) and evidence of the sources of the projectile populations [4-7].

The impact melt breccia and igneous rock archive: Chemical signatures of material accreting to the lunar crust and mantle have been identified from the budgets of highly siderophile elements (HSEs) and volatile elements in impact melt [5,6] and endogenous igneous samples [8-10]. HSE analyses of different lunar impact melt breccias imply that projectiles in the basin-forming epoch (~3.8-4.2 Ga) originated from primitive asteroids (i.e., ordinary and carbonaceous chondritic), differentiated asteroids (i.e., iron meteorite sampled from planetary embryo cores), and bodies that are compositionally dissimilar from those that we find in the current meteorite collection [5,6].

The regolith archive: The lunar regolith is a time capsule of small body migration in the Solar System.

Chemical signatures: Nitrogen isotope analysis of lunar soils and agglutinates indicate a common exogenously contributed 'planetary' chemical component in the lunar regolith [11]. Inorganic gas release measurements have shown that some soils have exogenously implanted volatile elements from cometary or carbonaceous chondrite impactors [12]. HSE chemistry of mature lunar regoliths suggest an addition of between ~1.6 to ~3.4 % primitive CI/CM-like chondritic meteorite material during space exposure intervals of tens to hundreds of millions of years [13,14]. It is important to note that this regolith 'meteoritic component' is a chemical signature, originating from the contribution of vaporised impactor material bound up in microscale metals and sulphides within comminuted impact melt breccias and glassy agglutinate structures.

Projectile debris: Survivability of projectiles to the Moon's surface is facilitated by low impacting velocities (<10 km/s) and by oblique (<10°) impact angles [15]. Examples of surviving projectile debris have been located in soils and regolith breccias, where impactor types include iron meteorites, chondrule fragment debris, carbonaceous chondrite silicate mineral debris, and an enstatite chondrite (see [7] for a review). All these fragments are very small (i.e., a few microns to few mm) and to date no cometary silicate debris has been directly identified in lunar regolith samples.

Constraining timing of projectile delivery to the regolith: Constraining regolith ages can be challenging, but it is critical for understanding the temporal variation of sources of small bodies delivered to the Moon [7,16]. The duration of a regolith’s space exposure can be determined by measuring abundances of cosmogenic nuclides, however, this does not tell us when in the past that exposure occurred. Regolith antiquity records are preserved in fused regolith breccias collected as hand specimens and rock fragments in the lunar soil [16]. Most accurate temporal records are likely preserved in trapped (ancient) palaeoregolith horizons found sandwiched between layers of radiometrically datable geological units, examples of which are now being identified from orbit using ground penetrating radar techniques or high-resolution images of layered bedrock exposures [17].

Conclusions: In the last decade new and improved analytical techniques have facilitated both the detection and characterisation of impactor species in Apollo samples and lunar meteorites [5-13,16]. New exploration methods should consider identification and the characterisation of impactor debris in different lunar terrains [17], as they may be associated with deposits that have a resource potential. Coupling these datasets with temporal constraints on impactor delivery will help to provide better geochemical and chronological constraints for models of Solar System dynamics, as well as identify the causes of impact spikes to the Earth-Moon system through time [1,4-7,16,17].

LUNAR METEORITES: NEW INSIGHTS INTO THE GEOLOGICAL HISTORY OF THE MOON K. H. Joy1 (katherine.joy@manchester.ac.uk), N. A. Curran1, J. F. Pernet-Fisher1, T. Arai2. 1SEAES, University of Manchester, Manchester, UK. 2Planetary Exploration Research Center, Chiba Institute of Technology, Chiba, Japan.

Overview. Studies of lunar meteorites have brought unique insights to the Moon in time and space, helping us to better understand lunar lithological diversity and geological history [1,2].

Understanding the global compositional diversity of the lunar surface. Rock and mineral fragments within lunar meteorite regolith breccias have revealed new types of lunar lithologies, and the existence of new minerals providing insights into the diversity of magmatic [3] and space weathering processes [4] across the Moon. Importantly, the compositions of lunar meteorite regolith breccia have been used to calibrate remote sensing geochemical datasets, providing a more accurate global perspective of the chemical diversity of the lunar surface [5].

Understanding the formation of the ancient lunar primary crust. Feldspathic lunar meteorites have provided the first samples from the Feldspathic Highlands Terrane on the farside of the Moon, offering new perspectives to the compositional diversity of the lunar primary crust [6-8] and the history of its formation [8, 9]. Recent studies of anorthositic material in feldspathic lunar meteorites [6-8, 10] further indicate that it is possible that the crust may not have formed in a simplistic single magma ocean floatation event, and that more complex geological processes may account for crustal compositional heterogeneity [8-10]. This debate is controversial because of the small sample sizes of rock fragments in lunar meteorites [9, 11], however, as additional samples are investigated with innovative geochemical and isotopic techniques, together with studies of high-spatial-resolution remote sensing data, new ideas are emerging about the diversity and evolution of the lunar crust.

Understanding the diversity and timing of mantle melting, and secondary crust formation. Basaltic lunar meteorites are compositionally more diverse than Apollo and Luna samples, with many very-low-Ti (VLT <1 wt% TiO2) and intermediate TiO2 (6-10 wt% TiO2) types found as small rock fragments in brecciated meteorites [12]. These offer new insights to the heterogeneity of the lunar mantle in regions both within and outside of the nearside PKT.

Basaltic lunar meteorites have also provided new insights about the temporal history of mare basalt eruption. Apollo mare basalts were typically erupted between 3.2 and 3.8 Ga, whereby older basalts have higher-Ti contents relative to the younger low-Ti basalts. In contrast, basaltic lunar meteorites represent both the youngest 2.93 Ga (NWA 032; [13]) and the oldest 4.35 Ga (Kalahari 009 [14]) sampled mare basalt lava flows. The lunar meteorites show no relationship between age and bulk rock Ti-composition [2], suggesting that the Apollo mare basalt dataset age-Ti correlation was an artefact of site sampling, and that secular melting in the lunar mantle is not coupled to the Ti-chemistry of the mare basalt source regions.

Understanding the impact bombardment history of the Moon and the inner Solar System. Lunar meteorite impact ages [15] and regolith breccia antiquity records provide a vital insight into studying the lunar cratering record and impact flux in regions distal to the Imbrium basin-forming event, which likely dominates the Apollo rock records. Lunar meteorite impact age data show no noticeable spikes prior to 4.2 Ga that would be consistent with ancient widespread basin formation caused by early Solar System accretonary debris [16]. Instead, like the Apollo samples, they show an enhanced late bombardment episode (peaking at ~3.7 Ga). However, this enhanced record appears to have a longer duration than witnessed by the Apollo samples and may reflect sampling of smaller and/or more localised impact cratering episodes [17]. In addition, regolith breccias with different formation ages offer temporal snapshots of regolith processing of the lunar highlands [18].

Future perspectives: The number of lunar meteorites is growing each year. Laboratory chemical, mineralogical, isotopic and chronological analysis of these samples has revealed important similarities and differences to samples in the Apollo and Luna sample collection, helping to test and constrain key models of the Moon’s geological evolution and its archive of impact bombardment in the inner Solar System [1, 2].

NEW INSIGHTS INTO LUNAR TRUE POLAR WANDER. J. T. Keane¹, I. Matsuyama¹, and M. A. Siegler²;³;¹
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Introduction: True polar wander (TPW) is the re-orientation of a planetary body with respect to its spin axis due to the redistribution of mass the object. As mass is redistributed (e.g. due to an impact, mantle plume, etc.) the planet reorients in order to remain in a minimum energy rotation state (with the maximum principal axis of inertia aligned with the spin vector). Thus, the study of TPW and the associated paleopoles is intrinsically related to large-scale geophysical processes, including impact basin formation [1], mantle convection [2], tidal heating [3], etc. In this paper, we summarize recent developments in understanding the polar wander history of the Moon, including: the first accurate measurements of the Moon’s fossil figure (and the primordial spin pole of the Moon), and the observation of a new class of lunar paleopole recorded in polar volatiles.

The Moon’s Fossil Figure: As first recognized by Laplace [4], the Moon’s rotational and tidal bulges are much larger than expected from hydrostatic equilibrium assuming the Moon’s present orbital and rotational state. This excess deformation has been ascribed to a “fossil figure”—an elastically supported lithosphere preserving an epoch of lunar history when the Moon was closer to the Earth and was subject to larger tidal/rotational potentials. While the presence of a fossil figure can explain the Moon’s observed figure (quantified by the Moon’s inertia tensor or degree-2 gravity), early efforts necessitated the formation of the lithosphere during a period of high eccentricity and/or higher-order spin-orbit resonance [5,6], which is problematic for the formation of an elastic lithosphere [7].

Keane & Matsuyama [1] and Garrick-Bethell et al. [3] independently explained this anomalous lunar figure by removing the contribution of impact basins from the lunar figure. Impact basins have some power in degree-2 topography and gravity and obscure the true underlying fossil figure. Keane & Matsuyama showed that South Pole-Aitken (and the other large basins to a much smaller extent) resulted in ~20° of polar wander. Furthermore, removing impact basins and TPW also results in a figure consistent with an early low-eccentricity, synchronous lunar orbit. Using a different technique, Garrick-Bethell et al. also found a small amount of polar wander due to basins, although they did not fully address the nature of the fossil figure. A detailed comparison of these two methodologies will be presented.

A Paleopole Recorded in Ice: Siegler et al. [2] recently identified an off-polar, antipodal polar hydrogen enhancements as candidate “volatile” paleopoles. Dynamical analysis indicates that this paleopole resulted from TPW due to the formation and evolution of the Procellarum KREEP Terrane (PKT). As polar volatile stability requires extremely low obliquities (<12°), the epithermal neutron paleopole likely tracks TPW in the last 3 Gyr, after the Cassini-state transition. This paleopole also provides a new window into the geologic history of the PKT, as the TPW is strongly dependent on the heating and uplift history of the PKT.

A Unified Chronology of Lunar True Polar Wander: Although there is significant scatter in the observed lunar paleopoles (Fig. 1), there is promise in unifying these paleopoles into a cohesive TPW chronology. The fossil figure [1,3] provides the “initial” spin pole of the Moon. Paleomagnetic poles likely trace the lunar pole during the first Gyr of lunar history when the core dynamo was active. Finally, the strong sensitivity of polar volatiles to spin geometry means that the volatile paleopole [2] are particularly sensitive to small amounts of polar wander, late in lunar history.

![Fig. 1: The many proposed lunar paleopoles.](Image)

SPACE WEATHERING RATES IN LUNAR SOILS. L. P. Keller\textsuperscript{1} and S. Zhang\textsuperscript{2}. \textsuperscript{1}ARES, Code XI3, NASA/JSC, Houston, TX 77058 (Lindsay.P.Keller@nasa.gov). \textsuperscript{2}Texas Materials Instit., U. Texas, Austin, TX 78712.

Introduction: Lunar soil grains record the combined effects of several regolith processes related to their impact and irradiation history. In fine size fractions of mature soils, pristine (unaltered) surfaces are rare, most silicate surfaces are amorphous (except for olivine) and contain variable amounts of nanophase Fe metal inclusions. It is these fine size fractions of lunar soils that dominate the bulk optical properties of a soil. The silicate surfaces are not all the same, and include high-T melts, solar wind amorphized/damaged crystals and impact-generated vapor deposits. A major unanswered question is the rate at which space weathering effects are acquired in lunar regolith materials. Here we use the accumulation of solar flare particle tracks in individual lunar grains to estimate their exposure age – we then use transmission electron microscope techniques to measure the space weathered rim thickness and composition to determine its formation process.

Materials and Methods: We analyzed <20μm anorthite grains in microtome thin sections from several different soils showing a range of maturity: 67701, 10084, 71501 and 62231. The microtome thin sections were analyzed using a JEOL 2500SE scanning and transmission electron microscope (STEM) equipped with a Thermo-Noran thin window energy-dispersive X-ray (EDX) spectrometer. We used the recent calibration of the solar flare track production rate in lunar anorthite and olivine to estimate exposure ages [1].

Results and Discussion: We focus here on anorthite which displays two physically and chemically distinct grain rim types. Solar wind damaged rims are amorphous, lack inclusions, and are compositionally similar to the host grain. The vapor-deposited rims on anorthite are also amorphous, but are compositionally different from the host, and have inclusions of nanophase Fe metal throughout their width. Previous work has shown that the two rim types are equi-abundant in mature soils [2], but it is also common to observe vapor-deposited material on top of a solar wind damaged layer. Over 90% of the grains we measured have solar flare track exposure ages <10 My.

The width of vapor-deposited rims on anorthite shows no correlation with exposure age suggesting that the deposition occurred in a single or only a few events during the grain’s lifetime (Fig. 1). The width of solar wind amorphized rims on anorthite increases as a smooth function of exposure age until it reaches a steady-state at ~180 nm after ~20 My (Fig. 1). Solar wind damage can only accumulate if the grain has a direct line of sight to the Sun, whereas solar flare parti-

![Figure 1](pdf)

**Figure 1.** A plot of rim thickness versus solar flare track exposure age for solar wind amorphized and vapor-deposited rims on lunar anorthite.
GRAIL Mission Constraints on the Thermal Structure and Evolution of the Moon


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Introduction: The GRAIL (Gravity Recovery and Interior Laboratory) mission has dramatically improved our knowledge of the Moon’s gravity field [1-3]. This has enabled new insights into many aspects of the Moon, including lateral and vertical variability of the crust, deep mantle and core structure, volcanic history, and impact processes. We focus here on GRAIL constraints on the thermal structure and thermal evolution of the Moon.

Radioactive Abundances: Taylor and Wieczorek used measurements of crustal thickness from GRAIL gravity and Apollo seismology, along with aluminum concentrations in mare basalts, to show that the Moon and Earth have similar bulk SiO2 abundances (±20%) [4, 5]. Because Al, Th, and U are all refractory elements, this implies that Th and U, which are the two main radioactive heat sources, are also present on the Moon in roughly terrestrial abundances. This is an improvement over the previous factor of ~2 uncertainty in Th and U abundances.

Lunar Radius Change: GRAIL observations demonstrate the existence of dense, quasi-linear structures that are hundreds of kilometers long. They have been interpreted as dike systems that formed in the pre-Nectarian to Nectarian, implying an expansion of the Moon’s radius by 0.6-4.9 km during its early history [6]. The extensional stress required to produce this expansion helps to constrain the Moon’s early thermal evolution, including the depth distribution of radioactivity in the lunar mantle [7].

Volcanic History: Much of the Moon’s early (pre 3.8 Ga) volcanic history is obscured by superposed basin ejecta. Although cryptomere is, in places, visible in remote sensing observations, its thickness and volume have previously been poorly constrained. Because mare basalt and Mg suite rocks are denser than the feldspathic crust, GRAIL Bouguer gravity observations constrain the volume of cryptomagmatism to be between 1.8 and 4.8·106 km3, which corresponds to 30-80% of the best-estimate volume of the visible mare [8]. GRAIL observations of the visible mare imply average basalt thicknesses of 0.7 to 1.5 km, locally reaching up to 7 km [9, 10]. These values overlap pre-GRAIL visible mare thickness estimates.

Deep Mantle Melt Layer: Apollo seismic observations have been interpreted as indicating the presence of a low velocity, partially molten mantle layer just above the core-mantle boundary [11], which if correct is an important constraint on the Moon’s current thermal structure. GRAIL observations of the k2 tidal Love number [12] permit a reduction in the Moon’s rigidity at the bottom of the mantle but favor a rigidity similar to the bulk of the mantle [13]. The monthly tidal dissipation measured by lunar laser ranging and GRAIL [12] has been interpreted in terms of both a hot, melt-free mantle [14] and a partially molten lowermost mantle [15].

Megaregolith Conductivity: GRAIL observations require a high porosity highlands crust, ~25% near the surface and declining to zero at a depth of 20-30 km [16]. This will act as an insulating, low thermal conductivity layer, increasing the internal temperature. However, the specific effects on the interior thermal structure are not yet well quantified.

ASSESSING THE COMPOSITIONAL DIVERSITY OF INTRUSIVE ROCKS ON THE MOON USING NEAR-INFRARED SPECTROSCOPIC DATA. Rachel L. Klima (Rachel.Klima@jhuapl.edu), Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA.

Introduction: Hyperspectral near-infrared data of the Moon from several missions in the last decade, including Chandrayaan-1 and SELENE have provided an unprecedented high-spatial resolution view of the mineralogy of the lunar surface. Coupled with measurements from gamma-ray and neutron spectrometers as well as thermal measurements from Diviner, these observations have advanced our understanding of the compositional diversity, including minor components such as thorium and hydroxyl, of intrusive lithologies exposed on the lunar surface.

Major Compositional Diversity of Intrusive Rocks: At near-infrared wavelengths, transition metal-bearing minerals exhibit strong, distinctive absorption bands that allow mineral composition to be evaluated. Depending on the mineral structure and the cations substituting into that structure, compositions can be quantified to different levels of uncertainty. If only one or two cations generally substitute with iron, as in the case of olivine and pyroxenes, specific composition of the mafic minerals can be directly interpreted. Transition elements such as Cr and Ti can be identified by absorption bands at visible wavelengths, while others such as Al and Na can only be inferred based on the way their presence affects the structure of the crystals, and thus the positions of the major iron absorption bands.

As originally characterized using Earth-based telescopic observations [e.g., 1], and then mapped at higher spatial resolution using multispectral data from the Clementine mission [e.g., 2], intrusive rocks are present across the lunar surface. These rocks are most often excavated from depth, exposed within central peaks of craters or along basin rings. Hyperspectral data enable more detailed characterization of absorption band shapes and depths to investigate the specific chemical composition of different mafic mineral phases. Using data from the Moon Mineralogy Mapper (M3) to quantify the specific composition of rocks that are spectrally dominated by orthopyroxene, Klima et al. [3] identified several broad regional enhancements of low-Ca, high-Mg pyroxene, including around the Imbrium and Apollo Basins. Also dominated by orthopyroxene, the South Pole-Aitken basin exhibits more iron-rich orthopyroxene than those surrounding the Imbrium basin. Gabbro, which is slightly more difficult to distinguish from basalt due to its similar clinopyroxene-rich mineralogy, is also observed, most notably near the center of the South Pole-Aitken basin in ‘Mafic Mound’ [4]. Finally, olivine exposures have also been discovered around numerous lunar basins using Spectral Profiler data from SELENE [5] and the composition of several olivine-rich regions has been explored using M3 data [6].

Minor Compositional Diversity of Intrusive Rocks: In some cases, mafic rocks also exhibit an absorption band near 3 microns, indicative of hydroxyl. Because adsorbed hydroxyl is interpreted as being present across much of the lunar surface [7-9], it is difficult to distinguish hydroxyl bound in the rocks from that that may have formed due to solar wind implantation. Observations of the central peak of Bullialdus crater indicate that the norites there exhibit a distinctive hydroxyl absorption that is significantly stronger than the immediate surroundings, which has been interpreted as endogenic water within the norites of the central peak [10]. The central peak of Bullialdus is also enhanced in thorium, as measured by the Lunar Prospector Gamma-Ray Spectrometer, suggesting that it is also KREEP-rich [10,11].

Relevance to the New Views of the Moon Two Book: Though many individual papers have been written about the results of near-infrared analyses of the Moon, these results really need to be evaluated in detail in a workshop-like environment with scientists from the sample community as well as those who study complementary remote sensing techniques. Though this has been done at smaller scales [e.g., 12], a unified view integrating compositional remote sensing techniques (as well as their respective uncertainties) with sample studies is key to understanding the compositional diversity and geological context of mafic material on the lunar surface.

SPACE WEATHERING DOMINATED BY SOLAR WIND AT EARTH-MOON DISTANCE.
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Introduction: Although it is generally agreed that micrometeorites and solar wind ions are the agents largely responsible for weathering the surfaces of airless bodies, it is still a matter of debate as to which of these plays a more important role in causing a surface to mature [e.g., 1-5]. However, the lunar swirls demonstrate the dominance of the solar wind on space weathering, at least at the Earth-Moon distance. This is based on mounting evidence that the lunar swirls and their characteristic properties are manifestations of the solar wind's interaction with the complex patterns and variable field intensities of the lunar magnetic anomalies [e.g., 6-15]. As such, the swirls are ideal for distinguishing space weathering effects from solar wind ions versus micrometeorites because the former are influenced by the magnetic anomalies, while the latter are not.

Discussion: Evidence that the swirls mature at a much slower rate, and that adjacent, off-swirl regions mature at an accelerated rate (compared with maturation rates at non-swirls regions) was demonstrated using spectral data from Clementine [10], Moon Mineralogy Mapper [11] by showing that there are different spectral maturation trends and different immature crater densities for regions on-swirl vs. off-swirl. Immature craters on-swirl exhibited a wide range in albedos, and only slight spectral reddening compared to the mature (off-swirl) soil. This is evidence of retarded weathering on the swirls. In contrast, spectra sampled from fresh craters and the mature regolith in off-swirl regions were all very dark, had a very limited range in albedos, and exhibited little to no spectral reddening. This is evidence of accelerated weathering at off-swirl regions.

Diviner Radiometer data shows an anomaly in the position of the silicate Christiansen Feature consistent with reduced space weathering [15]. In addition, these data show that swirl regions are not thermophysically anomalous, which strongly constrains their formation mechanism. The conclusion from this study [15] was that solar wind sputtering and implantation are more important than micrometeoroid bombardment in the space-weathering process.

Nanophase iron (npFe\(^0\)) is the space weathering product that has the strongest influence on reflectance spectra, and its abundance in a soil is correlated with that soil’s exposure age [16]. npFe\(^0\) is created in three ways: (1) sputtering, (2) impact vaporization and deposition, and (3) agglutination [e.g., 17-21]. The first two ways create npFe\(^0\) by breaking the Fe-O bond, Liberating O, and depositing native iron. These two processes typically work on very small scales (i.e., grain surfaces up to a few molecule layers deep), and create npFe0 particle sizes usually <10 nm in diameter. The third way involves micrometeoroid impacts of sufficient size to provide the energy for melting to occur, and generates a much broader size distribution of npFe\(^0\) particle sizes. Here, smaller npFe\(^0\) particles are created through chemical reduction by implanted solar wind hydrogen, while larger sizes are created via coalescence of smaller particles. Sputtering is largely caused by solar wind particles, 95% of which are protons. Micrometeorites are responsible npFe\(^0\) created by impact vaporization and agglutination. A solar wind proton is the only space weathering agent that can be influenced by the lunar magnetic anomalies. Magnetic shielding deflects solar wind ions away from the on-swirl surfaces and diverts them onto off-swirl surfaces. On-swirl maturation is retarded because (1) the flux of space weathering agents that create npFe\(^0\) is reduced and (2) the creation of larger npFe\(^0\) by agglutination is restricted by the decreased availability of small npFe\(^0\). Spectrally, this retarded space weathering process begins with a slow spectral reddening in the UV-VIS as the abundance of smaller npFe\(^0\) created by sputtering and vaporization deposited on grain surfaces increases. Eventually, the spectral effects of larger npFe\(^0\) particle sizes are observable once the abundance of npFe\(^0\) is sufficient to create these particle sizes by agglutination. Sampled off-swirl craters exhibit only spectral darkening (and accompanying reduction in absorption band depth) with little to no reddening. Off-swirl regions do not simply experience an increased flux in solar wind ions, the deflected protons create a greater proportion of larger npFe\(^0\) particles off-swirl relative to both on-swirl and lunar surfaces not influenced by a magnetic field.

Conclusions: These results underscore the importance of the solar wind as an agent of space weathering. Studying the swirls and magnetic anomalies on the Moon is ideal for distinguishing the optical, chemical, and physical effects of space weathering by solar wind ions vs. micrometeorites. The dominance of one of these agents over the other may be very different at locations other than the Earth-Moon distance, but the knowledge gained from studying space weathering at lunar swirls will improve interpretation of remote sensing observations of other airless bodies. Indeed, it has been suggested that anomalous color on asteroids could be indicative of the presence of a magnetic field [22].

THE FORMATION OF LUNAR SWIRLS: INTERNATIONAL INVESTIGATIONS REACH CONSENSUS.

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Introduction: Lunar swirls are high albedo, curvilinear surface features, the origin of which has remained elusive ever since they were first identified [1]. From the collection of measurements over the past 40 years, we know the swirls to be: 1) optically bright; 2) spectrally immature across the UV-VIS-NIR; 3) associated with magnetic anomalies (although swirls have not been detected at all magnetic anomalies).

There are 3 hypotheses for swirl formation: (1) fresh exposures from a recent comet impact [2]; (2) isolated regions where the magnetic fields have spared the surfaces from the effects of space weathering [3]; and (3) electromagnetic transport and accumulation of the finest fraction of the lunar soil [4]. The results from international collaboration using new as well as older data are converging on a single model for swirl formation.

Electromagnetic Field: The Surface Vector Mapping (SVM) method, developed [5], combines global magnetic field data from Lunar Prospector’s Electron Reflectometer and Magnetometer, and Kaguya’s Magnetometer. When compared with high albedo markings at several magnetic anomalies such as the Reiner Gamma anomalies, three-dimensional structures of the magnetic field on/near the surface are well correlated with high albedo areas. Their results support the solar wind standoff model [6]. However, recent results from Kaguya’s Plasma energy Angle and Composition Experiment reports that electrons are trapped in closed field lines of the magnetic anomaly and also electrons from the magnetic anomalies on the night side [7], supporting the existence of local electrostatic fields resulting from solar wind interaction with the magnetic anomalies.

Measurements of the surface-origin energetic neutral atoms by Chandrayaan-1’s Energetics Neutron Analyzer of the Sub-keV Atom Reflecting Analyzer has been used to determine how much solar wind is reaching the surface at the magnetic anomalies. For example, initial analysis [8] showed that a strong magnetic anomaly reflects solar wind protons, and that the solar wind flux below the magnetic anomaly is lower by half.

Electromagnetic Spectrum: Lunar Reconnaissance Orbiter’s (LRO) Mini-RF synthetic aperture radar on LRO provided a comprehensive set of X- (4.2 cm) and S-Band (12.6 cm) radar images of the lunar swirls, including the first radar observations of swirls on the farside of the Moon [16]. Swirls imaged with Mini-RF are indistinguishable from the surrounding regolith in both total radar backscatter and circular polarization ratio. This implies that average cm-scale roughness within the high-albedo portions of the swirls do not differ appreciably from the surroundings, and that the high optical reflectance of the swirls is related to a very thin surface phenomenon (<1 cm).

Three of LRO’s Diviner Radiometer spectral channels are near 8 µm, and were selected to estimate the wavelength of the Christiansen feature, which is sensitive to the bulk silicate mineralogy of the surface. Analysis of swirl regions shows an anomaly in the position of the silicate Christiansen Feature consistent with reduced space weathering [8]. In addition, these data show that swirl regions are not thermophysically anomalous, which strongly constrains their formation mechanism. The conclusion from this study [8] supports the hypothesis that the swirls are formed as a result of deflection of the solar wind by local magnetic fields.

Chandrayaan-1’s Moon Mineralogy Mapper were used to demonstrate that swirls surfaces do not mature at the same rate as regions away from magnetic anomalies [10]. In addition, maps derived from M³ data that depicts the relative OH abundance (using the depth of the 2.82 µm absorption feature) showed that the swirls are depleted in OH compared with their surroundings [10]. This is further support for the hypothesis of that the magnetic (or induced electric) field is shielding the swirls from solar wind protons.

LRO’s Wide Angle Camera color data consists of 7 channels that span the UV to visible. These data have been used [11,12] to demonstrate the unique detection quality of swirls in UV wavelengths. Even when swirls have only moderately elevated reflectance, or are often barely distinguishable in OMAT, band depth, or other spectral parameters, lunar swirls are clearly observable in 321/415 nm ratios. Far UV observations of swirls from LRO’s Lyman Alpha Mapping Project provided further evidence that swirls in both highlands and mare regions are spectrally relatively red (or less blue) than surrounding terrains, indicating a difference in weathering in the swirls vs. non-swirl regions. Although [13] concluded that swirl spectra exhibit a characteristic red spectrum at wavelengths > ~160 nm, which is also consistent with greater abundances of feldspathic material, we argue that when all the data are considered, it is only the solar wind shielding model that remains.

MARE FRIGORIS: WINDOW INTO THE EVOLUTION OF THE LUNAR MANTLE. G. Y. Kramer1, B. Jaiswal2, B. R. Hawke3, T. Ohman4,5, T. A. Giguere3,5, and K. Johnson1, 1Lunar and Planetary Institute, Houston, Texas, USA, 2ISRO Satellite Centre, Bangalore, India, 3Hawaii Institute of Geophysics and Planetology, University of Hawai‘i at Manoa, Honolulu, Hawaii, USA, 4Arctic Planetary Science Institute, Rovaniemi, Finland, 5Intergraph Corporation, Kapolei, Hawaii, USA.

Introduction: We recently completed a detailed investigation of Mare Frigoris and Lacus Mortis using remote sensing data from Clementine, Lunar Prospector, and Lunar Reconnaissance Orbiter, with the objective of mapping and characterizing the compositions and eruptive history of its volcanic units [1]. With the exception of two units in the west, the basalts in Mare Frigoris and Lacus Mortis are low-Fe, low-to very low-Ti, high-Mg, and high-Al, relative to typical lunar mare compositions [1-6]. In addition to several basalts units that make up the mare, the region hosts a variety of geologic features including light plains deposits, pyroclastic deposits, cryptomare, volcanic vents, rilles, graben, wrinkle ridges, lobate scarps, and gravity anomalies [7-9]. Mare Frigoris is crossed by numerous crater ejecta rays delivered from laterally distant impact events in the surrounding highlands, as well as more locally: from large impacts that penetrated the smooth basaltic crust and ejected underlying feldspathic materials. While these are all excellent reasons for future investigations of Frigoris, this abstract discusses the three most compelling reasons.

High-Al Basalts: The relatively low-Fe and high-Al abundances of the Frigoris basalts suggest they are high-alumina (HA) mare basalts - a unique group in the lunar sample collection. Basalt sample geochemistry demonstrates an inverse correlation between Al₂O₃ and FeO, which, compared to other mare basalts, indicates higher modal proportions of plagioclase and lower proportions of pyroxene and olivine [10]. Some HA basalts represent the oldest sampled mare basalts. Their aluminous nature suggests their sources contained significant plagioclase, which has implications regarding the efficiency of plagioclase separation in the crystallizing Lunar Magma Ocean (LMO) and hence the heterogeneity of the lunar mantle [11,12]. Identifying HA basalt exposures is important as they may represent outcrops of pre-4 Ga volcanism and be a window to early processes within and compositions of the lunar mantle.

Compositional Influence of PKT: Thorium abundances of most of the mare basalts in Frigoris are low, although much of the mare surface appears elevated due to contamination from impact gardening with the surrounding high-Th Imbrium ejecta. There are, however, a few regional thorium anomalies that are coincident with cryptomare units in the east, the two youngest mare basalt units, and some of the scattered pyroclastic deposits and volcanic constructs.

Gravity Anomaly: [13] mapped a pattern of linear gravity gradients that frames the Procellarum KREEP Terrain (PKT), the northern extent of which is coincident with the northern boundary of Mare Frigoris. [13] interpreted these gravity anomalies as a vast magma plumbing system for many of the basalts in Oceanus Procellarum. The unique signature of positive gravity anomaly and narrow belts of negative gravity gradient is consistent with thinning and rifting of the crust. The elevated heat flux in the PKT coupled with decreased pressure from mantle ascent into the rifts facilitated widespread partial melting and volcanism [13]. The relationship between this deep-reaching magma conduit and the largest extent of high-Al basalts on the Moon makes Mare Frigoris an intriguing location for further investigation. A sample-return mission to Frigoris would yield a diversity of geologic specimens most unlike those sampled by Apollo and Luna.

**A SUMMARY OF GEOLOGICAL, GEOCHEMICAL, PETROLOGICAL, AND ISOTOPIC EVIDENCE OF IMPACTOR SOURCES.** David A. Kring1, 1Center for Lunar Science and Exploration, USRA-Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058, 2NASA Solar System Exploration Research Virtual Institute (kring@lpi.usra.edu).

**Introduction:** The cover of a *Science* issue [1] with the initial Apollo 11 results features a picture of meteoritic metal discovered in a lunar regolith sample. From the moment that particle was found, efforts to assess the types of impactors striking the Moon (and, thus, Earth) have been underway. The last decade has blossomed with several new advances in the field, which are summarized here.

**Geological Signatures:** Measured impact crater size frequency distributions (SFD) have long been an analytical staple of lunar geology, providing the foundation for crater counting chronologies. In parallel, analytical pi-scaling has been used to calculate the sizes of impactors that produced observed impact craters. In a novel approach, Strom et al. [2] integrated those two techniques to determine the SFD of impactors that shaped the ancient lunar highlands. Their results indicated asteroids dominated the impact flux and that they may have been perturbed by resonances sweeping through the asteroid belt as Jupiter’s orbit shifted.

**Geochemical Signatures:** Kring and Cohen [3] used lunar impact melt siderophile abundances to argue that asteroids, not comets, dominated the impactors during the basin-forming interval 4.0–3.9 Ga. New analytical techniques for determining highly siderophile element concentrations, along with 187Os/188Os isotopic compositions, have been developed by Walker’s group [4-6] and others. Their data are broadly consistent with a diverse set of chondritic impactors and an additional contribution from a fractionated core-composition impactor. Fischer-Gödde and Becker [7] suggest the diversity is, instead, a mixing trend between a carbonaceous chondrite component and a type IVA iron meteorite component.

If the compositions of Liu et al. [6] reflect multiple impactors rather than mixing, then compositions change from carbonaceous chondrite affinities at 4.2 Ga to ordinary and enstatite chondrite affinities at 3.75 Ga (Fig. 1), which might be reflecting sweeping of resonances as postulated by [2] from the outer to inner portions of the asteroid belt. In the midst of that sweep, impactors with iron meteorite affinities occur, which could have been scattered from the terrestrial zone and deposited in the midst of the asteroid belt before the resonances moved.

**Petrological Signatures:** New electron microprobe imaging techniques made it feasible to conduct micron-scale surveys of lunar regolith breccias to locate relict particles of impactors. When combined with regolith closure ages, one can extract how the compositions of impactors changed with time. Joy et al. [8] reported carbonaceous chondrite particles in regolith breccias consolidated during the final phase of the basin-forming epoch (3.8–3.4 Ga) and a more diverse population of impactors over the last 2 billion years. Fagan et al. [9] showed that the younger population still includes carbonaceous chondrite components as late as 1.7 Ga.


![Fig. 1. Values of Pd/Ir in lunar impact melts as a function of their age. Annotated version of Fig. 9c of [6].](image-url)
STUDIES BASED ON GLOBAL SUBSURFACE RADAR SOUNDING OF THE MOON BY SELENE (KAGUYA) LUNAR RADAR SOUNDER (LRS). A. Kumamoto1, J. Haruyama2, T. Kobayashi3, Y. Yamaguchi4, A. Yamaji5, S. Oshigami6, K. Ishiyama1, N. Nakamura1, and Y. Goto7, 1Tohoku University, Aoba, Aramaki, Aoba, Sendai 980-8578, Japan. (kumamoto@stpp.gp.tohoku.ac.jp), 2Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Japan, 3Korea Institute of Geoscience and Mineral Resources, Daejeon, South Korea, 4Nagoya University, Nagoya, Japan, 5Kyoto University, Kyoto, Japan, 6National Astronomical Observatory of Japan, Oshu, Japan, 7Kanazawa University, Kanazawa, Japan.

Introduction: The Lunar Radar Sounder (LRS) onboard the SELENE (Kaguya) spacecraft successfully performed subsurface radar sounding of the Moon and passive observations of natural radio and plasma waves from the lunar orbit. The operation of LRS started on October 29, 2007. Until the end of the operation on June 10, 2009, 2363 hours’ worth of radar sounder data and 8961 hours’ worth of natural radio and plasma wave data were obtained [1]. We found subsurface regolith layers at depths of several hundred meters, which were interbedded between lava flow layers in the nearside maria. [2]. Using the measured depths and structures of the buried regolith layers, we could determine several key parameters on the past tectonic processes and volcanism in the maria as follows.

Tectonic processes in the maria: From the stratigraphy of lava flows in Mare Serenitatis, Ono et al. (2009) [2] suggested that the folds of lava flow unists S22 and S28 on the surface, and the folds of lava flow unit S11 below the surface were formed by the compressive stress after 2.84 Ga due to global cooling.

Volcanic activity in the maria: Based on the depth of the buried regolith layers, Oshigami et al. (2014) [3] determined the lava flow volumes below the surface, and their ages with reference to the ages of their connected lava flow units on the surface, which were determined by crater chronology [e.g. 4]. The average eruption rate of the lava flow in the nearside maria was estimated to be $10^{-3}$ km$^3$/yr at 3.8 Ga and decrease to $10^{-4}$ km$^3$/yr at 3.3 Ga.

Physical property of the basalt: Pommerol et al. (2010) [5] indicated that most echoes were found in low-TiO$_2$-abundant area, which suggested that the ilmenites attenuated the radar pulses. Ishiyama et al. (2013) [6] determined the permittivity of the uppermost basalt layer in the maria, and suggested that the porosity of the basalt (19-51% in Mare Humorum) was higher than that of Apollo rock sample.

Magnetic anomaly: Bando et al. (2015) [7] confirmed that there is no subsurface layer in depth range from 75 m to 1 km below the Reiner Gamma, and suggested that the source of magnetic anomaly was strongly magnetized thin (<75m) breccia layer.

Synthetic aperture radar analysis: Thanks to the high downlink rate from the SELENE/LRS (0.5 Mbps), we could obtain almost raw (simply pulsecompressed) waveform data from the lunar subsurface radar sounding. Using this dataset, synthetic aperture radar (SAR) processing was applied with trying several permittivity models in the analyses on the ground. Kobayashi et al. (2012) [8] applied SAR processing to this dataset and suggests that clear SAR image can be obtained even with simplified media model.

Summary: As described above, buried regolith layers found by SELENE/LRS are good indicators of the boundaries of the multiple lava flows below the surface. They will support the future investigations on the evolutions of volcanic activity and global and local tectonic processes. The SELENE/LRS dataset is provided via SELENE Data Archive (http://l2db.selene.darts.isas.jaxa.jp/index.html.en), which will be useful for researchers who are going to apply them to investigations based on new ideas.

THE NEW VIEW OF THE MOON: REDEFINING FUTURE SURFACE EXPLORATION USING THE LUNAR RECONNAISSANCE ORBITER.
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Introduction: The Lunar Reconnaisance Orbiter (LRO), now in its second Extended Science Mission, continues to return critical new data enabling innovative science studies. The Moon, with its compelling science questions, abundant resources, and vast unexplored surface area, represents a logical destination for future human and robotic exploration [1]. Here, we describe how LRO observations of the Moon continue to inform destinations for science and exploration, enabling a vigorous, sustainable program of precursor missions including automated sample returns [2-7], extended operations rovers [8] and human missions [9].

Background: The original purpose of LRO was to collect the dataset necessary to facilitate future human and robotic lunar exploration [10]. The Lunar Reconnaisance Orbiter Camera Team collected a comprehensive suite of data including geometric and photometric stereo observations, multispectral imagery, and high-resolution (0.5 m/pixel) observations for 50 high-priority sites identified by NASA’s Exploration Systems Mission Directorate as regions of interest (ROI) for future human and robotic exploration [11]. From launch to the present, the LRO team continues an extensive series of science observation campaigns addressing key planetary science objectives [12]. LRO data now show that our Apollo era understanding of the next destinations for surface exploration was incomplete. LRO observations have shaped the prioritization of destinations for future surface exploration and investigations that will address the themes outlined in [1].

Key Findings: Surface exploration, particularly nearside sample return, will address the following key planetary science questions:

Magmatic evolution of the lunar interior: Science results from LRO confirmed the presence of nonmare, siliceic volcanic constructs on the lunar surface [13-17]. Sample collection at locations such as Compton-Belkovich, Hansteen Alpha, the Lassell Massif, the Gruthuissen Domes, and Maian T will dramatically expand our knowledge of the compositional diversity, age, and differences in emplacement style of nonmare lunar volcanism.

Lunar volcanic processes: Low shields are ideal locations for targeted sample return to determine compositional or other differences between low shields and mare basalts that form plains [18-19]. Excellent candidate locations include the Marius Hills, Mons Rümker, Hortensius Domes, and the Isis and Osiris cones.

Lunar time-stratigraphy: Determining the absolute ages of geologically recent (i.e., Copernican and Eratosthenian) events is required to model crater production functions used to date surfaces on other terrestrial planets [e.g., 20]. Sample return locations with geologically recent materials include: the youngest (~1 Ga) Procyclicarum basalts [21]; Ina-like Irregular Mure Patches [22]; Copernicus crater (the defined division between the Eratosthenian and Copernican epochs); and Tycho, Arista, and Giordano Bruno craters.

Lunar resource potential: We need to understand the presence, grade, and tonnage of prospective lunar resource deposits. Any polar volatile mission should leverage LRO results to use solar power for exploration of polar cold traps [23]. Regional lunar dark mantling deposits (e.g., the Aristarchus 2 and Sulpicius Gallus ROI’s) are primitive materials that would yield insights into the lunar mantle and serve as accessible lunar ores, and are thus a key future resource, particularly for oxygen [24-26]. Exploration of these deposits will greatly facilitate design and flight qualification of in-situ resource utilization hardware to expand the capability and reduce the cost of Solar System exploration.

Conclusions: LRO data can be used to guide an integrated strategy for lunar exploration, offering a focused path to render ambitious voyages to Mars and beyond sustainable. Such a strategy involves a series of precursor missions building to human lunar surface operations that use the Moon to address strategic knowledge gaps [27], test key technologies (such as automated landing and ISRU), characterize the surface environment, demonstrate teleoperations, and determine the presence, grade, and tonnage of lunar resources, while comprehensively addressing lunar and planetary science questions outlined by the Planetary Decadal Survey [28].

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THE COMPOSITION OF THE LUNAR CRUST: AN IN-DEPTH REMOTE SENSING VIEW.  M. Lemelin¹, P.G. Lucey¹, L.R. Gaddis², K. Miljkovic³, and M. Ohtake¹, ¹Hawaii Institute of Geophysics and Planetology, Department of Geology and Geophysics, University of Hawaii at Manoa, USA, mlemelin@hawaii.edu, ²Astrogeology Science Center, United States Geological Survey, USA, ³Department of Applied Geology, Curtin University, Australia, ⁴Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Japan.

Introduction: The mineralogical composition of the lunar crust across the entire surface and at a wide range of depths has been inferred from remote sensing observations of complex craters and impact basins on the Moon. Results from recent studies suggest a difference in composition between the rock population of basin rings and central peaks. Hawke et al. [1] found that major portions of the inner ring of many impact basins are composed of pure anorthosite. Cheek et al. [2] conducted the first comprehensive survey of the mineralogy of an impact basin and confirmed that the innermost ring of Orientale is dominated by nearly pure anorthosite. Exposures of olivine and low-calcium pyroxene have also been reported in association with some basins [e.g., 3,4]. Central peaks seem to be on average more mafic than anorthosite; only 2 of the 34 central peaks studied by Lemelin et al. [5] have an average composition corresponding to anorthosite. A possible explanation for this apparent discrepancy is that central peaks and basin rings sample material at different depths into the lunar crust. However, this is difficult to assess because the depth of origin of the material exposed on the basins’ inner most ring is not well understood. Another explanation is that the compositions reported for basin rings are simply not representative of all basins, or of the rings as a whole.

To better constrain the composition of the lunar crust with depth, we (1) conduct a comprehensive study of the mineralogy of the inner most ring of 13 basins, and compare their mineralogy to that of the central peaks studied by Lemelin et al. [5], and we (2) use iSALE-2D hydrocode models to better constrain the depth of origin of the material exposed by the basin’s inner most ring.

Methods: We define the inner most ring material as the USGS “circumbasin materials” or “basin materials” [6] located on or within the diameter of the inner most ring of Neumann et al. [7]. We determine the composition of the inner most ring of these basins at ~62 m/pixel for all immature exposures (OMAT>0.2 [8]), using Multiband Imager data (750-1550nm, MAP level 02 [9]) and Hapke’s radiative transfer equations. We construct a spectral lookup table of the reflectance spectra of 6601 mixtures of olivine, low-calcium pyroxene, high-calcium pyroxene and plagioclase, at 7 amounts of submicroscopic iron (SMFe), an Mg# (Mg/Mg+Fe) of 65, and a grain size of 17µm. We also model the reflectance spectra of these mixtures for a grain size of 200 µm for plagioclase to account for the band depth observed in the Multiband Imager data [10], for a total of 92,414 spectra. We compare the modeled spectra that contained ±2 wt% FeO of a given pixel [5], and assign the composition to the best spectral match (in terms of correlation and absolute difference in continuum removed reflectance). We model the depth of origin of the material exposed by the innermost ring by simulating impacts for a variety of impactor sizes and crustal thicknesses with iSALE-2D. As the spatial sampling of these models does not allow direct detection of the rings, we use the top 10 km of the region of crustal thinning (a zone that includes the inner ring) as a proxy.

Results: The average composition of the inner most ring of 11 basins corresponds to anorthositic rock types (≥77.5 wt.% plagioclase), and the most abundant rock type is anorthosite (≥90 wt.% plagioclase) in 9 basins. We find isolated exposures of more mafic rock types in the near side basins and Moscoviense, but no ultramafic outcrops at the scale of the MI data. iSALE-2D modeling suggest that the top 10 km region of crustal thinning exposes material originating principally from two mean depths: a “shallow component” from the crust, and a “deep component” from the lower crust or the upper mantle. Using the average plagioclase content we modeled for each basin, and assuming that the crust contains 100 wt% plagioclase allows us to place constraints on the abundance of the shallow component present on the basins’ inner most ring more specifically. We find that the shallow component largely dominates the ring material. The isolated exposures of more mafic rock types we find might correspond to mantle material exposed by the deep component. Overall, the average composition of the basins’ inner most ring appear to be more anorthositic than the average composition of the central peaks studied by Lemelin et al. [5], although the more mafic central peaks are located in the South Pole Aitken basin, which we did not sample in our basin population.

NEW VIEWS OF LUNAR COMPOSITIONS AND ROCK TYPES REVEALED BY SPECTROSCOPIC DATA FROM CHANG'E-1 AND CHANG'E-3 MISSIONS. Zongcheng Ling1,2, Bradley L. Jolliff3. 1Shandong Provincial Key Laboratory of Optical Astronomy and Solar-Terrestrial Environment, Institute of Space Sciences, Shandong University, Weihai, 264209, China; 3Dept Earth & Planetary Sciences and McDonnell Center for the Space Sciences, Washington University in St. Louis; (zceling@sdu.edu.cn).

Introduction: Our initial direct knowledge about lunar compositions and mineralogies arises from the lunar samples at 9 sites from Apollo and Luna missions 50 years ago. In the early 21st century, newly acquired datasets from lunar missions (e.g., Kaguya, Chang'e, Chandrayaan-1, and LRO) have advanced our knowledge (especially the global view) of the Moon’s surface materials. Planetary spectrometers can provide detailed compositional and mineralogical information of the surface materials and thus has been one of the primary payloads for planetary orbiting and surface exploration missions (e.g., Chandrayann-1 M1 [1], Kaguya MI [2], MRO CRISM [3], MER Pancam[4], etc.). Here we review some of the science returns from the three payloads of Chang'e-1 and Chang'e-3 Yutu rover, i.e., Imaging Interferometer (IIM), Visible and Near-infrared Imaging Spectrometer (VNIS), and Active Particle-induced X-ray Spectrometer (APXS).

Chang'e-1 IIM results: As the first Chinese lunar imaging spectrometer, Chang'e-1 IIM has science goals to collect information on chemical and mineralogical compositions across the lunar surface [5]. IIM is a Fourier transform Sagnac-based imaging spectrometer first used for a lunar investigation and has already shown its potential for acquiring 32 bands in the visible to near infrared spectral range (0.48-0.96 µm). Preliminary lunar FeO, TiO2, and rock type maps have been derived using this dataset [5-9]. However, the IIM data processing procedures are still ongoing, e.g., we have presented the empirical correction method of correction for the line-direction (i.e., “flat-field correction”) and sample-direction (i.e., “spectral calibration”) non-uniformities [10-12], which have not been removed completely by previous data processing procedures. Fig. 1 shows our newly produced lunar global FeO distribution indicating well known inhomogeneities across the lunar highlands, but in detail different from previous Clementine UVVIS FeO maps.

Chang'e-3 VNIS and APXS results: China’s Chang'e-3 conducted the first lunar surface landing and roving mission after some forty years and provides new ground truth and discoveries [13-18]. VNIS data taken by the Yutu rover acquired mineral compositions along the traverse route, together with chemical compositions from APXS. With these data, we found a new type of lunar basaltic rock, intermediate in Ti and rich in olivine, distinct from samples returned by Apollo and Luna missions as well as lunar meteorites [18]. The study used the APXS to detect the elemental concentrations of two sites (i.e., CE3-0006 and CE3-0008). Mineral modes and mineral chemistries inferred from these data are consistent between the APXS and VNIS, thus making the Chang'e-3 site (i.e., “Guang Han Gong”) a good calibration site for the lunar remote sensing studies.

Conclusions: Global hyperspectral imaging data-sets from Chang'e-1 IIM have brought new science returns of lunar surface compositions and rock types, thus leading to a better understanding of lunar petrogenesis and crustal evolution. The in-situ spectroscopic measurements by Yutu yielded detailed compositional and mineralogical constraints of a new type of young basaltic rock. Future in-depth studies of these datasets from the Chang’e missions in combination with other datasets will improve our view of the Moon.

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Figure 1. Global lunar FeO derived from Chang'e-1 IIM data
IMPACT MELT (AGGLUTINITIC GLASS) OF LUNAR REGOLITH: A “VOLATILE RECORDER” OF THE LUNAR SURFACE. Y. Liu1, Y. Guan2, Y. Chen1, and L. A. Taylor3, 1Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109. 2Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125. 3Planetary Geosciences Institute, Department of Earth and Planetary Sciences, University of Tennessee, Knoxville, TN 37996. (Email: yang.liu@jpl.nasa.gov)

Introduction: Lunar regolith is an important repository of volatiles from exogenous (solar wind, cosmic rays, meteorites) and endogenous sources.

Recent studies have demonstrated that water is present in different forms (OH, H2O, and H2O ice) on the surface of the Moon [1-4]. Direct analysis of samples showed that H is bounded in the interior of the Moon [6-14]. Particularly, we demonstrated that solar-wind implanted H in lunar soils can be transferred and locked in the impact melt (agglutinitic glass) of the regolith [5]. Considering the diverse mineralogy and petrology of lunar regolith and the evidence of meteorite inputs [15], the agglutinitic glass could have potentially assimilated different sources of volatiles. Therefore, the study of agglutinitic glass in the lunar regolith of different ages could provide new insights on the interactions among airless terrestrial bodies, the Sun, and the interplanetary medium. The knowledge of the interactions obtained from the lunar soils is also extremely useful in the large context of recent discoveries of water (H) in the north pole of Mercury [16-17] and on the surface of 4 Vesta [18], which substantiate the requirement of a better understanding of meteorite inputs as well as solar-wind radiation effects.

Most of the data in Liu et al. [5] was derived on one lunar soil 10084 and only H was analyzed. In order to fully utilize agglutinitic glass as the lunar surface volatile recorder, we are studying multiple volatiles in lunar regolith of different composition, maturity, and ages.

Methods. Sample preparation was similar to Liu et al. [5, 19]. Samples before and after SIMS analysis were examined using a Hitachi SEM. Major-element compositions of samples were obtained using a JEOL JXA-8200 electro microprobe. Volatile contents and H isotopes were obtained using a Cameca 7f-Geo SIMS, following analytical protocols as in Chen et al. [20].

Results: The agglutinitic glass from different soils contains H up to 470 ppmw equivalent H2O, whereas the measured δD values range from large negative (-830 ‰) to large positive (+5500 ‰). With the limited agglutinites extracted from the ancient regolith breccias, our data suggest the ranges of H contents in agglutinitic glass are comparable between lunar soils and ancient regolith breccias.

The agglutinitic glass and other glass components from soils and ancient regolith breccias contain 13 to 156 ppm F and up to 18 ppm Cl. The F contents are much higher than those in nominally anhydrous minerals [21], but comparable to melt inclusions [11, 14]. In the preliminary dataset, about 20% of the Cl data are > 7 ppm, the upper end of Cl in volcanic glass beads and melt inclusions [6, 11,14].

Discussion: Direct use of δD as an indicator of H sources is complicated by the cosmic-ray generated D, particularly at low H contents. In order to assess the cosmic-ray generated D, we will use Li-isotope values as recommended in [22]. However, higher Cl contents of the agglutinitic glass may also indicate non-solar-wind exogenous sources. The generally high F contents also reflect sources other than igneous minerals. Thus, correlated Cl, F, H2O and δD may help to discern different volatile sources in the agglutinitic glass.

The development of agglutinitic glass as the surface “volatile recorder” will provide a new way to examine lunar surface samples. The MoonRise concept plans to return regolith samples from the South-Pole Aitken (SPA) basin, which have recorded exo-lunar inputs during the late-heavy bombardment period. Study of the SPA agglutinitic glass can provide new insights on water and organic deliveries to the Earth-Moon system.

NON-TRADITIONAL STABLE ISOTOPE CONSTRAINTS ON THE EVOLUTION OF MOON. T. Magna¹ and C. R. Neal², ¹Czech Geological Survey, Prague, Czech Republic (tomas.magna@geology.cz), ²University of Notre Dame USA (cneal@nd.edu).

Introduction: Past applications of less traditional stable isotope systems in Earth and planetary science were hampered by the lack of sensitive instrumentation that would allow a variety of interior and surficial processes to be distinguished. The development of MC-ICPMS has overcome many analytical issues and investigations of lunar materials have produced important observations concerning the provenance of lunar building materials [1,2], pre-impact status of the Earth [3], and differentiation of the lunar mantle [4,5]. But other isotope systems have also gained their importance in disentangling the processes of the lunar differentiation, degassing process, and the hydrous versus anhydrous nature of the Moon [6–10]. This contribution highlights the unique information that can be obtained from such isotope systems.

Major elements. Oxygen. A seminal study by [11], reconfirmed by [12], has provided the high-resolution data needed to demonstrate O isotope homogeneity between Earth and Moon. These data show that they formed from common materials homogenized as a consequence of the energetic Moon-forming impact. Systematic investigations of lunar maria also indicate a mineralogy-mediated O isotope dichotomy, manifested for low- and high-Ti basalts [13].

Magnesium. Although Mg is present in a significant proportion of lunar mantle, little attention has been made in characterizing Mg isotope systematics of various lunar reservoirs but recent analyses further confirm heterogeneous sources for mare basalts [7].

Iron. Fe isotope systematics also indicate a heterogeneous mantle but some sample-related inconsistencies resulted in different interpretations of the data [4,5], requiring further targeted studies. Computational evidence [3] suggests a unique character of the Earth–Moon tandem but careful experiments may produce important information on metal–silicate equilibration as well as effects of late-stage ilmenite accumulation from the lunar magma ocean on Fe isotopes.

Silicon. Conflicting results [2,14,15] exist for Si isotopes but preliminary results indicate small differences between anorthositic crust and mafic silicates [15]. It remains to be tested whether Si isotopes may be fractionated during magmatic differentiation.

Trace elements. Lithium. Although its geochemical nature is most applicable to low-temperature hydrous environments [16], available data show the lack of loss through any volatilization (as suggested by Fe and Mg data with similar condensation temperatures). Moreover, Li was among the first non-traditional stable isotope systems [6] to support the heterogeneous nature of lunar mantle sources for low- and high-Ti basalts [17], and to document implantation of Solar Wind into the very surface of lunar soils [6,18]. Also, the lunar anorthositic crust may be unique across the Solar System given its Li elemental and isotope systematics [6]; tracing dissemination of KREEP in lunar rocks may be possible using Li systematics.

Zinc, Copper. Volatile loss from the lunar interior in the aftermath of the Moon-forming impact has been assessed by Zn and Cu analyses of lunar soils and crystalline samples [8,9,19]. Large-scale depletion in Zn and Cu is explained through a Moon-forming impact event while volatile-rich reservoirs may locally exist, as exemplified by pyroclastic glass beads (but note enrichments in other, less volatile elements).

Chlorine. Hydrous versus anhydrous character of lunar volcanism has been contested with Cl isotopes in crystalline samples [10], showing a spectacular range of Cl isotope compositions far beyond other Solar System materials. The presence of specific Cl compounds in an H-poor environment have been proposed.

Conclusions: Several novel stable isotope systems explored in the last decade attested to source mantle heterogeneities that appear to be the major impetus in stable isotope dichotomy of lunar effusive volcanism. These major and trace element systems have gained considerable attention and are providing further constraints on the origin and evolution of the Moon.

ON THE SMALL DEPTH-DIAMETER RATIOS OF SMALL LUNAR CRATERS. P. Mahanti$^1$ and M.S. Robinson$^1$, $^1$LROC Science Operations Center, SESE, Arizona State University (pmahanti.lroc@gmail.com).

Introduction: The ongoing formation of small lunar craters (SLC; $D <$250 m) relentlessly modifies the local topography of the Moon. SLC form ubiquitously and are the most populous impact feature on the Moon, but also the least studied since appropriate topographic data was made available only recently. Robotic missions (e.g. Lunar Reconnaissance Orbiter (LRO), Kaguya, Chandrayaan-1) carrying high-resolution cameras (e.g. Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) [1], Terrain Camera [2] and Terrain Mapping Camera [3]) have now made it possible to observe and analyze the morphology of SLC in great detail.

SLC formation events are significant contributors to regolith formation and the current shapes of SLC are critical to our understanding of the regolith. Observed shapes of SLC reflect, at least in part, the target strength properties of the pre-impact surface (and perhaps, various layers below the surface) as well as change due to degradation (also dependent on target strength properties). From an exploration point-of-view, the morphology of small craters is relevant as SLC are common and will be the main obstacle in the path of a robotic and (or) human explorer; morphological details like the depth and slope will significantly affect exploration plans. Measurements of depth-to-diameter ratio provide primary aspects of SLC shapes.

Depth-to-diameter: Most of the measurements of $d/D$ for SLC in the past 4 years are based on NAC Digital Terrain Models (DTM; 2 m/p). Additionally some observations are based on shadow measurements [12,13] using NAC images (0.5 m/p). Measurements of $d/D$ for small highland craters ($N=540$, $D<150$ m, [6]) and craters on selected sites on mare and non-mare terrains ($N=850$, $D<300$ m, [7]) both showed median $d/D$ values ~0.13. Range of $d/D$ for the selected sites [7] was 0.11 - 0.15 and the $d/D$ range obtained corresponding to a power law fit for highland craters [8] was 0.12-0.15. A global selection of SLCs from ~50 sites ($N = 4477$, $D < 200$ m) also yielded median $d/D$ values of 0.13 [9]. A study including slightly larger craters ($N=554$, $D<1$ km, [13]) found a smaller average $d/D$ (~0.1) for randomly selected craters, possibly due to a larger percentage of degraded craters. Analysis of crater population ($D < 2$ km) at Lunokhod 1 and 2 study areas [12] also showed that less than 1% of the crater population had $d/D > 0.15$. Note that while the maximum crater size has varied in the past studies, approximately similar median statistics and range was obtained for $d/D$.

Implications: Fresh, primary SLCs can have $d/D < 0.15$ – sharply contrasting the expected $d/D$ (~0.2) for large craters ($D > 1$ km; [4,5]). The change in shape for fresh craters at different size can be attributed to target strength properties as well as the quick degradation rates. The shape variation causes power law’s ($d$ vs $D$; based on Apollo era observations [4,5]) to overestimate depths for SLCs. Analysis of $d$ vs $D$ relationships for SLCs must take target properties and density of observations into account.

From the morphological degradation studies [10-12] it is evident that fresher craters ($d/D > 0.15$) are $<\sim 10\%$ of a total SLC population (the actual percentage varying with target region) while older, more degraded craters ($d/D < 0.1$) are the majority. Since percentage contribution in a population is proportional to average lifetime, degradation rate of SLCs decrease with time.

Since low $d/D$ suggests lower impact velocities, it may be hypothesized that most SLCs are unrecognized secondaries, but this hypothesis does not explain what happens to the large number of primary craters being formed currently. Further, $d/D$ histograms are unimodal [10,11] and do not indicate separate groups of craters. It is possible that some percentage of observed SLCs are secondaries, but most of them are primaries that have degraded quickly.

The lifetime of SLC is affected by factors other than the average impact rate and average impact-based degradation rates [11]- SLCs can degrade quicker (or slower) than expected at equilibrium. Short spells of seismic shaking (from interior or due to nearby impacts, after crater formation) can also initiate mass wasting processes that increase the effective degradation rate. Active processes like impacts, volcanism and seismic shaking can alter target properties – large impacts and seismic events can induce target weakness and magma flow from volcanism can add discontinuous strength boundaries in the target layers which accelerate or slow the pace of degradation.

LOW-VELOCITY AND LOW-VISCOSITY ZONE AT THE LOWERMOST MANTLE OF THE MOON. K. Matsumoto1, Y. Harada2, Y. Ishihara3, and J. Haruyama3, 1RISE Project, National Astronomical Observatory of Japan (Mizusawa, Oshu, Iwate, 023-0861 Japan, koji.matsumoto@nao.ac.jp), 2Space Science Institute, Macau University of Science and Technology (Avenida Wailong, Taipa, Macau, China), 3Japan Aerospace Exploration Agency (Yoshinodai, Sagamihara, Kanagawa, 252-5210, Japan).

Introduction: The knowledge of internal structure of the Moon is a key to understand the origin and the evolution of our nearest celestial body. A large amount of seismic information was brought by the near-side network consisting of four seismometers of Apollo 12, 14, 15, and 16. The Apollo seismic data have contributed to internal structure modeling, but the structure below the deepest moonquake about 1,200 km depth was uncertain.

The Moon is also observed by selenodetic techniques such as Lunar Laser Ranging (LLR), satellite gravimetry, and satellite altimetry. Lunar properties obtained from these observations include the mass, mean radius, moments of inertia (MOI), frequency-dependent quality factor, and tidal Love numbers.

Here we report on the progress of investigation of lunar deep interior which focuses on the connection between viscoelastic property and tidal response of the Moon by complementing the Apollo seismic analysis with recent selenodetic observations.

Forward analysis: In the forward approach of [1], the quantitative effect of the low-viscosity zone located at the lowermost mantle on the frequency-dependent dissipation was investigated. By using the model of [2] as a reference, the quality factor and the complex Love number of the Moon with respect to the monthly and annual periods are calculated by changing the outer radius and viscosity of the lowermost mantle layer. After that, the viscosity of this specific zone was determined by comparing the model value with pre-GRaIL (Gravity Recovery and Interior Laboratory) observations. It was found that the existence of the low-viscosity layer leads to a value of the quality factor which is consistent with the LLR results [3].

With the viscosity of $2 \times 10^{16}$ Pa s and outer radius of 500 km, the model value satisfies the observed quality factor for both monthly and annual periods at the same time. The resulting viscosity value is extremely low considering that of the bottom part of the lunar mantle estimated by previous studies [4, 5]. The Love number corresponding to the viscosity value restricted by the quality factor is also consistent with SELENE and Chang’e-1 gravity results [6, 7]. Such an existence of an ultralow-viscosity layer in the lowermost part of the lunar mantle indicates that strong tidal dissipation is induced there.

Inverse analysis: Following the result of [1], explored by a Bayesian inversion approach were lunar internal structure models [8] which are consistent with both the seismic [9] and the recent selenodetic data. These models also include the low-velocity-viscosity zone (LVZ) at the base of the mantle. The selenodetic constraints includes the recent estimate of $k_2$ from GRAIL [10] which is accurate to 1% as well as updated estimates of the quality factors from LLR [11]. The seismic data mainly constrain the structure down to about 1200 km depth, while the selenodetic data have contributed to constraining the remaining deeper parts.

The inversion result shows that the thickness of the LVZ has a negative correlation with the radius of the fluid outer core and needs to be larger than 170 km to fit the observational data. The S-wave velocity and viscosity in the LVZ are estimated to be about $3 \times 10^{16}$ Pa s and 2.9 ± 0.5 km/s, respectively. The viscosity value strengthens the deep-seated dissipative property observed as a severe attenuation of seismic waves. The density of the LVZ is estimated to be larger than 3450 kg/m$^3$. If we assume that the TiO$_2$ content in the bulk silicate moon is 0.4 wt.% [12] and that the LVZ contains all the TiO$_2$, its content in the LVZ is larger than 11 wt.%, which supports a mantle overturn scenario.


**Introduction:** Planetary interior structure models suffer from an inherent non-uniqueness because there are more unknown model parameters than observational constraints. However, it is possible to constrain the likely range of interior structures using the available observational constraints. For the Moon, these constraints are derived from seismic, lunar laser ranging (LLR), magnetic, and gravity observations. The mean moment of inertia (MOI) is constrained by the combination of gravity and LLR observations [1], and the improved accuracy in the gravity data after the Gravity Recovery and Interior Laboratory (GRAIL) mission has reduced the MOI uncertainty significantly [2]. The Moon deforms in response to tidal forcing and this generates changes in topography and gravity that can be characterized by the tidal Love numbers. The amplitude of this deformation depends on the interior structure and therefore the tidal Love numbers provide additional interior structure constraints. The uncertainties in the tidal Love numbers were reduced significantly by analysis of GRAIL, LLR, and Lunar Orbiter Laser Altimeter (LOLA) data [2, 3, 4]. We infer the likely interior structures using Bayesian probability theory and the observed mass, mean solid MOI, and tidal Love numbers $k_2$ and $h_2$ as constraints.

**Anelastic correction to the tidal Love numbers:** The observed tidal Love numbers describe the lunar deformation at the tidal forcing frequency and contain both elastic and anelastic components. Therefore, the interior structure model must take into account the effects of anelasticity. However, evaluating both the elastic and anelastic components of the Love numbers requires specifying the viscosity of all the interior layers, which increases the number of interior structure parameters significantly. This in turn results in probability distributions that are significantly less resolved. Therefore, instead of calculating both the elastic and anelastic components of the Love numbers, we follow the approach of [5] and convert the observed Love numbers to elastic Love numbers.

**Results:** Interior structure parameters that affect the observed mass and mean solid MOI are generally better constrained because the uncertainties in these observational constraints are smaller than those of the elastic Love numbers by orders of magnitude. The mantle density is constrained to $3.36 \pm 0.02 \, \text{g cm}^{-3}$ (uncertainties represent the 95% credible region), near the mean density of the Moon because the mantle occupies a large fraction of the total volume. The radius and density of the layer between the mantle and the liquid core are constrained to $490_{-117}^{+106} \, \text{km}$ and $3.7_{-0.3}^{+0.3} \, \text{g cm}^{-3}$; the liquid core radius and density are constrained to $354_{-112}^{+113} \, \text{km}$ and $5.8_{-1.9}^{+1.7} \, \text{g cm}^{-3}$; and the solid core radius is constrained to $187_{-182}^{+139} \, \text{km}$.

The rigidities are constrained by the elastic Love numbers. The mantle rigidity is constrained to $66_{-3}^{+4} \, \text{GPa}$ with a strong preference for higher rigidities. The transition layer rigidity is weakly constrained with a preference for rigidities similar to that of the mantle. The elastic Love numbers decrease as the rigidity of any of the layers increases, and this dependence is large enough to provide a weak constraint on the transition layer rigidity.

The probability distributions of the solid core and crust rigidities are uniform, indicating that these interior structure parameters are not constrained by the elastic Love numbers. Although the elastic Love numbers decrease as the rigidity of these layers increases, this dependence is too weak to constrain the solid core and crust rigidities given the large uncertainties in the elastic Love numbers and the dependence on other parameters.

**Conclusions:** The observed mass and mean solid MOI provide the strongest constraints on the interior structure due to their small uncertainties relative to those of the elastic Love numbers. The elastic Love numbers provide constraints on the rigidities of the mantle and transition layer. Previous studies suggest the presence of a low rigidity ($\leq 30 \, \text{GPa}$) transition layer between the liquid core and the mantle using the tidal Love numbers as constraints [5, 6, 7]. In contrast, we find a probability distribution that weakly constrains the rigidity of this layer and a slight preference for rigidities similar to that of the mantle ($\sim 70 \, \text{GPa}$).

**Introduction:** At the time of publication of *New Views of the Moon* [1], it was thought that the Moon was bone dry with less than about 1 ppb H$_2$O. However in 2007, initial reports at the 38th Lunar and Planetary Science Conference speculated that H-species were present in both apatites [2] and pyroclastic volcanic lunar glasses [3]. These early reports were later confirmed through peer-review [4-8], which motivated many subsequent studies on magmatic volatiles in and on the Moon within the last decade. Some of these studies have cast into question the post-Apollo view of the Moon. The mineral apatite has been one of the pillars of this new field of study, and it will be the primary focus of this abstract. Although apatite has been used both to understand the abundances of volatiles in lunar systems as well as the isotopic compositions of those volatiles, the focus here will be on the abundances of F, Cl, and H$_2$O.

**Apatite in lunar rocks:** Apatite, ideally Ca$_5$(PO$_4$)$_3$(F,Cl,OH), is the most common volatile-bearing mineral in lunar rocks and along with merrillite, makes up the primary reservoir for phosphorus and rare earth elements on the Moon [9]. Apatite occurs in nearly all lunar rock types (apatite has not been reported in ferroan anorthosites or volcanic glass beads), but the ubiquity of apatite in lunar samples should not be misconstrued as apatite being abundant because it is always a trace mineral and can be somewhat elusive in many samples. Nonetheless, a substantial amount of new data on lunar apatite have emerged in the last decade from both electron probe microanalysis (EPMA) and secondary ion mass spectrometry (SIMS) instruments, in part due to the recent development of high quality apatite standards [9]. One can now begin to assess the variability of apatite occurrences and compositions among the various lunar rocks types [9].

Apatites in lunar samples range in crystal habit from anhedral to euhedral and range in size from sub-micron to 2 mm [9]. Many of the anhedralapatites are clearly late-crystallizing phases that are filling the available space interstitial to the earlier formed phases. Although there has been one report of a chlorapatite in sample 14161, 7062b [9], and hydroxylapatite has been reported in the brecciated matrix of Northwest Africa (NWA) 773 [9], nearly all of the apatites that have been analyzed in lunar samples are fluorapatite [9]. However, within the fluorapatite field there is substantial compositional variability in the volatile abundances of apatite that correlates with lunar rock type (Figure 1). Specifically, apatite grains in mare basalts typically contain little chlorine (Figure 1), and many of the grains have elevated hydroxyl abundances (Figure 1). Apatite grains in the magnesian suite, alkali suite, and KREEP-rich impact melts are enriched in chlorine compared to mare basalts, and they typically have much lower water contents (Figure 1). A compilation of apatite F-Cl-OH components from mare basalts and highlands alkali and Mg suite samples are presented in Figure 1, which was used to demonstrate a heterogeneous distribution of volatiles in the lunar interior [9].

**Conclusion:** This work demonstrates the utility of apatite in advancing our understanding of lunar volatiles, hence apatite should be among the topics covered in the endogenous lunar volatile chapter in NVM II.

Truncated ternary plot of apatite X-site occupancy (mol%) from highlands apatite and mare basalt apatite plotted on the relative volatile abundance diagram from [10]. The solid black lines delineate fields of relative abundances of F, Cl, and H$_2$O (on a weight basis) in the melt from which the apatite crystallized. The diagram was constructed using available apatite/melt partitioning data for fluorine, chlorine, and hydroxyl [11-12].

TIMING AND CHARACTERISTICS OF MARE VOLCANISM ON THE FARSIDE AND IN THE CENTRAL REGION OF THE PKT REVEALED BY KAGUYA.

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Introduction: Unraveling the timing of mare volcanism on the Moon is essential for understanding its thermal evolution. Using image data from orbital satellites, a considerable number of maria have been dated by crater size-frequency distribution mesurements [e.g., 1-5]. Using Kaguya data, we have also performed crater counting on mare deposits in the South Pole-Aitken (SPA) basin and in the Feldspathic Highland Terrane (FHT), as well as on young basalts in the Procellarum KREEP Terrane (PKT) [6-10]. Here we review our findings.

Farside Mare Volcanism: Our model ages of farside mare deposits indicate that mare volcanism on the farside began at least as early as 3.9 Ga and continued until \(~\sim\)2.0 Ga (Fig. 1) [6, 7, 9, 10]. From a comparison of model ages in the FHT and the SPA basin, we found that mare volcanism in these regions ended at the same time, suggesting that the SPA basin forming impact might have had only a minor effect on mare volcanism in the region [9]. The total volume of mare basalts in the Moscoviense basin is estimated to be 9,500–16,000 km³ [7]. From a comparison with that within a same-sized nearside basin, we found that magma production in the farside mantle was 3–10 times less than that of the nearside, consistent with previous estimate [11].

Mare Volcanism in the PKT: The latest mare eruption on the Moon occurred within the PKT [e.g., 2]. Model ages of mare basalts in the region indicate that mare volcanism in this region continued until \(~\sim\)1.5 Ga (Figs. 1 and 2) [2, 7]. Hiesinger et al. [2] found a possible peak of volcanic activity at \(~\sim\)2.0 Ga on the basis of their model ages. Our model ages also reveal the existence of this peak more clearly (Fig. 2) [8].


Fig. 1. Model ages of mare basalts [1-3, 6-10]. Ap, Apollo; Au, Australe; Fe, Fecunditatis; F–S, Freundlich–Sharonov; Hu, Humorum; Im, Imbrium; In, Ingenii; Mo, Moscoviense; Ne, Nectaris; OP, Oceanus Procellarum; Or, Orientale; Po, Poincare’; Se, Serenitatis; Sm, Smythii; SPA, South Pole–Aitken; Tr, Tranquillitatis.

Fig. 2. Age distribution of mare basalts in the PKT [2, 8]. Each Gaussian represents a single basalt unit. The width of the Gaussian corresponds to the age uncertainty. Each Gaussian has an area weighted by its unit area. The thick curve is created by summing the Gaussians. The histogram of mare basalt ages is also shown.
RELATIVE AGES OF GRABEN AND WRINKLE RIDGES ON THE NEARSDIE OF THE MOON REVEAL CONTRADICTORY RELATIONSHIPS. A. L. Nahm1, A.-K. Dudde2, and E. Hauber1, 1Institut für Planetenforschung, German Aerospace Center (DLR), Rutherfordstr. 2, 12489 Berlin, Germany, amanda.nahm@dlr.de, ernst.hauber@dlr.de; 2Nelson Mandela School, Pfalzburger Str. 30, 10717 Berlin, annakatharinadudde@yahoo.com.

**Introduction:** Crosscutting relationships are used to determine the relative ages of geologic units or structures such as faults. Understanding the relative ages of events is critical to understanding the geologic history of a region or a planetary body. Understanding the tectonic history of the Moon, particularly the timing of fault formation, provides crucial constraints on the evolution and sources of stress.

Tectonic activity on the Moon is exhibited by three morphologies: graben, wrinkle ridges (WR), and lobate scarps. Contractual deformation, likely from global contraction andmare subsidence, is hypothesized to postdate extensional deformation, effectively ‘shutting off’ normal faulting on the Moon [e.g., 1, 2]. The current understanding of lunar tectonics indicates that graben formation/extensional deformation ceased around 3.6 Ga [3], though the individual normal fault known as Rupes Recta formed ≤ 3.2 Ga [4]. In contrast, contractional deformation in the form of wrinkle ridges and lobate scarps appears to have continued until ~1.2 Ga [2] and <1 Ga [e.g., 2, 5, 6].

Based on this information, crosscutting relationships between wrinkle ridges and graben are expected to consistently show graben to be older than wrinkle ridges. However, rare crosscutting relationships indicate that wrinkle ridges are both older [e.g., 7] and younger than the graben [1]. Unfortunately, no list or compilation of the locations of these crosscutting relationships exists in the literature against which the timing can be compared. Thus, we have assembled a list of locations of crosscutting relationships along with interpretations of the sequence structural deformation (Table 1).

**Discussion:** The locations of 33 crosscutting interactions have been catalogued and are listed in Table 1. In general, ~60% of observed interactions show graben are older than wrinkle ridges, consistent with the summary given above. However, in five cases, the wrinkle ridges appear to be older than the graben. Thus, graben and wrinkle ridge formation may have been contemporaneous for at least a portion of the geologic history of the Moon, or graben and wrinkle ridge formation were temporally distinct. This is supported by the timing of wrinkle ridge formation (ending ~1 Ga, but may have begun ~4 Ga [8, 9]), as well as the observations provided here. At the very least, these results indicate that the canonical view of lunar tectonics (that is, graben formed before wrinkle ridges) is overly simplistic and warrants a detailed investigation of these interesting structures.

**Table 1. Catalog of observed crosscutting relationships between graben and wrinkle ridges.**

<table>
<thead>
<tr>
<th>Relationship Type</th>
<th>Approx. center long.</th>
<th>Approx. center lat.</th>
</tr>
</thead>
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<tr>
<td>Graben older</td>
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<td>45.77</td>
</tr>
<tr>
<td></td>
<td>-25.34</td>
<td>45.90</td>
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<td></td>
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LAVA FLOW EMPLACEMENT AND RELATED FEATURES ON THE MOON. D.H.
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Introduction: Most lava flows on the Moon were emplaced via effusive, voluminous eruptions of low viscosity lavas (e.g., [1]), forming the mare basalts. Data of unparalleled resolution and coverage collected during recent lunar missions have facilitated improved observations of known, localized volcanic features as well as the identification of new features. Such features include pyroclastic vents, cones, irregular mare patches, and sinuous rilles, as well as the confirmed presence of non-mare volcanic features (silicic domes).

Volcanic Features and their Implications:
Pyroclastic vents: Pyroclastic materials indicate that local eruptions of lava contained an abundance of volatiles. A global survey had been compiled with 20th century data sets [2], but the high resolution and global coverage of Lunar Reconnaissance Orbiter (LRO) data have been used to identify new, smaller vents [3], and the high spatial and spectral resolution of Chandrayaan’s Moon Mineralogy Mapper (M3) data have been used to characterize the mineralogy of those deposits [e.g. 4]. Recent laboratory studies of returned pyroclastic beads have confirmed the high volatile content of these materials [5,6], indicating the Moon’s interior is not as depleted in volatiles as once thought.

Silicic domes: “Red spots” with high Th and low FeO contents had been identified previously on the Moon [7-13], but data from LRO’s Diviner instrument indicates a high silica content in the Compton Belkovich complex, Gruithuisen Domes, Aristarchus Plateau, Hansteen Alpha, and Lassell Massif [14-15], indicating evolved, silicic lavas erupted on the Moon.

Cones and shield volcanoes: Previous studies of lunar cones have indicated that cones may have formed as the result of strombolian eruptions at the terminal stages of effusive mare eruptions [e.g. 16]. Recent studies using M3 data have indicated the Marius Hills have a weaker 1 µm absorption band than surrounding mare, a difference interpreted to indicate higher silica content, more opaque minerals, and/or a weaker olivine content in the cone lavas [17]. These compositional differences indicate a long and complex volcanic history of the region. Other work using GRAIL gravity data has suggested the Marius Hills formed atop a large low-lying shield volcano [18], a feature not previously identified on the Moon.

Irregular Mare Patches: Anomalous lava flows with bulbous, irregularly shaped mounds have long been identified on the lunar surface (e.g., Ina, [7,19-20]). These features have typically been interpreted to indicate small effusions of lava along a fissure [19] or episodic outgassing of subsurface volatiles [20]. Analyses of new LRO imagery have suggested instead that these textures arose from lava flow inflation, such as that in McCartys flow, NM [21], and may represent the youngest volcanism on the Moon [22].

Sinuous rilles: Lava channels have been observed on the Moon since Lunar Orbiter [23], but the specifics of their formation are still debated: Are these features formed by construction [24-26], mechanical erosion [27-28], thermal erosion [e.g. 29-36], or a combination of the two erosion regimes [34-37]? LRO imagery and altimetry data have indicated both leveled and incised lava channels formed on the lunar surface [37]. These interpreted origins indicate some lava flows were emplaced during brief eruptions of slightly more viscous lavas that formed levees, while other lava flows were emplaced during long-lived eruptions of hot, low-viscosity lavas that incised into the substrate [37]. On-going analyses using LRO’s suite of new data are evaluating whether previously calculated discharge rates are representative of eruption dynamics or of localized “fill and spill” channel flow dynamics [38].

Concluding Remarks: Observations of new types of volcanic features and of finer-scaled details of known features have shown the Moon to be more complex than previously considered and, thus, these features should be incorporated into a volcanism chapter in New Views of the Moon 2.

COMPOSITION OF THE LUNAR HIGHLAND CRUST AND MANTLE AND ITS IMPLICATIONS. M. Ohtake¹, S. Yamamoto², K. Uemoto³, Y. Ishihara¹, ¹Japan Aerospace Exploration Agency (JAXA) (ohtake.makiko@jaxa.jp), ²National Institute for Environmental Studies, ³Tokyo Univ.

Introduction: Recent remote sensing data of the lunar surface obtained by lunar exploration missions give us large amounts of geochemical, mineralogical, and morphological information of the lunar surface from which we can derive fundamental knowledge of the lunar highland crust and mantle composition.

Composition of the highland crust: Extremely pure anorthosite (PAN), composed of nearly 100% anorthite, which is significantly higher than previous estimates of 82 to 92 vol.%, are widely observed by the SELENE (Kaguya) Multiband Imager at central peaks of younger and least contaminated craters in the lunar highlands [1]. These PAN rocks are estimated to be uplifted to the lunar surface from depths of 3 to 30 km (possibly even as deep as 50 km) suggesting the presence of a global layer of PAN rock in the crust. The global distribution of the PAN rocks regardless of its original depth is further demonstrated [2]. The abundance of the already low mafic mineral abundance in the PAN rocks appears to further decrease with depth according to the compositional analyses of the ejecta of basins of different size, which corresponds to different depths of origin [3]. All these data suggest that the PAN layer is a main component of the highland crust. The extreme composition of the PAN rocks appears to be difficult to generate in large quantities directly from the magma ocean. However, recent computer simulation [4] of the crustal formation revealed that it is possible to generate pure anorthositic crust as a result of simple cooling, segregation, and accumulation processes, which matches the real observation.

The Mg# (Mg/(Mg+Fe) in mol%) of the mafic mineral phase in the highland crust was found to change laterally and continuously from 50 to 70 on the near side up to 80 on the farside [5]. Contamination by high-Mg# basin ejecta from South Pole-Aitken is not likely to be the source because the mafic mineral abundance decreases as the Mg# increases toward the highest-Mg region from the surrounding basin. The presence of crustal material with higher Mg# on the farside than previously estimated, which is 50 to 70 based mainly on the returned lunar samples collected from the nearside, suggests higher Mg# of the melt during plagioclase crystallization on the farside. This result further implies that the farside crust consists of rocks that crystallized from less-evolved magma than the nearside crust. This interpretation is supported by the independent observation that Thorium abundance in the farside highland crust based on the SELENE gamma-ray data is lower, which suggests the earlier crystallization from the magma, than the nearside crust [6]. A simple yet plausible model for interpreting these observations is asymmetric crustal growth. Also, the higher Mg# of the melt during plagioclase crystallization (which evolved from the bulk LMO) further indicates the possibility of higher Mg of the bulk LMO.

Composition of the mantle: No sample originating directly from the lunar mantle is known among currently available lunar samples and lunar meteorites. Therefore, it is critical to understand the composition of the lunar mantle based on the remote-sensing data of the exposures of mantle materials.

It is suggested that the lunar mantle material exposed at rims of big basins such as Imbrium (1200 km) and within and around SPA basin (2500 km). Mineralogical analyses of these big basins indicate that the major mafic mineral phase observed at SPA (except its central part, where impact melt pool is assumed to be located) is low-Ca pyroxene [7], but olivine is observed [8] at the rim of other relatively smaller basins such as Imbrium. These observations likely suggest vertical heterogeneity (possibly two compositional layers) of the lunar mantle, which apparently correspond to the original depth rather than the results of lateral variation because of the comprehensive occurrence of olivine at basins smaller than SPA [8].


Fig.1 Mg# of the lunar highlands. Dotted circles denote major basins in the highland region. Mare and regions with high HCP/LCP ratios are indicated in sea green. Yellow stars indicate collection sites of the returned lunar samples.
NEW INFRARED VIEWS OF THE MOON FROM DIVINER. D. A. Paige¹ and The Diviner Team, ¹Dept. of Earth, Planetary and Space Sciences, UCLA (dap@moon.ucla.edu)

Introduction: During the past decade, remote sensing datasets have filled many gaps in lunar knowledge. The Diviner Lunar Radiometer Experiment on the Lunar Reconnaissance Orbiter has mapped the lunar surface for almost seven years, acquiring a dataset of unprecedented quality, detail, and coverage. The analysis of these data has provided several new views of the moon that can be summarized as follows.

Lunar Thermal Environment: Surface and near-surface temperatures of the moon represent a key boundary condition on the thermal state of the lunar interior, lunar surface processes, the behavior of volatiles, and the interaction between the lunar surface and the lunar exosphere. LRO’s polar orbit has enabled Diviner to acquire multi-spectral infrared observations over the entire lunar surface at all local times at a spatial resolution of <500 meters. These measurements enable detailed characterization of diurnal and seasonal surface temperature variations, which provide valuable information regarding regolith structure and evolution, as well as the behavior of volatiles. They also reveal the moon to have one of the most extreme thermal environments in the solar system, although some highly rocky areas may have more hospitable thermal environments for long-term human habitation.

Lunar Regolith Properties: Diviner’s time-varying multispectral measurements provide information on the bulk thermal properties of the regolith from cm to meter scales. More than 98% of the moon’s surface is covered with fine-grained dust that increases in density with depth. Young impact craters have excavated large (>1m) blocks that are readily detectable as warm anisothermal anomalies in nighttime infrared maps. The youngest impacts on the moon are surrounded by extensive regions containing low-density soil and are detectable as cold anomalies in nighttime infrared maps. The creation of these “Diviner cold spots” appears to be a ubiquitous lunar process.

Lunar Regolith Evolution: By correlating crater age measurements from lunar samples and crater counts with Diviner rock abundance data, it has been possible to obtain a much clearer picture of the rate at which the lunar surface evolves over time. The typical time-scale for the degradation and burial of ejecta blocks on the lunar surface by micrometeorite bombardment is on timescales ~500 million years. By cataloging the density of rocky craters in various states of degradation, it has been possible to infer that the impact flux as recorded by the moon has increased by a factor of two during the past 300 million years. Superposed on this process is the creation and degradation of lunar cold spots, which appears to occur on timescales of ~200,000 years.

Lunar Composition: Diviner uses three narrow channels near 8 microns wavelength to map the location of the Christiansen Feature, a thermal emission feature which is related to bulk silicate polymerization, occurring at shorter wavelengths for feldspathic minerals and longer wavelengths for mafic minerals. Diviner’s compositional maps show that Most lunar terrains have spectral signatures that are consistent with known lunar anorthosite and basalt compositions. However, the data have also reveal the presence of highly evolved, silica-rich lunar soils in kilometer-scale and larger exposures, expanding the compositional range of the anorthosites that dominate the lunar crust, and shown that pristine lunar mantle is not exposed at the lunar surface at the kilometer scale. Together, these observations provide compelling evidence that the Moon is a complex body that has experienced a diverse set of igneous processes.

Polar Volatiles and Heat Flow: Diviner has made extensive thermal emission measurements in the lunar polar regions. The results show that the moon’s permanently shadowed regions are considerably colder than had been pre-LRO models had predicted. The moon’s polar regions contain extensive surface and subsurface regions that are cold enough to permit the thermal stability of water ice and other volatile and organic species. LCROSS detected the presence of a number of volatile species at its impact site in Cabeus Crater. Diviner measured temperatures of lower than 37K in this area, which allows for the thermal stability of the diverse range of volatiles that LCROSS detected. Other data sources suggest that the moon’s polar cold traps are depleted in water ice and other volatiles, at least near the surface. This is in sharp contrast to the results of Earth-based radar and MESSENGER observations at Mercury, which show the presence of abundance near-surface water ice. Diviner has measured annual minimum brightness temperatures of less than 20K in localized areas in the lunar south polar region. These measurements can be used to infer upper limits for the heat flow rate from the lunar interior. The results suggest that average global heat flow on the moon is considerably lower than that measured at the Apollo 15 and 17 sites, which is consistent with measurements of the concentration of radiogenics in the lunar crusts and models for the composition of the lunar mantle.
**Introduction:** NASA’s Mini-RF instrument on the Lunar Reconnaissance Orbiter (LRO) and the Arecibo Observatory (AO) in Puerto Rico have been operating in a bistatic architecture (AO serves as the transmitter and Mini-RF serves as the receiver) over approx. a 2.5 year period in an effort to understand the scattering properties of lunar terrains as a function of bistatic (phase) angle. In that time, 28 observations of the surface have been acquired for the lunar nearside and poles. These observations include mare materials, highland materials, pyroclastic deposits, and a variety of craters (polar and non-polar). The primary motivation for acquiring these data is to characterize the opposition response of lunar terrains at S-band wavelengths (12.6 cm) to differentiate the Circular Polarization Ratio (CPR) response of materials that are rough from surfaces that harbor water ice.

**Background:** The transmitter for Mini-RF bistatic observations is the 305 m Arecibo Observatory radio telescope in Puerto Rico. For each observation, the antenna is pointed at a target location on the moon and illuminates the lunar surface around that location with a circularly polarized, S-band (2380 MHz) chirped signal that has a fixed peak power of 200 kw and tracked the Mini-RF antenna boresight intercept on the surface of the Moon. The data returned provide information on the structure (i.e., roughness) and dielectric properties of surfaces and buried materials within the penetration depth of the system (meter(s) for Mini-RF) [1-4]. The bistatic architecture allows examination of the scattering properties of target surfaces for a variety of bistatic (phase) angles.

Laboratory data and analog experiments, at optical wavelengths, have shown that the scattering properties of lunar materials can be sensitive to variations in bistatic angle [5]. This sensitivity manifests as an opposition effect. Analog experiments and theoretical work have shown that water ice is also sensitive to variations in phase angle, with an opposition effect that it is tied primarily to coherent backscatter [6,7]. Differences in the character of the opposition response of these materials offer an opportunity to differentiate between them, an issue that has been problematic for radar studies of the Moon that use a monostatic architecture [8].

**Observations:** CPR information is commonly used in analyses of planetary radar data [1-4], and is a representation of surface roughness at the wavelength scale of the radar (i.e., surfaces that are smoother at the wavelength scale will have lower CPR values and surfaces that are rougher will have higher CPR values). High CPR values can also serve as an indicator of the presence of water ice [9]. We use CPR as a function of bistatic angle to explore the opposition response of lunar materials at S-band wavelengths.

Data of mare materials, highland materials, pyroclastic deposits, and a variety of craters (polar and non-polar) have been acquired over the course of Mini-RF bistatic operations. Observations of mare materials and pyroclastic deposits show a uniform CPR response for bistatic angles < 10°. Observations of crater ejecta show variations in CPR, as a function of bistatic angle, that are not uniform for Kepler and Byrgius A or consistent from crater-to-crater. The response of Kepler and Byrgius A is suggestive of an opposition effect. The inconsistency from crater-to-crater may be related to the age of the deposit and/or target material properties. Observations of the floor of Cabeus crater show variations in CPR, as a function of bistatic angle, that are also indicative of an opposition response.

**Results:** Mini-RF has acquired a significant amount of bistatic radar data of the lunar surface in an effort to understand the scattering properties of lunar terrains as a function of phase angle at S-band wavelengths (12.6 cm). Observations that include mare materials, highland materials, and pyroclastic deposits have not shown an opposition response over for bistatic angles of ~0.1° to 10°. In contrast, observations of the ejecta blankets of young, fresh craters have shown an opposition response but the character of the response varies for each crater. Observations of portions of the floor of the south polar crater Cabeus also show an opposition response. The character of the radar response from the crater, as a function of bistatic angle, appears unique with respect to all other lunar terrains observed. Analysis of data for this region suggests that the unique nature of the response may indicate the presence of near-surface deposits of water ice.

Overview. Limited sampling of primary crustal units, such as highland ferroan anorthosites (FAN), by the Apollo missions have made refining crustal formation models challenging. However, our recent understanding of lunar crustal formation and evolution has developed through the combination of analytical advances, wider observations of global lunar structure, and the increased availability of anorthositic material sampled as clasts within meteorite regolith breccias.

Highland sampling issues. Through studying lunar meteorites, we are able to sample the global diversity of the lunar highlands; many containing components of anorthositic material from the feldspathic highland terrane [1]. In most cases, these anorthositic clasts are very small (< 5 mm). This has resulted in problems interpreting their petrology, particularly for applying the criteria set out by Warren [2] for identifying ‘pristine’ igneous rocks sourced from the primary FAN, and secondary magmatic Mg-Suite and high-alkali suite highlands groups. Furthermore, the small sizes of these clasts make it easy to misinterpret ‘secondary’ impact-melt textures with ‘primary’ igneous textures [3], and make difficult it to conduct ‘bulk rock’ analyses to identify the chemical signatures associated with impact-melts.

Technique Advances. New sampling approaches and analytical techniques over the last decade has enabled more geological information to be extracted from these small highland samples. In particular, in situ LA-ICP-MS and SIMS mineral incompatible trace-element (ITE) analyses have now become routine tools for investigating the petrogenesis of rocks [4,5], helping to unravel the problem of igneous vs impact rock. The ITEs are particularly helpful as they are generally robust to significant post-crystallisation-modification. In particular, trace-element analyses of FAN plagioclase, in combination with advances in isotope geochronology e.g., [6] and the wealth of new remote sensing missions e.g., [7] has enable a number of important observations that are helping to refine crustal formation models [8].

Highland chemical variations. Recent studies have highlighted compositional differences within anorthosite samples sourced from the primary highlands crust. For instance, an important sub-set of clasts identified within some regolith breccias are the magnesian anorthosites (Mg#plag > 65 [9], cf. FAN Mg#plag < 65 [2]). The identification of these lithologies are consistent with remote sensing data that suggests there is a general chemical dichotomy between magnesian farside anorthosites relative to ferroan nearside anorthosites [10]. In addition to these broad major-element differences, recent ITE studies have shown that plots of plagioclase Eu-anomaly vs. ITE for suites of anorthosite clasts from individual meteorites can lie on distinct compositional trends indicating that anorthosite suites may be more petrologically heterogeneous than previously thought [4,11]. The results of these geochemical studies clearly point to a model of lunar anorthosite formation that is more complex that a single global plagioclase flotation formational event [8].

Implications of crustal formation models: The observations outlined above have resulted in a number of possible variations to the traditional global floatation crustal formation models [8]:

1) A long-standing model that has gained some favour to account for the chemical variations in anorthosite chemistry is serial magmatism model [8]. This hypothesis suggests that multiple large plagioclase-rich diapirs, sourced from geochemically different mantle regions, accreted to form the lunar crust [8, 9, 12].

2) To account for the differences in anorthosite Mg# content, studies have proposed an asymmetrical plagioclase flotation model, whereby the nearside remains hotter than the farside, causing earlier farside plagioclase crystallisation from a more primitive parental magma relative to the nearside [8, 10].

3) Large impacts could also account for anorthosite chemically variably [13]. Crystallisation and subsequent plagioclase flotation of large impact melt sheets may give the appearance of ‘pristine’ primary rocks [14], their true origin having been ‘blended in’ with the surrounding lithologies during impact gardening.

Summary. There is still much to be learnt about the suite of lunar highlands from the material available to us in the Apollo and lunar meteorite collections. In particular, with micro analytical tools now readily available, the study of small rocklets or individual mineral has been demonstrated to be an effective diagnostic tools for classifying and understanding lunar samples with little or no petrographic context.

The last decade has brought an unprecedented flux of new data about the compositional character of the lunar crust as derived from remote measurements. The data come largely from diverse advanced sensors on Kaguya, Chandrayaan-1, and LRO. The stratigraphy of compositional properties of the crust is further constrained by integrated geophysical data from LRO and GRAIL. Although these data are necessarily incomplete, they provide fundamental new perspectives and there is much to discuss!

Example crustal composition highlights include:

- Discovery and mapping the distribution of Pure Anorthosite (PAN) as a magma ocean product
- Expanding the search for and detection of olivine across the Moon and opening issues associated with Mg-suite vs mantle origin
- Discovery of a new rock type, Mg-spinel anorthosite, that appears to be associated with Mg-suite emplacement
- Likely identification of small highly silicic regions
- Discovery of widespread surficial OH as well as local concentrations of OH/H2O
- Recognition and mapping of the relative abundance and distribution of Mg-rich pyroxene across the highlands
- Virtual exploration of basins and large craters that provide (complex) clues to the interior
- Numerous ‘unusual’ or ‘special’ areas continue to be identified (Compton Belcovich, Ina, Hansteen Alpha, etc.)
- Etc.

These global and regional data should be discussed as an integrated whole within the context of modern detailed lunar sample information.

Example issues to address/discuss (in no particular order):

- What is the origin of the Mg-suite and how is it related to FAN/PAN?
- Ie... what IS the lunar crust and how was it formed?
- How can/should we distinguish between lower crust and the mantle?
- What IS the lunar mantle?
- Did mantle ‘overturn’ occur and if so, how did that event affect the lunar crust?
- How well mixed (and how deep) is the megaregolith?
- What caused the apparent highly asymmetric distribution of radiogenic elements?
- How can compositional properties observed in and around craters/basins improve our understanding of the cratering process? And visa-versa?
- Etc., etc., etc.
CHARACTERISTICS AND EVOLUTION OF THE LUNAR REGOLITH. J. B. Plescia¹, 1The Johns Hopkins University, Applied Physics Laboratory, Laurel MD 20723 USA (jeffrey.plescia@jhuapl.edu).

Introduction: The lunar regolith is the fragmental layer that covers the surface of the Moon (Figure 1). This is the surface that is observed by remote sensing instruments (with penetration depths ranging from microns to meters) and from which lunar samples were collected and returned to Earth. It is also the surface on which surface instrumentation was placed. Understanding the characteristics, formation and evolution of the lunar regolith is thus critical to understanding the data and samples.

Data from recent lunar missions and research have provided a more precise picture of the nature of the lunar regolith and how it varies laterally and vertically. Those data have also begun to show how the regolith evolves over time. Of particular interest is the properties of regolith in areas of permanent shadow where the surface temperature can reach 40K [1].

Formation Mechanisms: The lunar regolith is composed of rock and mineral fragments as well as agglutinitic glass, with particle sizes ranging from microns to tens or hundreds of meters. Projectiles ranging in size from micro-meteorites to asteroids have impacted the surface over billions of years continuously reducing the size of the particles and vertically mixing the materials [2-7]. In addition to physical destruction, thermal fatigue [8-9] can induce mechanical failure reducing the grain size over time. The result is a layer that is meters thick overlying more intact basalt in the mare and a basin-ejecta megaregolith in the highlands [10-11].

Each new impact excavates material from depth that is typically less mature than the surrounding regolith and it forms a deposit of material ranging from boulders to dust surrounding the crater. As that new material is exposed, it is subjected to mechanical and thermal stress and the effects of space weathering.

Physical Properties: The Apollo core samples demonstrate that while the regolith is layered, the layers are not laterally continuous. Layers represent individual impact ejecta deposits and those deposits extend only about 1 crater diameter from the source crater. The result is an overlapping of approximately circular deposits of varying thickness and diameter.

The density of the regolith increases rapidly with depth over the upper 1 m and then appears to be more or less constant (although there is no direct data). UV and visible photometry shows that the uppermost few microns to millimeters is composed of a fine-grained, very porous structure having low density.

Volatile Storage: The regolith has an abundance of H in the polar areas, particularly in areas of permanent shadow. The H-bearing species is assumed to be H₂O although the material has not been directly sampled. Thermal modeling, ultraviolet and radar data suggest it is H₂O [12-15]. OH and H₂O occur across the surface as an ephemeral adsorbed layer that migrates on a diurnal time scale. It has also been suggested that there is significant transport of H (or H-bearing species) into and out of the regolith on diurnal time scales [18]. Understanding the processes of volatile migration requires an understanding the physical structure of the regolith (e.g., porosity, permeability).

Summary: Our understanding of the properties of the lunar regolith, its formation, and the role it plays in the production, transport and storage of volatiles has changed dramatically over the last decade. We now have sufficient information to quantitatively understand the active processes.

ON THE PROVENANCE & DISTRIBUTION OF THE LUNAR HIGHLANDS MAGNESIAN-SUITE.
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Introduction: What is the provenance of the magnesian-suite rocks? Posed in the first volume of New Views of the Moon [1], this question has motivated several lines of research aimed at advancing our understanding of the ancient, plutonic magnesian-suite samples. Below, I summarize the distribution and petrogenesis of the lunar highlands Mg-suite in light of recent experimental and orbital data.

Pink Spinel Anorthosites (PSA): NASA’s M³ experiment remotely identified a potentially new lunar rock type, PSA [2]. The lithology contains spinel (MgAl₂O₄) with no mafic silicate signature observed in the visible to near infrared wavelengths, suggesting a unique origin. This type of spinel is rare among the lunar samples, but most commonly observed within the Mg-suite pink spinel troctolites (PST) [3]. Akin to the plutonic Mg-suite, PSA detections are associated with the central peaks of craters and basin walls, indicative of intrusive lithologies excavated during impacts [4]. [3] experimentally investigated the hypothesis that PSA formed by magma-wallrock interactions within the lunar crust [5,6]. Results indicate PSA is best explained as the reaction product between the Mg-suite parent melt and anorthosite [3]. If true, the chemical connection between PSA and Mg-suite is profound; remote detections of PSA can be used as a new proxy for Mg-suite lithologies on the Moon [3]. Moreover, the presence of PSA (and extension, Mg-suite) on the lunar farside and regions outside of the Procellarum KREEP terrane [4] may indicate KREEP is not a primary component of Mg-suite petrogenesis [3].

Troctolite Petrogenesis as told by Spinel: Two competing hypotheses suggest melts parental to the lunar troctolites formed (A) by partial melting of a hybridized source region (ultramafic cumulates + plagioclase-bearing rocks + KREEP) [7] or (B) when magma-wallrock interactions within the anorthositic crust increased the Al-contents of initially plagioclase-undersaturated, MgO-rich melts [8]. However, phase equilibria experiments testing melt compositions from both (A) & (B) [9,10] yield major and accessory mineral compositions consistent with PST only, and do not produce magmatic chromite (FeCr₂O₄) as observed in the remaining troctolites (and dunites) [10]. Instead, experiments and modeling suggest plagioclase undersaturated Mg-suite melts are parental to chromite-bearing troctolites (and dunites) [10]. Instead, experiments and modeling suggest plagioclase undersaturated Mg-suite melts are parental to chromite-bearing troctolites (and dunites) [10]. Whereas spinel in the PST is an indicator of (B) [10]. The process of (B) is likely restricted to the magma-wallrock interface due to slow diffusion rates of Al₂O₃ in basaltic melts [11] and thus, spinel-bearing lithologies are expected to represent a volumetrically minor, but perhaps widespread, component of the lunar crust [10]. The conclusions are supported by the paucity of PST among the Mg-suite samples (though possibly not representative) and also the low number (~20) of global PSA detections [4]. New estimates of the plagioclase undersaturated Mg-suite parent are provided by [10].

Buoyancy-driven Mg-suite Magmatism: Finally, the lack of extrusive (and predominance of intrusive) Mg-suite samples is surprising considering that mare basalt flows cover ~18% of the lunar surface [12] and are 200–300kg/m³ greater in density than estimates for Mg-suite parental melts [13]. Motivated by recent measurements of crustal density from GRAIL [14], buoyancy-driven magmatic ascent of Mg-suite melts was investigated [15,16]. Results from [15,16] suggest present day, low-crustal densities measured by GRAIL (due to increased estimates of porosity) are needed to have prevented ancient, low-density Mg-suite parental melts from buoyantly erupting. Because the Mg-suite samples are ancient (> 4.1Ga) and predominantly intrusive, the results imply the primary lunar crust was fractured soon after solidification perhaps creating a porous, low-density barrier to eruption [16]. The Mg-suite parental melt estimated by [10] is consistent with intrusive petrogenetic models, and potential regions of eruption predicted for alternative Mg-suite melts are focused within the nearside southern highlands [16]. The Mg-suite eruptive area in the nearside southern highlands [15,16] is strongly correlated with a number of PSA detections [4] and positive Bouguer anomalies (possibly buried Mg-suite) [17] identified within the region. The findings suggest the nearside southern highlands is the most promising region to explore ancient intrusions and possible volcanic deposits of the lunar highlands Mg-suite [16].

LRO Lyman Alpha Mapping Project (LAMP) Far-UV Maps: A New View of the Moon. K. D. Retherford1, T. K. Greathouse1, G. R. Gladstone1, A. R. Hendrix2, K. E. Mandt1, A. F. Egan3, D. E. Kaufmann3, P. O. Hayne3, S. A. Stern3, J. Wm. Parker1, M. W. Davis1, C. Grava1, D. M. Hurley2, J. T. S. Cahill3, A. M. Stickle5, Y. Liu1, M. A. Bullock3, W. R. Pryor6, P. D. Feldman4, J. Mukherjee1, P. Mokashi1, C. J. Seifert1, and M. H. Versteeg1; 1Southwest Research Institute, San Antonio, TX (krechtferd@swri.edu), 2Planetary Sciences Institute, Tucson, AZ, 3Southwest Physics Laboratory, Laurel, MD, 4Central Arizona University, Coolidge, AZ, 5Johns Hopkins University Applied Physics Laboratory, Laurel, MD, 6Jet Propulsion Laboratory, Pasadena, CA, 7Johns Hopkins University Applied Physics Laboratory, Laurel, MD.

Abstract. Far ultraviolet (FUV) maps obtained using the Lunar Reconnaissance Orbiter (LRO) Lyman Alpha Mapping Project (LAMP)’s innovative nightside observing technique [1,2] reveal features on the Moon in a new light. Dayside FUV albedo maps obtained using the more traditional photometry technique with the Sun as the illumination source are very complementary. Together, these LRO-LAMP investigations provide a unique perspective on the lunar “hydrological cycle,” connecting the surface abundance of water frost trapped in the Moon’s cryosphere to volatile transport processes involving the lunar exosphere.

LAMP Instrument. The LRO-LAMP UV imaging spectrograph is studying how water is formed on the Moon, transported through the lunar exosphere, and deposited in permanently shaded regions (PSRs)[2,3]. Importantly, the nightside imaging technique allows LAMP to peer into the PSRs near the poles, and determine their UV albedos. LAMP nightside and dayside brightness maps cover wavelength range 57-196 nm. Lyman-α, on-band and off-band albedo maps (i.e., on and off the water frost absorption band at ~165 nm) are useful for constraining the abundance of surficial water frost [1,4,5].

Key Results. Global nightside and dayside maps are divided (at ±60° latitude) into polar and equatorial regions with stereographic and equirectangular projections, respectively. Additionally, new spectral image cube maps have been created for several regions of interest with 2 nm resolution, and are being expanded to cover the full globe.

LAMP FUV albedo measurements indicate ~1-2% surface water frost areal-mixing abundances in a few PSRs based on spectral color comparisons, and we find that many PSRs may have porosities of ~0.7 based on relatively low albedos at Lyman-α [1,5]. The FUV albedo maps reveal lower albedo regions and/or spectral shapes consistent with water frost within the coldest PSR regions, determined with correlative analyses using LRO-Diviner maps [5]. Mandt et al. [6] reported an updated analysis of the PSR reflectance measurements, and more recent work includes a search for albedo changes on monthly timescales.

Global dayside FUV albedo maps enable comparisons between the nightside and dayside photometry techniques to help validate the use of Lyman-α and starlight as illumination sources. Analysis of dayside spectra for selected regions complement the nightside maps, and are used to investigate space weathering and hydrated surface signatures [7,8]. A lab study of the FUV reflectance properties of Apollo samples, lunar simulants, and water ice is underway to further characterize the UV reflectance technique [9]. The FUV spectral inversion property of the lunar albedo discovered by the Apollo 17 UVS is confirmed with the LAMP dataset [4]. Hendrix et al., [10] report that swirl regions show a UV-reddening, perhaps in response to differences in space weathering processes within these regions, and Cahill et al., [11] report follow up comparisons between LAMP maps and imagery from other LRO instruments.

TESTING AND RESILIENCE OF THE IMPACT ORIGIN OF THE MOON. K. Righter¹ and R.M. Canup²,
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Introduction: The leading hypothesis for the origin of the Moon is the giant impact model, which grew out of the post-Apollo science community [1]. The hypothesis was able to explain the high E-M system angular momentum, the small lunar core, and consistent with the idea that the early Moon melted substantially. The standard hypothesis requires that the Moon be made entirely from the impactor, strangely at odds with the nearly identical O isotopic composition of the Earth and Moon, compositions that might be expected to be different if Moon came from a distinct impactor [2]. Subsequent geochemical research has highlighted the similarity of both geochemical and isotopic composition of the Earth and Moon [3], and measured small but significant amounts of volatiles in lunar glassy materials [4], both of which are seemingly at odds with the standard giant impact model. Here we focus on key geochemical measurements and spacecraft observations that have prompted a healthy re-evaluation of the giant impact model, provide an overview of physical models that are either newly proposed or slightly revised from previous ideas, to explain the new datasets.

Isotopic measurements Si, Mg, K, O, Fe, Ti, Cr, W, Mo, Ru: Many isotopic measurements of lunar and terrestrial materials have revealed nearly identical values for the two bodies. Although for some isotopic systems the inner solar system is quite uniform, there are some isotopic differences. For example a small difference between lunar and terrestrial W and O [5,6] isotopic composition has been measured. The significance of the similarities/differences is actively debated.

Volatiles: Lunar glasses contain measurable amounts of H, C, and S, which was surprising since many previous studies had concluded that lunar materials are dry or even “bone dry” [4,7]. The rock record on Earth does not extend back as far as that on the Moon, but it comes close with studies of zircons from various Archean terranes such as the Jack Hills in Australia [8]. Such zircons have O isotopic compositions indicating influence of water at the surface of the Earth, suggesting water was delivered early in Earth’s history, and that the early Earth-Moon system may have contained more volatiles than previously thought. New LRO measurements of volatiles at the lunar surface has also prompted re-evaluation of the origin and abundance of lunar volatiles [9].

Response to new data: These new geochemical data, especially the isotopic data – have forced the issue of why the Moon is not different in composition from Earth, as apparently predicted by the standard giant impact scenario. Various revised or new ideas have been proposed to explain the new data.

Exploration of planetary dynamics: If a spun up Earth was impacted, the material ejected is mostly from Earth [10]; a drawback is that this hotter resulting disk may be at odds with a volatile-bearing Moon. In a hit and run collision [11], impact geometry allows more of the Moon to originate from proto-Earth’s mantle, but raises the question “where is the impactor now?”. Solutions involving orbital resonances and Trojan Moons allow the Moon to be accreted from material originating from nearly the same region as that of Earth [12].

Exploration of disk dynamics: The dynamics and evolution of the circumterrestrial disk include many unexplored aspects. Outcomes of recent modelling [13] indicate that silicate Earth material might mantle impactor material in the lunar interior as the circumterrestrial disc collapses into the Moon. Alternatively, isotopic equilibration between hot Earth and the lunar disk may explain the Earth-like Moon [14], but this might cause disk instabilities that make it unviable.

New ideas motivated by geochemical data: Late stochastic accretion, in which Earth and Moon get different amounts of late chondritic additions, was proposed to explain W differences [15]. Other geochemical and isotopic modelling indicate that inner solar system material is Earth-like; in that case O isotopes are expected to be similar, and W can be explained by Monte Carlo simulations [3].

Each of these new or revised ideas has pros and cons, which will be evaluated. Attempts will be made to propose tests that might help distinguish these models and test their viability, including geochemical, dynamic, and exploration-based data or measurements.

VOLATILES IN EVOLVED LUNAR ROCKS: CONNECTING WATER AND CHLORINE. K. L. Robinson1*, J. J. Barnes1, M. Anand2, G. J. Taylor3, and I. A. Franchi1. 1DPS, The Open University, Walton Hall, Milton Keynes MK7 6AA UK. 2Dept. of Earth Sciences, Natural History Museum, London, SW7 5BD, UK. 3HIGP, The University of Hawaii at Manoa, 96822 USA. *katie.robinson@open.ac.uk

Introduction: Apatite [Ca8(PO4)6(OH,F,Cl)] is a useful tracer for investigating the history of volatiles in the Moon. Hydrogen (typically reported in terms of equivalent H2O or OH and referred to as ‘water’) in apatite has been measured in most major lunar rock types [1-9], and seems to vary both in terms of abundance (e.g. “wet” and “dry” reservoirs) and isotopic composition [6,10] in the lunar interior. Chlorine is also an important lunar volatile. The range of ratios of 35Cl to 37Cl (expressed as δ37Cl relative to standard mean ocean chloride) in the Moon (−4 to > +36 ‰) is much larger than that of Earth’s mantle (−0 to +1 ‰, [9,12-16]). Previous work by Robinson et al. [10-11] on a set of quartz monzodiorites (QMDs) from Apollo 15 showed that their apatites have extremely low D/H ratios, which may represent a primitive H component in the lunar interior. We present δ37Cl data for apatite in these same samples, which may help clarify the sources and history of lunar volatiles.

Samples and Methods: We studied apatite in three QMD thin sections: 15404, 51 and -55, and 15403, 71. Apatite in these sections had been previously measured for H2O content and δD at the Open University and Univ. of Hawaii [10-11]. All of these apatite grains have extremely low δD values (~440 to -750 ‰) and < 300 ppm H2O [10-11]. Two additional apatite crystals in 15404, 55 were measured for Cl isotopes using the OU Cameca NanoSIMS 50L following an established protocol [9, 15].

Results and Discussion: Apatite grains in the QMDs studied here are very enriched in 37Cl with respect to Earth’s mantle. They exhibit a relatively narrow range in δ37Cl values, from ~ +19 to ~ +29 ‰. The uncertainties on these measurements was usually better than 2 ‰.

Lunar apatites exhibit a large range in δ37Cl values (-4 to +36 ‰) [9,12,14-16], and an astonishing range in δD values (-750 to +1200 ‰) [2,4-11]. A number of processes may have affected the isotopic composition of H and Cl. High δD values recorded by apatite in lunar basalts have been attributed to magmatic degassing of H2, which likely enriched the residual melt in D [4-5,7-8]. Degassing of Cl in the form of metal chlorides may also have enriched basaltic melts in the heavier 37Cl isotope, causing isotopic fractionations of up to 20 ‰ [19]. On a wider scale, Cl degassing from the lunar magma ocean has been suggested to have caused the apparently elevated (~+30 ‰) δ37Cl composition of urKREEP [15-16]. This argument is supported by the positive correlation between Cl isotopic composition and KREEP component (defined by incompatible trace element ratios) in lunar samples [15-16, 20]. The Cl isotopic composition of apatite in the QMDs studied here are consistent with the compositions of apatite from other KREEP-rich samples [9,12,15]. However, this similarity in Cl isotopic composition makes it more difficult to reconcile the ultralow δD values of apatite in the QMDs [10-11], which are highly anomalous among lunar rocks. It appears that in the KREEPy parental melts to the QMDs, water and Cl were decoupled, and our results indicate that perhaps Cl and water were derived from different sources within the Moon.

Conclusions: The distribution in the lunar interior of both water and Cl is heterogeneous. Cl appears to be decoupled from water and related instead to urKREEP, as proposed by [14]. The Apollo 15 QMDs contain very dry apatite [10-11] and are high in KREEP content. They have correspondingly high δ37Cl values. However, their anomalously low δD values (as low as -750 ‰ [11]) cannot be explained by any of the processes discussed so far and therefore, may indicate a unique source of H in the lunar interior.

HOW EXOSPHERIC SODIUM AND POTASSIUM MIGRATE ON THE MOON: THE VIEW FROM LADEE. M. Sarantos1, A. Colaprete2, J. Szalay3, J.L. McLain4, D. H. Wooden2, A. Poppe5, 1Heliophysics Science Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA, 2NASA Ames Research Center, Moffett Field, CA 94035 USA, 3LASP, University of Colorado, Boulder, CO 80309 USA, 4Solar System Exploration Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA, 5Space Sciences Laboratory, UC Berkeley, Berkeley, CA 94720 USA.

Introduction: Almost thirty years after the discovery from Earth telescopes of tenuous Na and K exospheres enveloping the Moon [1], recent measurements from the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft posed new questions [2]. With their high temporal cadence and continuous coverage, LADEE data revealed the long-term and short-term evolution of these exospheres, thus providing previously unavailable information about the time scales for loss of Na and K. These observations advance our understanding of how Na and K - two particular examples of volatiles that are easy to observe because of their good spectroscopic properties - are distributed, transported, and sequestered in near-surface environments of Inner Solar System bodies.

Findings: We present models of the exosphere-extreme surface system used to interpret the LADEE measurements. The simulator accepts as input partially constrained microphysical parameters of the gas-surface interaction (such as source rates, cross sections for different source processes [3]) to make testable predictions of the exosphere and extreme surface (~top 1 Å).

Two key pieces of evidence provided by LADEE are the response of the atmosphere to showers, and the amplitude of the observed monthly variation for these exospheric species with lunar phase. By combining parameters that are required to explain the rise and fall of the atmosphere during and following showers with parameters required to explain the monthly variation, we can derive: 1) the "temperature" of the impact vaporization source; 2) the relative importance of source processes for adsorbed particles; 3) the residence times and sink rates for adsorbed particles of these species on the lunar surface; and 4) the exogenuous amount of Na and K brought in by interplanetary dust.

We find that the migration parameters of Na and K likely differ in time and/or with selenographic location. For instance, the best qualitative agreement with the observed monthly amplitude of lunar Na was achieved either when the Na source rate is assumed to peak at Mare, or – alternatively - if the residence time for photodesorption of adsorbed Na is much shorter on Mare soils, or even if Highlands soils are more reactive. Soil maturity appears to be affecting the redistribution rates. These findings underline the need for new laboratory experiments to be performed on lunar samples in order to fully interpret LADEE measurements.

**Magmatic Evolution 2. A New View of Post-differentiation magmatism.** C.K. Shearer¹, C.R. Neal², L.R. Gaddis³, B.L. Jolliff⁴, and A.S. Bell⁵. ¹Institute of Meteoritics and Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131 (cshearer@unm.edu). ²Department of Civil & Env. Eng. & Earth Sciences, University of Notre Dame, Notre Dame, IN 46556. ³Astrogeology Science Center, U.S. Geological Survey, Flagstaff, Arizona. ⁴Washington University, St. Louis, Mo 63130.

**Introduction:** Lunar magmatism is represented by numerous episodes of intrusive and extrusive activity ranging from ~ 4.4 Ga to perhaps younger than 1.0 Ga [1]. These magmatic episodes shaped the lunar crust and are expressions of the thermal evolution of the mantle, lithosphere, and crust. Lithologies representing these periods (excluding the primary ferroan anorthositic suite) include magnesian suite, alkali suite, high-Al basalts, KREEP basalts, cryptomere basalts, mare basalts, felsic volcanics, and pyroclastic deposits. The role of magnesian anorthosites within these magmatic rock suites is still a point of debate. In “New Views of the Moon” (first edition, hereafter NVM1) Chapter 4 “Thermal and Magmatic Evolution of the Moon” [2] examined the timing, composition, and petrogenesis of lunar magmatism and its relationship to lunar thermal evolution. More recently, several missions, new state-of-the-art sample measurements, new lunar samples (meteorites), and sophisticated modeling have provided a new perspective on lunar magmatism. We use these new observations to expand our understanding of these episodes of lunar magmatism.

**New Observations:** The intent of this writing team is to integrate new measurements, observations, and models into our understanding of lunar magmatism at the beginning of the 21st century. Here, we highlight only a few of these new observations.

**Crystallization ages of the first stages of post-differentiation magmatism:** Recent studies indicate ages for primordial crust (ferroan anorthosites), first stages of secondary crust (Mg-suite magmatism), and model ages for KREEP and mare basalts sources overlap at approximately 4.38 Ga [3,4]. What is the origin of such a major thermal-magmatic event?

**Role of volatiles and volatile-elements in lunar magmatism:** Since the return of samples by the Apollo program, the Moon has been considered “dry.” However, numerous recent studies have revealed that H-species played a role in lunar magmatism [5-7]. Estimates of the relative proportions of H-species (e.g. H₂, OH, H₂O) at the low ΩO₂ of the Moon indicate that H₂ is an important constituent of basaltic magmas and related volatiles [8]. What was the H-speciation and systematics of H and other volatiles in lunar magmas? What role did volatiles play in mantle melting and lunar magmatism?

**Pyroclastic glass deposits:** Studies of pyroclastic glass beads indicate that their eruption was driven by volatiles. Observations from LRO and M⁵ indicate that the distribution of volcanic glass across the lunar surface is much more widespread than previously documented [9,10]. These deposits represent many eruptive styles. What is the relationship between volatile composition and abundance during such eruptions? Do these deposits represent melting of fundamentally different mantle sources than the crystalline mare basalts?

**Felsic magmatism:** Felsic material was discovered in samples returned by Apollo; however, this type of nonmare volcanism is rare. Examples occur in the PKT, but data relating the samples to geologic context is scarce. LRO observations have identified volcanic features with silica- or alkali-feldspar-enriched volcanics, and these volcanics extend to the lunar farside [11-12]. How are these expressions of nonmare magmatism generated? Over what duration and environment were these magmas produced?

**Models for the relationship between basin formation and magmatism:** NVMI explored the role of impact-basin formation initiating melting and providing pathways for magmas to the lunar surface [2]. The relationship between magmatism and impacts has been modeled and vigorously debated [e.g. 13,14]. More recently several models have explored the effect of the South Pole-Aitken basin formation on triggering magmatism in the mantle beneath the antipodal nearside [e.g. 15]. Depending on the age of SPA, this event could trigger either mare magmatism starting at ~ 3.85 or the 4.38 Ga thermal-magmatic event.

**Magmatism < 1Ga:** Since NVMI, new observations suggest magmatic and fumarolic activity has occurred as recently as 10-100 Ma [1,16]. Such young magmatism requires a new approach to understanding the thermal history of the Moon.

Evidence for surface volatiles on the Moon and Mercury: A Planetary Comparison

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**Introduction:** An analysis of lunar polar surface volatiles would be incomplete without comparison to similar thermal environments of the planet Mercury. The Moon and Mercury both have cold, permanently shadowed regions featuring temperatures low enough to preserve water ice and other volatiles. With data from the Lunar Reconnaissance Orbiter (LRO) and MESSENGER missions, we can now begin to make detailed comparisons of surface reflectance data to evaluate evidence of surface polar volatiles on these two solar system bodies.

**Background:** Both LRO and MESSENGER carried 1064-nm wavelength laser altimeter instruments that provide a unique, zero-phase measurement of surface reflectance. Surfaces measured by the Mercury Laser Altimeter (MLA) showed higher than average surface albedo within some shadowed craters near the North Pole [1]. Modelling surface temperatures with MLA topography, these same areas were found to provide thermally stable environments for surface water ice to survive for geologic time [2]. In addition to the Lunar Orbiter Laser Altimeter (LOLA), LRO also carries a UV spectrometer, LAMP, which can detect surface frosts in polar regions illuminated by the Lyman-Alpha background illumination.

**This study:** We further develop the study of Paige et al. [2] and apply a similar technique to newly available data from LOLA. In the previous studies for Mercury [1,2] MLA data were unavailable at latitudes northward of 84° due to the MESSENGER orbit. Since this time, a campaign of off-nadir measurements has extended both MLA topography and reflectance measurements to colder areas nearer to the North Pole. We assert that the presence of a surface volatiles could result in characteristic “bumps” and “dips” in brightness as a function of maximum surface temperature, a *volatility spectrum*.

**Results:** Figures 1-3 show the volatility temperatures of several volatile materials plotted as vertical lines on top of a point cloud (grey) of all available MLA (Fig 1), LOLA (Fig 2) and LAMP (Fig 3) data as a function of maximum surface temperatures from Diviner and MLA/thermal modeling. Maximum surface temperature controls the abundance of surface ice measured by remote spectroscopy. These comparisons suggest that both the Moon and Mercury may harbor surface volatiles, but that these volatiles are not the same on the two planets and may have different sources. Understanding these sources has important implications for the delivery and retention of volatiles in the inner solar system.

DYNAMIC MOON: NEW IMPACTS AND CONTEMPORARY SURFACE CHANGES. E.J. Speyerer¹, R.Z. Povilaitis², M.S. Robinson¹, P.C. Thomas², R.V. Wagner¹, ¹School of Earth and Space Exploration, Arizona State University, Tempe, AZ, ²Cornell Center for Astrophysics and Planetary Science, Cornell University, Ithaca, NY.

Introduction: Random bombardment by cometary and asteroidal materials shape and alter the surface of the Moon as well as other planetary surfaces. While this concept is not new, observations from the Lunar Reconnaissance Orbiter Camera (LROC) [1] provide our first detailed look at surface changes associated with these impact events. Since the start of the mission, LROC has acquired over a million Narrow Angle Camera (NAC) images of illuminated terrain. From this collection, 14,092 are observations of regions of the Moon where previous NAC observations with similar lighting geometry exist (i.e. incidence angle difference <3°, incidence angle < 50°, and nadir pointing). These before and after image pairs, called temporal pairs, enable the search for a range of surface changes, including new impact craters, secondary disturbances, and mass wasting events that formed between the time the first and second images are acquired.

New Impact Craters: To date, NAC temporal pairs have uncovered 222 resolved impact craters ranging in diameter from 1.5 to 43 m. Furthermore, reimagining of two of the impact flashes recorded on 3/17/2013 and 9/11/2013 by Earth-based observers revealed 18 and 34 m diameter craters, respectively [2-4].

Using ratio images created from the temporal pairs, we can analyze the reflectance change and expanse of surface changes associated with each impact event. Fig. 1 shows the result of an impact that created an 18 m crater (42.6°N, 257.8°E). The new impact formed four distinct reflectance zones around the crater: proximal high reflectance zone, proximal low reflectance zone, distal high reflectance zone, and distal low reflectance zone. These complex patterns and reflectance zones are present at multiple new impact craters, including the 3/17/2013 impact crater [2].

Secondary Surface Changes: In addition to capturing new impact craters, NAC temporal pairs have also uncovered over 47,000 small reflectance changes, or “splotches”. These splotches do not exhibit visible crater rims, but only modify the observed surface reflectance (Fig. 2). While some of the splotches might be the result of small, primary impact craters (< 3 pixels), most splotches are the result of secondary surface disturbances associated with larger, nearby impact events. Robinson et al. [2] identified 248 splotches around the 3/17/2013 impact site. While splotches are generally circular, Robinson et al. [2] noted that some splotches were wedge shaped and pointed back to the primary impact crater indicating a likely emplacement direction. Our analysis of temporal pairs has also identified clusters of splotches around other new impact craters supporting the idea that many splotches are secondary features.

Summary: LROC NAC temporal imaging enables the detection and measurement of new impact and secondary surface changes. These observations provide a new view on the cratering process itself. Continued observations through the LRO mission will enable us to refine the contemporary impact rate and quantify the rate of regolith gardening caused by secondary surface changes.

REVIEW OF GEOCHEMICAL CONSTRAINTS ON THE FORMATION AND COMPOSITION OF THE LUNAR CORE. E. S. Steenstra¹ and W. van Westrenen². ¹Faculty of Earth and Life Sciences, VU University Amsterdam, The Netherlands (e.s.steenstra@vu.nl).

Introduction: The pressure (P) – (temperature) T conditions during lunar core formation and core composition provide constraints on key processes during the initial interior thermal and chemical evolution of the Moon. For example, PT conditions of core formation yield estimates for the depth of the lunar magma ocean. The chemical composition of the lunar core controls its physical properties (e.g., density, liquidus), crystallization path, and therefore affects the onset and duration of a lunar core dynamo [1-3]. It will also affect the metal-silicate partitioning of heat producing elements between the mantle and core [4]. Since the publication of New Views of the Moon 1, siderophile element depletions in the lunar mantle have proven to be an important tool to investigate the P-T conditions during lunar core formation [5,6] and provide independent constraints on the composition of the lunar core [5,7]. Here, we provide a brief summary of recent work that studied the P-T conditions that prevailed during core formation in the Moon, as well as constraints on lunar core composition.

Lunar mantle siderophile element depletions: The stepwise depletion pattern of siderophile elements in the lunar mantle, relative to its building blocks, strongly suggests full equilibration between metal and silicate (Fig. 1). As the metal-silicate partitioning of siderophile elements is dependent on P, T, oxygen fugacity (fO₂) and composition, the extent of their depletions in the lunar mantle reflect the conditions that prevailed during lunar core formation.

Core formation in the Moon: Siderophile elements depletions in the lunar mantle, in conjunction with models based on experimental data that predict their metal-silicate behavior as a function of P-T-X-fO₂, have been used to argue for a deep lunar magma ocean implying the Moon was fully molten after it formed [5-7]. Rai and van Westrenen [5] showed that for temperatures between the solidus and the liquidus, all 7 considered siderophile element depletions can only be reconciled with segregation of a 2.1±0.4 mass% lunar core, that contains at least 6 wt% sulfur (S). Steenstra et al. [6] showed that the depletions of 15 refractory and (highly) volatile siderophile elements (VSE) can be matched with formation of a pure Fe 2.4±0.1 mass% core, at superliquidus conditions in a fully molten Moon. Therefore, the siderophile element depletions in the Moon do not require the formation of a S-rich lunar core. This study also showed that the Moon experienced only minor loss of some VSE, because their depletions do not require additional devolatilization.

Composition of the lunar core: The existence of one or more light elements in the lunar core is inferred from lunar seismograms [2] and the existence of a lunar core dynamo [3]. S seems unlikely given its low abundance in the lunar mantle and moderately siderophile behavior at the P-T-X conditions relevant for lunar core formation. Instead, geochemical evidence point to carbon (C), which also agrees with current geophysical constraints (Fig. 2).

Outlook: Future work should test if the lunar mantle depletions of other volatile siderophile elements can be reconciled by core formation only, and if they can be explained by formation of a C-rich lunar core.

Introduction: The Miniature Radio Frequency (Mini-RF) instrument flown on NASA’s Lunar Reconnaissance Orbiter (LRO) is a Synthetic Aperture Radar (SAR) with a hybrid dual-polarimetric architecture. I.e., the instrument transmits a circularly polarized signal and receives orthogonal horizontal and vertical linear polarizations (and their relative phase) [1]. The information returned by the radar can be represented using the classical Stokes parameters \([S_1, S_2, S_3, S_4]\) [2], which can also be used to derive a variety of other products that are useful for characterizing radar scattering properties of the lunar surface.

To investigate the scattering properties of lunar crater ejecta blankets, we use two products derived from the Stokes parameters: the circular polarization ratio (CPR) and the \(m\)-\(\eta\) decomposition of \(S_1\). Radar returns from the young craters provide insight into the scattering properties of ejecta blankets, differentiation between ejecta properties in different lunar terrains, and possible identification of styles of ejecta deposition and mixing. Examining these properties for young craters across the surface of the Moon, in both mare and highlands terrain, provides a new perspective on the ejecta emplacement process and surface evolution due to impacts. Further, comparing Mini-RF returns with other data sets (e.g., optical, FUV, VNIR) allows deeper insights into the surface (and near subsurface) evolution of the Moon, and improve our understanding of the primary weathering process on the moon and how ejecta emplacement processes modify the surface.

Observations of Scattering Properties: Average profiles of the Stokes parameters (e.g., \(S_1\) and \(S_4\), CPR, and the \(m\)-\(\eta\) decomposition of \(S_1\)) were calculated as a function of radius for each crater. Though some commonalities in the scattering profiles are seen for all observed craters, differences are noted with crater diameter and between craters in different terrains. CPR signatures differ between mare and highlands regions, and have (with few exceptions) logical progressions with crater size. For example, larger craters tend to have higher CPR near the crater rim than smaller craters within similar terrains. For the majority of highlands craters (and for select mare craters), the CPR profile is characterized by a “bench” of high CPR before evolving to lunar background values, likely representing areas of ejecta mixing with lunar regolith. Though seen around mare craters, this same profile shape is not seen universally for craters in the mare.

The \(m\)-\(\eta\) story is less straightforward. Craters in both major terrain types, and across diameter ranges, fall into each of three categories [3]. Possible variables that could affect the scattering characteristics include: crater age, degradation state, terrain type, local variations within terrains (e.g., layering), or crater diameter.

New views of subsurface layering: New observations suggest that measures of lunar crater ejecta CPR can isolate the surface expression of discrete subsurface layering within mare terrain [4]. Average CPR profiles outward from the crater rim were analyzed for twenty-two young mare craters and observations across a range of crater sizes and relative ages exhibit significant diversity within mare regions. Comparing these CPR profiles with LROC imagery shows that the magnitude of the CPR may be an indicator of crater degradation state, which may manifest differently at radar compared to optical wavelengths. Comparisons of radar and optical data also suggest relationships between subsurface stratigraphy and structure in the mare and the amount of blocky material found within the ejecta blanket [4]. Initial examination of NAC images for all craters with a “shelf” in the CPR profile showed outcrops of distinct layers in the crater walls. When the CPR plateaus at the crater rim and extends outward a short distance layers were noted at the top of the crater rim in a capping layer. These high CPR plateaus may be due to the capping layer fragmenting differently than material beneath it, or to the presence of impact melt at the crater rim [e.g., 5]. If, instead, the shelf was farther away from the rim in the CPR profile, these layered outcrops were documented farther down the crater walls. If no shelf is seen in the CPR no layering is visible in the crater walls. These observations suggest that surface CPR measurements may be used to identify near-surface layering, providing a new way to examine the near subsurface of the mare.

Conclusions: Radar observations provide a powerful way to examine crater ejecta processes across the lunar surface. These observations become increasingly powerful when paired with other data sets, providing a new perspective on surface evolution processes (e.g., ejecta emplacement and degradation).

D-POOR HYDROGEN IN LUNAR MARE BASALTS ASSIMILATED FROM LUNAR REGOLITH. A.H. Treiman1, J.W. Boyce2,3, J.P. Greenwood4, J.M. Eiler1, J. Gross5, Y. Guan2, C. Ma2, E.M. Stolper2. 1Lunar & Planetary Institute, 3600 Bay Area Boulevard, Houston, TX 77058 USA (treiman@lpi.usra.edu), 2Division of Geological & Planetary Sciences, Caltech. 3 Dept. Earth, Planetary, and Space Sciences, UCLA. 4Dept. Earth & Environmental Sciences, Wesleyan University, Middletown, CT 06459. 5Dept. Earth and Planetary Sciences, Rutgers University, 610 Taylor Rd., Piscataway NJ 08854.

Introduction: Apatite grains in lunar mare basalts contain hydrogen that ranges in D/H ratio by more than a factor of two [1-4]. This range has been interpreted to represent: multiple indigenous components including mantle and KREEP [5], degassing during emplacement [2,4], cometary infall [1], meteoritic infall [2,5,6], and/or solar wind from the regolith [7,8].

Samples & Methods. Six thin sections of five mare basalt samples were analyzed by ion microprobe for this study: two high-Ti basalts (10044,12, and .644; 75055,55); and three low-Ti basalts (12039,42; 12040,211; MIL 05035,6). All contain small grains of apatite (>100 μm) in their mesostases, consistent with late crystallization of apatite from their magmas. We also analyzed the gabbro lithology of NWA773, and the KREEP-rich lithology in NWA 4472. Analyses for H, D/H, and Cl and 37Cl/35Cl in their apatites were obtained at the Caltech Center for Microanalysis using a Cameca 7f-GEO SIMS with standard protocols [10,11].

Results: For most of these basalts, the D/H ratios in their apatite grains decrease with a measure of the basalts’ time spent at elevated temperature. We use the Fe-Mg homogenization of their pyroxenes (Fig. 1) as a proxy for integrated thermal history, and use the spread of Mg# (molar Mg/(Mg+Fe)) in their pyroxenes from literature data (Fig. 1). Most basalts with homogeneous pyroxenes (i.e., low Mg#max/Mg#min) have apatite grains with low D/H (δD ≈ -100‰); most basalts with heterogeneous pyroxenes (i.e., varying or zoned Fe/Mg; high Mg#max/Mg#min) have apatite with high D/H (δD up to ~+1100‰). This relationship suggests that low D/H values were acquired during thermal processing, i.e. during Fe-Mg chemical equilibration, during or after emplacement. Chemical exchange or metamatism like this has been documented in other lunar samples [9,13].

This light hydrogen is likely derived from solar wind implanted into the lunar regolith (with δD from -125‰ to -800‰), and could enter basalts either by assimilation of regolith or by vapor transport from regolith heated by the flow [14]. If a basalt could not interact with regolith rich in solar wind (e.g., it was emplaced onto other fresh basalts), its apatite could retain a magmatic D/H signature, which could explain the data for 12018 [12]. The high D/H component (in the apatites of unequilibrated basalts) is most reasonably that indigenous magmatic hydrogen, i.e. representing hydrogen in the basalt’s source mantles, or magmatic hydrogen that was residual after partial degassing of H2.

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Introduction: The NWA 773 clan is a group of 11 named meteorites, with a total mass of 2.6 kg (Fig. 1). The NWA 773 clan meteorites comprise 6 lithologies, present in variable proportions in each meteorite that trace magmatic evolution from early, magnesian lithologies, to late-stage, ferroan lithologies. This group of meteorites is unique in that it comprises a collection of petrogenetically related lithologies that represents an intrusive and extrusive magmatic system on the Moon. A similar lithologic assemblage is not represented in the Apollo or Luna sample collections. Given their chemical and petrographical similarities, these meteorites are thought to be launch paired, despite where they were found on Earth, where reported find locations are too far apart to represent a strew field.

Lithologies: The 6 lithologies present in the NWA 773 clan range from magnesian to ferroan lithologies, tracing magmatic evolution. Four of these lithologies are intrusive gabbros. The olivine gabbro (OG) is the most magnesian lithology. The olivine bearing gabbro (OBG) and anorthositic gabbros (AG) are intermediate lithologies. The ferroan gabbro (FG) is an iron-rich, late-stage, lithology. One extrusive lithology, the olivine phric basalt (OPB), also occurs. A fragmental or regolith breccia matrix occurs in most of the NWA 773 clan meteorites. Most of the breccia is composed of fragments of the other lithologies.

Ages: A variety of methods have been used to obtain age-dates on lithologies in the NWA 773 clan. Pb-Pb Ages obtained through in situ analysis of zircon and baddeleyite grains in the OG, FG, and breccia are ~3.1 Ga [5, 9, 10].

Relationships and Formation: On the basis of mineral compositions, modal mineralogy, and trace element characteristics, Jolliff et al. (2003) suggested that some of the lithologies in the NWA 773 clan were related via a common liquid line of descent, possibly a similar source region to that of Apollo 14 green glass b1 [3]. The relationship among lithologies in the NWA 773 clan is supported by overlapping pyroxene major- and minor-element compositions among the lithologies [10]. Pyroxene compositions become progressively ferroan from OG → OBG → AG → FG. Textural evidence also supports a relationship between the AG and FG. Some regions of the two lithologies are nearly identical in texture and modal mineralogy, suggesting that the FG may have formed as small pockets of residual melt in the FG.

The chemical similarities among the lithologies suggest that the NWA 773 clan lithologies could represent a magmatic system on the Moon. We suggest a model where the intrusive lithologies crystallized along a common liquid line of descent in a shallow magma chamber from OG → OBG → AG → FG, where the FG crystallized from residual melt pockets within the AG. In our model, the basalt component (OPB) that erupted to the surface sometime after the formation of the OG.

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FACTORS AFFECTING CRATER SIZE-FREQUENCY DISTRIBUTION MEASUREMENTS: INSIGHTS SUPPORTED BY THE LRO MISSION. C. H. van der Bogert1, H. Hiesinger1, M. Zanetti2, J. B. Plescia3, L. R. Ostrach4, P. Mahanti2, H. M. Meyer2, A. S. McEwen4, J. H. Pasckert1, G. Michael2, T. Kneissl1, and M. S. Robinson4, 1Institut für Planetologie, Westfälische Wilhelms-Universität, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany (vanderbogert@uni-muenster.de); 2Western University, London, ON, Canada; 3Applied Physics Laboratory, Johns Hopkins University, Laurel, MD; 4NASA Goddard Space Flight Center, Greenbelt, MD; 5Arizona State University, Tempe, AZ; 6University of Arizona, Tucson, AZ; 7Freie Universität, Berlin, Germany.

Introduction: LRO observations [1,2] provide the means to investigate smaller (<100 m) lunar features, and to count smaller diameter craters on many different terrains with the objective of defining their relative and absolute ages. Indeed, the LRO mission has helped revitalize lunar science, allowing current studies to revisit and reinterpret work done during the Apollo era, in addition to pursuing new studies. In particular, a renewed effort is being made to understand the caveats and limitations of the determination of relative and absolute model ages via crater size-frequency distribution (CSFD) measurements. Here, we summarize several factors that affect CSFD measurements: illumination angle, count area size and slope, secondary cratering, and target property effects, including strength vs. gravity scaling and differential degradation effects. Updated and improved tools for measuring and fitting CSFDs [3-5], as well as for assessing crater randomness and clustering [6], have aided in the investigation of these factors.

Illumination angle: Earlier work [e.g., 7-9] showed that fewer craters are visible at smaller incidence angles, where noon=0°. Using LROC data, [10] determined that 60°-80° incidence is ideal for consistent crater identification and measurement, and advised that similar incidence angles be used for consistent age determinations.

Count area size: Efforts to examine smaller features using NAC imagery has driven assessment of the smallest counting area necessary for meaningful results. Ages for small, young features have good accuracy (e.g., 10% for a 1 km² area on a 100 Ma old surface). However, old surfaces require larger minimum count area sizes, because the minimum crater diameter that can be fit with a model age increases with increasing surface age due to the increasing equilibrium diameter. Larger count areas are then required to account for the sparseness of larger craters [11].

Count area slope: Craters degrade faster on slopes, leading to a decrease in crater density with increasing slope for craters less than ~1-2 km [12]. Using LROC WAC images, [13] showed this trend holds at a slower rate for craters >1-2 km. Because the degradation of the larger craters is dominated by gravity, rather than material properties, these craters can be used to quantify and correct the slope effect.

Secondary cratering: The contamination of CSFDs with both field and self- secondaries is a major concern. Not all field secondary craters (formed by subsequent primary impacts) have obvious secondary crater morphologies and their CSFDs can have similar slopes as the production function [14]. Estimates of the level of field secondary contamination range from 50-25% (D<200m) [15] to negligible [16]. There is also debate regarding the magnitude of self-secondary cratering (SSC) [17] of impact deposits formed in one primary event. SSCs could explain an excess of craters on the impact ejecta versus melt deposits, resulting in an older apparent age of the ejecta, as well as cause over-estimates of the recent impact rate [e.g., 18-20].

Target properties: The discrepancy between ejecta and melt ages may also be explained by differences in their target properties [21]. Craters <1 km form in the strength-scaling regime, which can result in significant final diameter differences for contrasting target types [e.g., 21,22]. This effect appears to be size-dependent for craters <1 km diameter [27]. Thus, care must be taken to identify the equilibrium diameter separately for each CSFD measurement.

Implications: The factors discussed complicate the determination of both relative and absolute model ages. All of developments reported here, using LRO images, are also relevant to CSFD measurements and relative/absolute dating of other planetary bodies.

THE BULK COMPOSITION OF THE MOON: MERELY EARTH-LIKE, OR EARTH-LITE?

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The Moon’s bulk composition is important as a constraint on lunar origin, and as the starting point for models of lunar geochemical evolution. Dating from before the Apollo era it was obvious that in comparison to Earth, the Moon’s moderate density (3344 kg m\(^{-3}\)) implies major depletion in Fe-metal (core). However, it has always been appreciated that the relative proportions of oxidized iron might be an entirely different story. In fact, recent years have seen an accumulation of evidence pointing toward a high degree of Moon-Earth noncore compositional similarity.

Apart from the undoubted Fe-metal disparity, basically three aspects of putative lunar bulk-compositional peculiarity were once popular [e.g., 1], and to varying extents remain semi-plausible. (1) In terms of major elements, relative to bulk silicate Earth (BSE) the bulk silicate Moon (BSM) was inferred by some to feature roughly 1.5× enrichments in Al\(_2\)O\(_3\), CaO, along with some 26 other refractory lithophile elements, most notably the heat-producers Th and U (the one other heater-element, K, albeit not refractory conveniently correlates with Th and U among lunar materials). (2) FeO was inferred to be enriched by a similar (albeit basically unrelated) factor in the BSM relative to the BSE. (3) The Moon was for several decades “known” to be depleted by immeasurable orders of magnitude in water (OH), along with less drastic but still large depletions in all other volatiles, relative to the Earth. The demise of model/prejudice (3) was rather sudden and dramatic, starting with [2]; such that today debate centers more on the 180° opposite hypothesis that the Moon and the Earth may contain nearly equal proportions of water [e.g., 3, 4]. Still, and despite their importance for understanding lunar origin and evolution, the water, refractory-lithophile and FeO issues remain in need of clarification.

Isotopic composition is a significant, genetically diagnostic aspect of bulk composition. As advances in technique have furnished more and more precise constraints, the stable isotopes have tended to reveal a remarkable degree of Earth-Moon similarity. Oxygen isotopes [5] are the most precisely constrained, but the Earth-Moon similarity is most impressive because other stable isotopes that manifest great diversity among planetary materials, such as those of Cr and Ti (which are not in any simple way overall-correlated with O isotopes), also show indistinguishable Earth and Moon compositions [6, 7]. A match in any one of these isotopic systems, even a very close match, is conceivably a statistical fluke. Consistent match-up among several different systems greatly compounds the improbability of some such fluke. The isotopic evidence implies that Earth and its Moon came preponderantly from a single distinctive reservoir of solar system material.

Heat flow (HF) is an excellent means of constraining bulk-Moon Th and U (and probably with them, Al\(_2\)O\(_3\), CaO, etc.). Yet until this year [8], HF had only been measured at two central nearside sites. The new measurement is only an upper limit, but it greatly clarifies the Moon’s global HF. Assuming that most of the Moon’s Th and U are in its crust [9], the new result [8] is difficult to reconcile with BSM Th any higher than 90 ng/g; which leaves only modest potential for disparity vs. the BSE (~75 ng/g). GRAIL’s finding of a lower crustal mass [10] has also annihilated the old mass-balance incentive for high BSM Al\(_2\)O\(_3\) and CaO.

The traditional way of constraining both FeO and water is by analogy between mare basalts and terrestrial basalts such as MORB. However, the mare source was not a tectonically stirred near-uniform reservoir but a grossly heterogeneous magma-ocean cumulate pile. It may be wishful thinking to assume that melting is as composition-independent (especially for a melting-fluxer like water) in the latter case as in the former. A simple density modeling approach [7] enabled by the GRAIL data-bonanza suggests that FeO is mildly enriched in the BSM. As evidence accumulates for Earth-Moon similarity in water content, it should be borne in mind that plenty of evidence shows the Moon is at least mildly depleted in most volatile elements. The lunar K/U ratio is tightly constrained to be about 1/4 that of the BSE. The major element sodium is clearly depleted by a similar factor. Mare and KREEP basalts consistently show F/Nd depleted by about an order of magnitude, and Cl/Nb depleted by nearly two orders of magnitude, versus MORB [11].

MASS WASTING ON THE MOON: IMPLICATIONS FOR SEISMICITY. R. C. Weber,1 A. L. Nahm2–3, B. Yanites2, and N. Schmerr1, 1NASA Marshall Space Flight Center (renee.c.weber@nasa.gov), 2DLR Institute for Planetary Research, 3University of Idaho, 4University of Maryland.

**Introduction:** Seismicity estimates play an important role in creating regional geological characterizations, which are useful for understanding a planet’s formation and evolution, and are of key importance to site selection for landed missions. Here we investigate the regional effects of lunar seismicity with the goal of determining whether surface features such as landslides and boulder trails on the Moon are triggered by fault motion (Fig. 1).

**Lobate scarps:** Lobate scarps, the typical surface expressions of thrust faults resulting from tectonic compression, are widely observed on the Moon [1]. Compared to other types of tectonic faults, surface-cutting thrust faults require the largest amount of stress to form and/or slip, and thus are expected to result in large quakes. While normal faults, graben, and wrinkle ridges are also abundant on the Moon, these structures would generate smaller theoretical maximum quakes than lobate scarps thrust faults. Thus, we optimize our chances of finding mass wasting associated with faults by studying lobate scarps.

**Methodology:** We first calculate the theoretical maximum quake that could occur as a result of slip on a fault and then determine the effects on the surrounding surface morphology. The expected damage area indicated by seismic wavefield modeling is compared to mapped imagery to determine the likelihood of a quake having triggered mass wasting.

**Theoretical maximum quake.** Following the method outlined in [2], the theoretical maximum quake magnitude is derived from basic fault properties. These are either estimated from imagery or derived from laboratory rock experiments or elastic dislocation models, and include the fault length, width, dip angle, and depth of faulting. Fault displacement is calculated using displacement-length scaling such that $D = \gamma L$, where $\gamma$ is determined by rock type and tectonic setting [3].

The best measure of the size of a quake is the seismic moment, which is calculated by multiplying the shear modulus of the ruptured rock by the area of the ruptured portion of the fault and the average displacement produced during the quake [2]. The seismic moment represents the total energy consumed in producing displacement on a fault, regardless of the local strain rate or fault formation mechanism.

**Seismic wavefield modeling.** In order to determine the dimensions of an area affected by seismic shaking, we model the ground motion resulting from the theoretical maximum quake along a given fault. We use the Serpentine Wave Propagation Program (WPP), a numerical code for simulating seismic wave propagation in 3D [4, 5]. The initial model of a given fault includes regional topography derived from digital elevation models, and the Moon’s background 1D velocity.

**Geomorphological analysis:** Peak vertical ground motion occurs within a few kilometers of the main shock and drops off rapidly away from the source. Thus we should expect most of the mass wasting phenomena to occur in the immediate vicinity of the fault. However, this result may depend on regional effects such as surface slope and megaregolith thickness; a thicker megaregolith (as might be expected in the vicinity of large craters) would tend to focus shaking in some of the crater basins.

We will compare the observed extent of mass wasting in the vicinity of a fault to the modeled event magnitude and peak ground motion in order to establish a method to translate quake parameters into mass wasting estimates. This has been performed for terrestrial examples focused on determining landslide area and density over time in seismically active regions [6]. We expect to find systematic variations in fit parameter estimates for each body, reflecting different gravitational strengths, regolith cohesion properties, and other geomorphic settings local to each study region.

**Introduction:** The Diviner Lunar Radiometer Experiment onboard LRO has been acquiring solar reflectance and infrared radiance measurements nearly continuously since July of 2009 [1]. Diviner is providing the most comprehensive view of how regoliths on airless bodies store and exchange thermal energy with the space environment. Approximately a quarter trillion calibrated radiance measurements of the Moon, acquired over 5.5 years by Diviner, have been compiled into a 0.5° resolution global dataset with a 0.25 hour local time resolution. Maps generated with this dataset provide a global perspective of the surface energy balance of the Moon and reveal the complex and extreme nature of the lunar surface thermal environment [2]. Impact craters from meter-scale to basin-scale are found to modify the thermophysical and radiative properties of the regolith over large distances as seen in reflectance and infrared observations demonstrating the dominating effect impacts, as a geologic process, have had on the global physical properties of the lunar surface.

**Results:** The hottest nighttime temperature anomalies are associated with young rayed Copernican-age craters. The thermal signature of Tycho is asymmetric, consistent with an oblique impact coming from the west and rays require material with a higher thermal inertial than nominal regolith. Rays are observable as thermal anomalies in nighttime temperatures indicating a contrast in thermophysical properties in addition to having a higher reflectance, however nighttime brightness temperatures do not display anisothermality indicating the thermal contrast of the ray must largely result from objects smaller than ~0.5 m. The coldest nighttime surfaces are associated with lunar cold spots [3], highly insulating regions around very young craters extending ~10–100 crater radii. The three largest cold spots have surfaces that remain >5 K colder than mean zonal temperatures and maintain this temperature difference throughout the night. The modification of the regolith by the formation of the Orientale basin is observable over a substantial portion of the western hemisphere despite its age (~3.8 Ga), and may have contributed to mixing of highland and mare material on the margin of Oceanus Procellarum where the gradient in radiative properties at the mare-highland contact is broad (~200 km). A lobe of the Montes Rook Formation extends beyond the Cordillera scarp in the southwest corner. The thermal signature is consistent with impact melt. A thermally distinct annulus of material ~300 – 600 km wide extending outward from the Cordillera ring corresponds to a region of low radar return [4] implying the unit is related to the radar-dark halos observed around other sizeable craters.

GLOBAL DISTRIBUTIONS OF LARGE EXPOSED AREAS OF LUNAR MAJOR MINERALS AND ITS IMPLICATIONS. Satoru Yamamoto¹, Ryosuke Nakamura², Tsuneo Matsunaga¹, Yoshiaki Ishihara², Makiko Ohtake³, and Junich Haruyama⁴. ¹National Institute for Environmental Studies, Japan (yamachan@gfd-dennou.org), ²National Institute of Advanced Industrial Science and Technology, Japan, ³JAXA, Japan.

Introduction: Recent hyperspectral remote sensing observations of the Moon have revealed the existence of large exposed areas (LEAs) of end-members of various lunar minerals [e.g.,1,2]. The identifications of the LEAs are based on diagnostic absorption bands at 1 μm and 2 μm in continuous reflectance data (hyperspectral data) obtained by remote sensing observations. The material at each LEA is dominated by a pure lunar mineral, and its exposure areas span several km wide sites.

In the last six years, survey studies to reveal the global distributions of LEAs for various lunar minerals have been conducted using all the data measured by Spectral Profiler (SP) onboard SELENE/Kaguya, which has obtained hyperspectral data for about 70 million points on the Moon [2]. These survey studies use a data mining approach, in which the survey program picks up spectra that exhibit diagnostic absorption bands of target minerals among all the SP data. Here, we review the global distributions of the various lunar major minerals revealed by the SP global surveys, and their implications.

Global Distributions: Fig. 1 shows the global distributions of the LEAs for olivine-rich sites [3], purest anorthosite (PAN) sites [1,4,5], low-Ca pyroxene-rich (LCP) sites [6,7], high-Ca pyroxene-rich (HCP) sites [8], spinel-rich sites [9], and glass-rich sites [10]. These distributions have been revealed by the SP global surveys, but they include most of the LEAs found by other studies based on spectral data by the Moon Mineralogy Mapper (M³) and Multiband Imager [e.g., 1].

The olivine-rich sites are distributed around the impact basins located in thinner crust regions, especially on the nearside of the Moon. On the other hand, PAN sites are widely distributed over the Moon, and many PAN sites are found in thicker crustal regions. Based on the relation between the olivine-rich and PAN sites, it has been proposed that there is a massive PAN layer below the uppermost mixing layer in the Feldspathic Highland Terrane (FHT) [4].

The LCP-rich sites are distributed around the South Pole-Aitken (SPA), Imbrium, and Procellarum basins, while there is no LCP-rich site in the FHT, which is covered by the mixing layer including LCP. One of the most intriguing is that the smaller impact basins do not possess LCP-rich sites. For example, the Moscovien and Crisium basins, which have the thinnest crust on the Moon, possess the olivine-rich sites, but not LCP-rich sites. This may require the existence of the olivine-rich layer below the PAN crust. Only the huge impact events such as SPA basin could excavate the deep mantle region to expose the LCP-rich materials on the lunar surface [6,7].

The HCP-rich sites in the highlands are found at fresh, small craters, but not huge impact basin in the FHT. In each crater, the HCP-rich sites are distributed at ejecta, rim and floor, while the central peaks are dominated by PAN [8]. This indicates that a HCP-rich zone overlying the PAN layer, which may be a residue of mafic-rich melt during the flotation of plagioclase, exists below the mixing layer in the FHT [8].

Contrary to the above minerals, most of the LEAs for the spinel [9] and glass-rich sites [10] are found at the lunar pyroclastic deposits (LPD). However, they are found at limited LPDs, and most of the other LPDs do not possess the spinel and glass-rich sites. This suggests that there is a variation in the composition and volatile contents of source magmas from the deep lunar interior.

A comprehensive model that treats all the data sets of the global distributions of the LEAs is highly needed. This would provide new insight into the structures and evolution of the lunar crust and mantle.

Fig.1: Global distributions of the LEAs of various lunar minerals and glasses revealed by SP for (left) the nearside and (right) farside of the Moon. The background map is the total crustal thickness map by SELENE.

THE USE OF FIELD PORTABLE INSTRUMENTATION IN PREPARING FOR THE NEXT GENERATION OF LUNAR SURFACE EXPLORATION. K. E. Young, J. E. Bleacher, A. D. Rogers, C. A. Evans, A. McAdam, W. B. Garry, L. Carter, T. Graff, S. Scheidt, T. D. Glotch, R. Zeigler, P. Niles, and P. Abell; ¹CREST/University of Maryland, College Park, College Park, MD, 20742; ²NASA Goddard Space Flight Center, Greenbelt, MD, 20771; ³Stony Brook University, Stony Brook, NY, 11974-2100; ⁴NASA Johnson Space Center, Houston, TX, 77058; ⁵Jacobs, NASA JSC, Houston, TX, 77058; ⁶University of Arizona, Tucson, AZ, 85721; corresponding author email: Kelsey.E.Young@nasa.gov

Introduction: The six Apollo lunar surface missions represent the only opportunity that the lunar community has had to explore the surface of the Moon in situ with humans and bring back sample volumes appropriate for conducting detailed follow-up laboratory analyses. The samples returned to Earth by the Apollo astronauts have been a priceless resource in furthering our understanding of lunar geology. Further in situ surface exploration is needed, however, to have a complete understanding of the lunar geologic history. The Lunar Exploration Roadmap and the NRC (National Research Council) Scientific Context for the Exploration of the Moon documents [1,2] lay out the priorities for future lunar exploration. Many of the highly prioritized objectives described in [1,2] are directly related to lunar surface activities, and include scientific objectives that require detailed sampling.

Specifically, Objective Sci-A-2 in [1] addresses the “development and implementation of sample return technologies and protocols”, specifically highlighting “Developing a sampling strategy for the Moon”, “Understanding the scientific requirements for sample curation, packaging, and transport to Earth”, and “Understanding what analyses (field and laboratory) need to be done on the Moon to aid field studies and optimize the value of samples returned to Earth” as high priority objectives for future lunar surface exploration.

Apollo Era Field Geology: While the Apollo program was very successful at sample collection and storage for return to Earth, the tools with which the astronauts were able to collect rock and soil samples consisted solely of tools for breaking rocks off outcrops or scooping samples up off the ground for return to Earth. However, technology has advanced substantially in the decades since Apollo 17.

The lunar community must continue to develop and test new and emerging technologies for use in the next generation of lunar surface exploration to best address the high priority science objectives described in [1,2].

The Next Generation of Planetary Field Geology: Future lunar surface exploration should build off of the legacy of the Apollo program but also capitalize on the substantial advancements being made in instrumentation for terrestrial analysis. Specifically, development is ongoing to develop and field test a suite of high-resolution field portable technologies designed to give the user in situ analytical data in real-time that will inform both traverse completion and sample collection and curation for return to Earth. Understanding how an astronaut will work with and interpret these data to inform traverse and sample high-grading activities in real-time is crucial to the integration of this high-resolution technology into crewed planetary surface exploration.

Instruments in Development: Numerous field portable technologies are currently being tested to determine their utility for lunar surface exploration. To do this, we visit lunar analog sites [3] and deploy suites of instrumentation designed to interrogate each site’s geologic history as well as collect and high-grade samples for return for laboratory analyses (in an architecture similar to crewed lunar exploration). Field instruments considered in this study include X-Ray Diffraction, X-Ray Fluorescence, multispectral imagers, Light Detection and Ranging, airborne imagers, and Ground Penetrating Radar.

Although these are clearly not the only instruments being considered for future lunar exploration, they represent a crucial first step in understanding how acquiring multiple datasets in real-time during geologic exploration can impact the ability of crewmembers to answer valuable science questions in situ and collect as diverse a sample suite as possible.

Study Objectives: This submission to the New Views of the Moon 2 volume will detail ongoing efforts to test existing off-the-shelf instrument capabilities for field science, as well as document continued efforts to develop new instruments for lunar surface exploration. We will also place the usefulness of these techniques in the larger context of the geologic training of future astronaut classes [4]. It is critical that these technologies are developed in concert with the lunar community if we hope to successfully accomplish the scientific objectives detailed in [1,2].

Self-Secondary Crater Populations on Copernican Continuous Ejecta Blankets. M. Zanetti¹, B. Jolliff², C. H. van der Bogert³, H. Hiesinger⁴, J. Plescia⁵, N. Artemieva⁶. ¹Western University, London, ON Canada (Michael.Zanetti@uwo.ca). ²Washington University in St Louis, MO; ³Westfälische Wilhelms-Universität Münster, Germany; ⁴Johns Hopkins University / Applied Physics Laboratory, MD; ⁵Planetary Science Institute, Tuscon, AZ.

Introduction: Continuous ejecta blankets were thought to completely resurface the area surrounding the parent crater (~1 crater radius from the rim) through ballistic sedimentation and the deposition of thick ejecta deposits [1]. The ejecta blanket should therefore be devoid of craters immediately following its emplacement, and the melt deposits and ejecta units should both accumulate subsequent craters at the production rate. However, recent measurements of small craters (<1 km diameter) have shown a discrepancy in cumulative crater size-frequency distributions (CSFDs) and corresponding absolute model ages (AMAs) between the melt and continuous ejecta blankets at Copernican aged craters [2 –5], stirring debate between primary competing hypotheses of target material properties affecting measured crater diameters [e.g. 2, 6-9] or self-secondary cratering contamination [5, 10, 11].

Hypotheses for CSFD Discrepancy: Experiments and modeling show that crater diameter is dependent on the material properties of the target (e.g. competent impact melts produce smaller diameter craters compared with less competent ejecta units, and in turn have CSFDs and AMAs correspondingly lower than the ejecta) [6-9]. Target properties are suggested to account for up to 20% differences in crater diameter between melt and ejecta, and a crater diameter correction factor for target properties has shown promise to account for discrepancies [6-9]. However, target properties cannot easily explain all of the crater population differences and morphologic observations described below. Self-secondary craters (SSCs), a population of craters formed on the continuous blanket by late-arriving ejecta fragments from the parent crater [10], are an alternative possibility that can account for the melt/ejecta discrepancy.

Evidence for Self-Secondary Cratering at Tycho and Aristarchus: Crater density maps and CSFDs of large area counts of all craters >50 m diameter on the continuous ejecta at Aristarchus and Tycho (and elsewhere) crater show that the ejecta blankets accumulated more craters than impact melt deposits, irrespective of crater diameter. This deficiency of craters on ejecta persists even at LRO-NAC scale (>3m craters resolved). Large area counts also show an increasing crater density with distance from the parent crater rim and strong correlation of melt ponds and melt veneer with low crater density regions [5]. Morphological observations of putative ghost craters in impact melt ponds at Tycho crater, and craters infilled by flowing melt seen at Aristarchus, Tycho, Necho, and Giordano Bruno [5, 12-14] suggest craters formed on the continuous blanket in the short time between ejecta emplacement and melt solidification. With respect to a formation mechanism for SSCs, preliminary hydrocode modeling results of ejecta spallation and excavation suggest that high-angle ejecta (>80° launch angle with velocities of 0.8-1.2 km/s) capable of producing SSC impactors is possible for moderately oblique parent impacts [14]. The travel time of fragments can be >20 mins, allowing for the emplacement of the ejecta curtain and ballistic sedimentation to occur before impact into the newly formed continuous ejecta blanket.

Discussion and Implications: Self-secondary cratering provides a plausible explanation for the observed population differences between melt and ejecta, increasing crater density with distance from the parent crater rim, as well as morphological observations of melt-filled-craters and ghost-craters. Although target material properties are an important parameter in determining the final crater diameter, they do not account for the population differences measured on the continuous ejecta or ghost-craters. Target properties no doubt play a role in the observed melt/ejecta age discrepancy, and self-secondary cratering cannot be invoked to explain other issues with CSFDs and AMAs addressed by material properties (e.g. mare/highlands differences, thick vs thin regolith cover). If a population of self-secondary craters is produced by a parent impact event, then the production functions derived from CSFDs of craters on the continuous ejecta blanket of Copernicus, Tycho, North Ray, and Cone craters may not reflect the true impact flux of small crater (<500 m) forming projectiles for the inner Solar System. CSFDs measured on impact melt ponds, despite suffering from target material property effects, are the most likely surfaces to record the true impactor flux, which may necessitate a re-formulation of the lunar cratering chronology over the last ~1Ga.

LUNAR IMPACT GLASSES AS CLUES TO THE MOON’S BOMBARDMENT HISTORY. N. E. B. Zellner1 and J. W. Delano2, 1Department of Physics, Albion College, 611 E. Porter St., Albion, MI 49224, nzellner@albion.edu, 2Department of Atmospheric and Environmental Sciences, University at Albany (SUNY), Albany, NY 12222 USA

Introduction: Lunar impact glasses provide important information not only about the Moon’s impact rate over the past ~4.5 billion years, but also about its composition. These glasses are small (~200 μm), numerous in the Apollo regolith samples, and homogeneous (e.g., xenocryst-free). Analyses of hundreds of impact glasses from the Apollo 14, 16, and 17 landing sites have allowed us new insights not only into when and how often the Moon has suffered impact events but also into which lunar glasses have compositions that should be suitable for obtaining reliable ages via 40Ar/39Ar dating.

Compositions: As described in [1], melt structure (i.e., fraction of non-bridging oxygen atom, X(NBO); [2,3]) of a lunar glass affects the diffusivity of radiogenic 40Ar. Additionally, this diffusivity depends on temperature variations resulting from diurnal heating of the lunar surface. Essentially, glasses with feldspathic highlands compositions are more likely to suffer diffusive loss of radiogenic 40Ar during extended residence in the shallow (<2-cm depth; [1]) regolith compared to glasses with more mafic compositions.

X(NBO) values were calculated for all lunar impact glasses with 40Ar/39Ar ages. As seen in Figure 1, glass shards are more likely to retain argon compared to (large or small) glass spherules and more likely to report old ages [4]. Impact glass spherules, on the other hand, are short-lived, perhaps because spherules are prone to shattering during impact gardening of the lunar regolith as a result of thermal stresses in those impact glasses acquired during quenching from hypervolcanicus temperatures [4,5].

Chronology: The lunar impact flux is uncertain [e.g., 6,7,8], but specific lunar impact glasses can elucidate some of the details of the Moon’s bombardment history. In particular, the results of this study show that shape, size, and composition of an impact glass matter for determining its formation age via 40Ar/39Ar dating. Figure 1 shows the distribution of currently available ages among lunar impact glasses of sufficient size to have retained at least 90% of their radiogenic 40Ar depending on X(NBO) value [4]. Many of the impact episodes have been documented elsewhere (e.g., ~500 Ma [e.g., 9]; ~800 Ma [e.g., 10]; ~3700 Ma [11]), and there are others that may be statistically significant. See Figure 8 in [4] for details.

Conclusions: As reported in [4] and as seen in Figure 1, several trends become apparent:

(1) Impact glass spherules are more likely to have young ages. Therefore, an increase in the recent impact flux may not be the correct interpretation.

(2) Impact glass shards are more likely to have old ages. Their large compositional ranges and multiple old ages (Figure 1) suggest that these glasses are products of multiple impact events into compositionally diverse terrains, including at least one that has not been documented elsewhere [ImHKFM; 11].

(3) The oldest impact glass shards could represent the last remnants of an initially large population of impact glasses generated during the tail end of the late heavy bombardment. Additionally, the absence of lunar impact glasses with 40Ar/39Ar ages >3900 Ma could reflect either an increased rate of shattering of glasses during intense gardening of the regolith and/or higher rates of diffusive Ar loss from impact glasses when the regolith had a steeper thermal gradient than the present one.


Figure 1. Lunar impact glass spherules (circles) and shards (squares) that would have likely retained at least 90% of their radiogenic 40Ar during 750 Ma of residence at a time-integrated temperature of ~290K. Uncertainties in age that are larger than the size of the symbols are shown. From [4].