Program
New Views of the Moon 2 — Asia

April 18–20, 2018 • Fukushima, Japan

Institutional Support

The University of Aizu
Lunar and Planetary Institute
Universities Space Research Association

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Abstracts for this workshop are available via the workshop website at https://www.hou.usra.edu/meetings/newviews2018/
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University of Aizu
Aizuwakamatsu City, Fukushima Prefecture, Japan

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Wednesday, April 18, 2018
LUNAR MISSIONS AND PLANS FOR EXPLORATION
9:00 a.m. University of Aizu Auditorium

Chair: Clive Neal

9:00 a.m. Sato N. S. *

*JAXA’s Space Exploration Scenario [#6031]*

Japan Aerospace Exploration Agency (JAXA) has been studying space exploration scenario, including human exploration for Japan since 2015, which encompasses goals, knowledge gap assessment, and architecture assessment, and technology roadmap.

9:15 a.m. Bussey D. B. J. *

*NASA’s Human Exploration and Operations Mission Directorate’s Lunar Activities [#6014]*

NASA’s Human Exploration and Operations Mission Directorate (HEOMD) has a number of ongoing lunar-related activities, relating to both robotic and human exploration.

9:30 a.m. Calzada-Diaz A. * Acierno K. Rasera J. N. Lamamy J.-A.

*ispace’s Polar Ice Explorer: Commerically Exploring the Poles of the Moon [#6010]*

This work provides the background, rationales, and scientific objectives for the ispace Polar Ice Explorer Project, an ISRU exploratory mission that aims to provide data about the lunar polar environment.

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

*Critical Robotic Lunar Missions [#6056]*

Perhaps the most critical missions to understanding lunar history are in situ dating and network missions. These would constrain the volcanic and thermal history and interior structure. These data would better constrain lunar evolution models.

10:00 a.m. Ohtake M. * Hoshino T. Karouji Y. Shiraishi H.

*Overview of a Japanese Lunar Polar Mission [#6018]*

In this presentation, we discuss an overview of the lunar polar mission studied in Japan.


*Development of the Lunar Polar Hydrogen Mapper Mission [#6024]*

The Lunar Polar Hydrogen Mapper is a 6U CubeSat mission launching on SLS EM-1. The spacecraft will orbit at a low altitude perluene over the lunar south pole and carries a miniature neutron spectrometer to map small scale hydrogen enrichments in PSRs.

10:30 a.m. BREAK

10:45 a.m. Karouji Y. * Abe M. Haruyama J. Ohtake M.

*HERACLES Mission Landing Site Candidates and Its Science with Possible Return Samples Discussed in Japanese Science Communities [#6053]*

HERACLES mission landing site candidates and its science with possible return samples is in discussion in Japanese science communities. We will present its status.
Hiesinger H. * Flahaut J. Ivanov M. Orgel C. Xiao L. Huang J. van der Bogert C. H. Head J. W.

*Characterization of Potential Landing Sites for Upcoming Lunar Missions [#6029]*

We report on our work related to the characterization of potential landing sites for the upcoming Chinese and Russian lunar missions.

11:15 a.m. DISCUSSION — Moderator: Neal C. R.
12:45 p.m. Nagaoka H. * Karouji Y. Hasebe N. Ohtake M.

Geochemical and Petrological Investigations of Lunar Meteorites Tell Us New Insights of Lunar Crust [#6028]

In this work, geochemical and petrological features of lunar crust are reported and discussed on the basis of recent geochemical and petrological studies of lunar meteorites and returned samples.

1:00 p.m. Naito M. * Hasebe N. Nagaoka H. Shibamura E. Ohtake M. Kim K. J. Wöhler C. Berezhnoy A. A.

Improved Lunar Iron Map Obtained by the Kaguya Gamma-Ray Spectrometer [#6051]

The lunar iron distribution is determined by the observation data of Kaguya Gamma-ray Spectrometer (KGRS). The excellent energy resolution of KGRS enables us to produce high quality FeO map with lower limit of about 3 wt%.

1:15 p.m. Crites S. T. * Lemelin M. Lucey P. G. Ohtake M.

The Mafic Component of the Lunar Highlands Crust: New Insights from Kaguya Multiband Imager and Rock Type Models [#6019]

Using Kaguya MI-based quantitative mineral maps, we model the contributions of three different endmembers to the highlands crust: magma ocean anorthosite, post-magma ocean igneous activity, and large basin ejecta incorporating mafic lower crust or mantle.

1:30 p.m. Sun L. * Taylor G. J. Martel L. M. V. Lucey P. G. Lemelin M.

A Comprehensive Study of Mineralogy at Apollo 17 Landing Site [#6045]

We combine quantitative XRD analysis of 43 Apollo-17 lunar soil samples from 19 stations and MI mineral maps to study the detailed mineralogy of this area.

1:45 p.m. Simon J. I. *

Age Paradox of Silicic Lithologies and Remotely Observed Surface Features on the Moon [#6021]

This abstract is on silicic magma generation and the potential age disparity between remotely observed lunar silicic volcanic centers and Apollo granitoid samples.

2:00 p.m. Klima R. L. * Bretzfelder J. M. Greenhagen B. T. Buczkowski D. L. Ernst C. M. Petro N. E.

Integrating Existing Data to Understand the Nature of the Lunar Mantle [#6046]

We examine the mafic massifs surrounding the Imbrium basin in Near and Mid-IR to search for potential mantle material. The southwestern rim may be most promising for excavation of ultramafic material.

2:15 p.m. DISCUSSION — Moderator: Ohtake M.

2:45 p.m. BREAK
Wednesday, April 18, 2018
LUNAR INTERIOR
3:00 p.m. University of Aizu Auditorium

Chair: Amanda Nahm

3:00 p.m. Kumamoto A. * Yamaguchi Y. Yamaji A. Oshigami S. Ishiyama K. Nakamura N. Haruyama J. Miyamoto H. Nishibori T. Tsuchiya F. Ohtake M.
Studies Based on Lunar Global Subsurface Radar Sounding Data Obtained by SELENE (Kaguya) [#6026]
Several studies based on lunar global subsurface radar sounding data obtained by SELENE/LRS will be reviewed. From the subsurface structures of the buried regolith layers, we can discuss the evolution of tectonic and volcanic processes in the maria.

3:15 p.m. Nahm A. L. * Johnson M. B. Hauber E. Watters T. R. Martin E. S.
Global Map and Classification of Large-Scale Extensional Structures on the Moon [#6001]
New view of the moon / From extensional structures / Global graben map.

3:30 p.m. Hanada H. * Ooe M. Gusev A. Petrova N.
Is It Possible to Observe Free Core Nutation of the Moon? [#6023]
We propose to observe variation of deformation and gravity on the lunar surface in order to detect the effect of resonance of Free Core Nutation.

3:45 p.m. Laneuville M. * Cebron D.
Core Supercooling and High Magnetic Field on the Early Moon [#6007]
Petrologic studies show that supercooling is required for nucleation. We investigate how this affects inner core growth and magnetic field generation on the Moon.

4:00 p.m. Ogawa M. O. *
The Initial Condition-Dependence of the History of the Lunar Magmatism Inferred from Numerical Models [#6004]
Numerical models of a coupled magmatism-mantle convection system have been developed to understand how the evolution of the mantle depends on its initial thermo-chemical state 4.5 Gyr ago.

4:15 p.m. DISCUSSION — Moderator: Ishihara Y.

4:45 p.m. BREAK
Sato H. Ishihara Y. Ohtake M. Otake H.
Polar Color Mosaic of the Moon from SELENE MI Observations [#6011]
We derived new polar color mosaics from SELENE Multi-band Imager observations using improved photometric normalization and mosaicking algorithm to explore the polar colors.

Kato T. Miura Y.
Main Difference with Formed Process of the Moon and Earth Minerals and Fluids [#6039]
Minerals show large and global distribution on Earth system, but small and local formation on the Moon. Fluid water is formed as same size and distribution on Earth and the Moon based on their body-systems.

Togashi S.
Magmas Evolved from a Crustal-Component-Enriched Bulk Silicate Moon Model Compared with Lunar Meteorites [#6008]
Magma (~1% melt) evolved from the cBSM (a crustal-component-enriched Bulk Silicate Moon model) would have sub-chondritic Ti/Ba, Ti/Th, Sm/Th, and La/Th ratios, mostly similar to those of lunar meteorites with intermediate Fe concentration.

Struck J. T.
The Moon as Its Own Planet [#6038]
The Moon is large enough so that the Moon can be considered its own planet. The Moon can be seen as revolving around the Sun, sweeping out an area, being round, having the characteristics of being a planet.

Lucey P. G. Honniball C. I. Brennan R. Burkhard L. Sandford S. Sun L.
Multispectral Polarization Measurements of Eight Lunar Soils [#6049]
The spectral polarization properties of eight lunar soils were measured to investigate space weathering effects and support the Korean Pathfinder Lunar Orbiter mission.

Tombrowski L. W. Mardon A. A.
Lunar Lava Tubes: A Potential Option for Future Human Habitation on the Lunar Surface [#6043]
Discussion of the potential benefits and difficulties of utilizing lunar lava tubes as habitats for manned missions to the Moon.

Tomic A. T.
Plants in Space [#6003]
I do not believe that humans in current form are able to reach any interstellar distances. Probably genetic and cyber biology will come up with the solutions, but until then we still can try to grow plants in space.

Miura Y.
Unique Moon Formation Model: Two Impacts of Earth and After Moon’s Birth [#6037]
The Moon rocks are mixed with two impact-processes of Earth’s impact breccias and airless Moon’s impact breccias; discussed voids-rich texture and crust-like composition. The present model might be explained as cave-rich interior on the airless-and waterless Moon.
Carle Pieters

9:00 a.m. Keane J. T. * Johnson B. C. Matsuyama I. Siegler M. A.

*New Views of the Moon’s Spin [6033]*
New geophysical data and numerical models reveal that basin-scale impacts routinely caused the Moon to tumble (non principal axis rotation) early in its history — plausibly driving magnetic fields, erasing primordial volatiles, and more.


*Impact History of the Moon [6027]*
Establishing an absolute planetary chronology has important ramifications for understanding the early structure of the solar system and the geologic history of the planets. The Moon is the cornerstone for understanding this impact history.


*LRO LAMP Photometric Corrections and Far-UV Investigations of New Impact Craters, Cold Spots, and Space Weathering on the Moon [6055]*
We report the initial results of FUV investigations of new impact craters, cold spots, and space weathering along crater rims and walls with the photometrically corrected LRO LAMP data.


*Space Weathering — Outstanding Questions and What’s Next [6054]*
We present our consensus view of the key outstanding questions in lunar space weathering, and how we can set about answering them.


*Space Weathering in the Thermal Infrared: Lessons from LRO Diviner and Next Steps [6057]*
Global data from the LRO Diviner show that the thermal infrared is affected by space weathering. We will present and discuss hypotheses for the unanticipated space weathering dependence and next steps.


*New Global Observations of Lunar Regolith Maturation in the Far-Ultraviolet [6035]*
A look at recent global LAMP far-ultraviolet observations of lunar swirls and regolith maturation.

10:30 a.m. DISCUSSION — Moderator: Pieters C.
Chair:  Ben Bussey

11:00 a.m.  Plescia J. B. * Robinson M. S.
Lunar Regolith — Surface Processes [#6034]
The nature of the regolith and surface processes on the Moon has significantly evolved from our understanding a decade ago, which was largely based on Apollo-era data.

11:15 a.m.  Costello E. S. * Ghent R. R.  Lucey P. G.
Regolith Overturn Due to Secondary Impacts [#6050]
Our mixing model includes secondary impacts and suggests that secondary impacts have thoroughly reworked the top meter of lunar regolith in the past 1 Gyr.

11:30 a.m.  Patterson G. W.  Carter L. M.  Stickle A. M.  Cahill J. T. S.  Nolan M. C.  Morgan G. A.  Schroeder D. M.  Mini-RF Team
Mini-RF S- and X-Band Bistatic Radar Observations of the Moon [#6061]
The Mini-RF instrument onboard the NASA LRO mission is collecting S- and X-band bistatic radar data to provide new insights regarding regolith development on the Moon, the diversity of lunar volcanism, and the current inventory of polar ice.

11:45 a.m.  LUNCH

12:45 p.m.  Basu Sarbadhikari A. *
Implications for Formations of Alkali-Rich Rocks of the Moon [#6022]
Silica-depleted and alkali-rich rocks on the Moon indicates requirement of the revision of LMO composition; the Moon has formed much cooler than by the giant impact and with high volatile content similar to the Earth.

1:00 p.m.  Gaddis L. R.  Horgan B.  McBride M. * Shearer C. K.  Stopar J.  Lawrence S.
Lunar Pyroclastic Deposits: Outstanding Questions [#6044]
We summarize major outstanding questions to be addressed to understand the lunar pyroclastic deposits and their value for future lunar exploration.

1:15 p.m.  O’Brien B. J. *
Science Causes and Synergistic Engineering and Commercial Consequences of Movements of Fine Dust (MOFD) on the Moon [#6040]
Failures 1969 Apollo 11 EASEP and 2014 Yutu immobilisation bookend engineering and operational consequences of movement of fine dust MOFD. So we challenge DTVCs to simulate decrease in situ dust over 25 hour data tranche DDE vertical silicon-covered cell.

1:30 p.m.  DISCUSSION — Moderator: Demura H.
Endogenous Lunar Volatiles [*#6030*]

This abstract discusses numerous outstanding questions on the topic of endogenous lunar volatiles that will need to be addressed in the coming years. Although substantial insights into endogenous lunar volatiles have been gained, more work remains.

2:15 p.m. Hashizume K. *  
*Supplies and Storage of Volatiles on Moon* [*#6009*]  
I would like to review the current situation of volatile studies of Moon, particularly on the origins and behaviors of volatiles at the lunar surface.

2:30 p.m. Saxena P. * Killen R. M. Airapetian V. Petro N. E. Mandell A. M. CANCELED  
*Post-Formation Moderate Volatile Transport and Loss on the Moon: Lunar Stratigraphy and Paleo-PSR’s* [*#6017*]  
Post-formation moderate volatile loss and transport on the Moon may be recorded in lunar stratigraphy and in paleo-permanently shadowed regions.

2:45 p.m. Honniball C. I. * Lucey P. G. Kaluna H. M. Li S. Sun L. Costello E.  
*Groundbased Lunar Surface Water: Latitude, Longitude Systematics and Detection, and Abundances at Small Geologic Targets* [*#6042*]  
Three micron groundbased observations of lunar surface water show latitude and time variations. Water abundances were derived for small geologic features.

3:00 p.m. Fagan T. J. * Fujimoto A. Kosaka D.  
*Role of Fluids in Lunar vs. Terrestrial Gabbros During Late-Stage and Post-Magmatic Crystallization, a Case Study* [*#6013*]  
Incompatible elements, including H\(_2\)O, are concentrated in late-stage magmatic pockets in gabbros from the Earth and Moon. Feldspar near the pockets is albitized by water (Earth case) or has discontinuous, unexplained changes in composition (Moon).

3:15 p.m. DISCUSSION — Moderator: Nagaoka H.

3:45 p.m. BREAK
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FUTURE MISSION CONCEPTS
4:00 p.m. University of Aizu Auditorium

Chair: Hiroyuki Sato

4:00 p.m. Neal C. R. * Lawrence S. J.
New Views of the Moon, 2: The Future [#6060]
Landed robotic missions to undertake in situ analyses or sample return will advance the future goals of many NVM-2 chapter subjects.

4:15 p.m. Shearer C. K. *
Sampling Volatile-Rich Lunar Materials. Collecting, Preserving, and Reading the Volatile Record of the Moon. [#6047]
What lessons did we learn from the Apollo program that provide us insight into the future examination and sampling of volatile-rich lunar materials?

4:30 p.m. Pieters C. M. * Head J. W.
What is Next? The Lunar Crust Provides Keys for Understanding Solar System Issues at 1 AU [#6058]
The Moon provides a unique opportunity for integration of remote sensing, in-situ, and sample analyses that will address broad and important solar system issues in the years ahead.

4:45 p.m. Tanaka S. * Goto K. Shiraishi H. Kawamura T. Yamada R. Murakami H.
Ishihara Y. Hayakawa M.
Science Objectives and Mission Concept of APPROACH Mission [#6025]
This paper reports science objectives and an outline of mission concept of APPROACH mission which will investigate internal structure of the Moon by seismic and heat flow observations. It was submitted to JAXA’s M-class mission this January.

5:00 p.m. Onodera K. * Tanaka S. Goto K. Shiraishi H. Kawamura T. Yamada R. Murakami H.
Ishihara Y. Hayakawa M.
Measurement of Rock Size-Frequency Distribution for Understanding the Surface Environment of APPROACH Landing-Site Candidate [#6048]
We measured rock size-frequency distribution of a landing-site candidate for a future lunar penetrator mission, and estimated the probability of success of deployment.

Tanaka S. Aizawa T.
Active Seismic Exploration Package on the Moon [#6015]
We have been designing and developing an active seismic exploration package in order to investigate from shallow to deep formation of the Moon. We present the basic concept of our seismic exploration package and its experimental results.

5:30 p.m. DISCUSSION — Moderator: Neal C. R.
Friday, April 20, 2018
NEW VIEWS OF THE MOON 2: WHAT NEXT?
9:00 a.m.  University of Aizu Auditorium

Chair: Charles Shearer

**Moon Diver: A Discovery Mission Concept for Understanding the History of the Mare Basalts Through the Exploration of a Lunar Mare Pit [#6032]**

Moon Diver is a Discovery-class mission concept designed to explore a lunar mare pit. It would be the first mission to examine an in-place bedrock stratigraphy on the Moon, and the first to venture into the subsurface of another planetary body.

9:15 a.m.  Haruyama J. *

**Possible Lunar Lava Tube and Its Skylight Hole as Resource for Lunar Science and Exploration [#6052]**

Recent studies on lunar lava tube and its skylight hole as resource of science and exploration is summarized with an introduction of UZUME project.


**Lunar Meteorites: What’s Next? [#6059]**

Using our crystal ball to predict which lunar meteorites will be found, and how these can address big picture lunar science questions.


**Returning to the Moon: Building the Systems Engineering Base for Successful Science Missions [#6012]**

Enabling science return on future lunar missions will require coordination between the science community, design engineers, and mission operators. Our chapter is based on developing science-based systems engineering and operations requirements.

10:00 a.m.  DISCUSSION — Moderator: Hiesinger H.

10:30 a.m.  BREAK

10:45 a.m.  Mathew J. *  Kumar B.  Sarpotdar M.  Suresh A.  Nirmal K.  Sreejith A. G.  Safonova M.  Murthy J.  Brosch N.  

**Prospects for Near Ultraviolet Astronomical Observations from the Lunar Surface — LUCI [#6041]**

We have explored the prospects for UV observations from the lunar surface and developed a UV telescope (LUCI-Lunar Ultraviolet Cosmic Imager) to put on the Moon, with the aim to detect bright UV transients such as SNe, novae, TDE, etc.

11:00 a.m.  Durst S. *  Takahashi Y. D.  

**Astronomy from the Moon and International Lunar Observatory Missions [#6036]**

Astronomy from the Moon provides a promising new frontier for 21st century astrophysics and related science activity. International Lunar Observatory Association is an enterprise advancing missions to the Moon for observation and communication.
11:15 a.m. Terazono J. *  
*Importance of E/PO Activity in Lunar Science [#6020]*
Upon rise of momentum for lunar science and explorations, we should regard importance of E/PO (Education and Public Outreach) in this area. The author will show significance of strategy and human resource cultivation of this area.

11:30 a.m. Radley C. F. *  
*The Lunar Space Elevator, a Near Term Means to Reduce Cost of Lunar Access [#6016]*
LSE built from existing commercial polymers, launched, and deployed for <$2B. Prototype weighing 48 tons with 100 kg payload pays for itself in 53 sample return cycles. Reduces the cost of soft landing on the Moon >3x, sample return cost >9x.

JAXA established JAXA Lunar and Planetary Exploration Data Analysis Group (JLPEDA) at 2016. Our group has been analyzing lunar and planetary data for various missions. Here, we introduce one of our activities.

12:00 p.m. DISCUSSION — Moderator: Haruyama J.

12:30 p.m. CLOSING REMARKS, ADJOURN
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Lunar Meteorites: What’s Next?
NEW VIEWS OF THE LUNAR IMPACT CRATERS WITH CENTRAL PEAKS

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Earth has one natural satellite, the moon whose character remained rather mysterious during centuries of telescopic study [www.NASA.Gov]. The moon is so close to the Earth at an average distance of only 384,400 Km. In July 1969, a human stood for the first time on the surface of moon by NASA. The Moon is geologically different from Earth (NASA). The lunar landscape is characterized by impact craters, with or without peaks (see www.NASA.Gov Fig1 here). Three dimensional view of the Alphonsus crater on moon is an example of craters on moon with central peak (Fig1 red circle) and rilles (blue arrows). The surface of moon is covered by a regolith of lavas, basalts and dust (www.NASA.Gov). The sand is the best material to simulate the basalts (& other volcanic plutonic rocks) used by author for simulation of particle flow and craters peaks formation (Fig2). Different numerical models (Figs2) and physical models (Figs3) by author showed that isostasy is very important for balancing the craters on planetary systems like Earth's moon. The models here in this report run by Earth's gravity. The numerical models set up as finite element models by plaxis(Fig2a,f,k,p,u) by illustration of sand material (blue color-Fig2a,f,k,p,u) and clay (pink Figs 2u,v,w,x,y) in the size of 12x5 meter boxes(Fig2). The physical models by sand and PDMS used for simulation of central peaks in craters in cm scales(Fig3). With or without extension(Figs2) the particles of sand flow(red and blue vectors in Fig2) from the country rock rims into crater only by loading changes(blue arrows-Fig2). In Fig2 from top two bottom row1 show the finite elements model after deformation. The row 2 show the total displacements of particles of sand. The row 3(Fig2) show the total displacements in shading. The row 4(Fig2) show the horizontal displacements vectors and row5 show the vertical displacements (Fig2). The numerical models suggest that the material flow upward to the crater and made the central peak (Fig2,3). The analogue models by sand and PDMS in cm scales confirm the finding and suggest upward flow of the materials around a crater in to the crater (Figs3). The changes in the vertical loading generated flow of particles in sand models(Figs2-3). The viscous materials (clay here in numerical models) beneath the sand can flow as uprising diapirs(Figs2,3) into the upper rising materials (Figs2,3). Any change in stress field changed the regolith balance (Fig3c) and generated uprising material seen in the lunar craters as central peak exposures (Fig1- see also logo of meeting called new view of the moon 2). Six types of uprising materials seen beneath craters(Fig3). The shallow (Figs 2, 3b,c,e,f) and deep flowing material (Fig2a,d and3) flow upward into the crater. The flat floor of crater on moon may be caused in part by the collection of materials that roll or slump off the walls of the crater and partially fill it and some of it may formed by up building diapirs(Fig2,3). Injection of new material from below can generated internal domes(Fig3d,e,f). I suggest readers to compare Different columns of Fig 2 together to understand different particle flows in different conditions of stress-strain fields and compare numerical models (Figs2) of sand ±basal clay (in m) with physical model (Fig3 in cm scales) simulated by sand and PDMS (polymer). To see better please use "zoom in" object. To visit other craters on Moon see www.NASA.Gov.

Fig1

Fig2

Fig3
IMPLICATIONS FOR FORMATIONS OF ALKALI-RICH ROCKS OF THE MOON. A. Basu Sarbadhikari

Introduction: Study of the lunar highland crust yields the record of oldest crust formation history of the terrestrial planets. New discoveries such as surface-cited water [1], pink spinel associated with lunar highland crust [2] and many others through probing the lunar surface in unprecedented details in recent past indicates a lot of unknowns of lunar crustal composition that need to be worked out. High abundance of Na are observed by LROSS impact at the Cabeus crater of the southern highland [3] and Chandrayaan-1’s X-ray Spectrometer (C1XS) near Tycho crater at the nearside of the southern highland has detected Na-rich domains (3-7 wt% Na$_2$O) [4,5]. The modal mineralogy and the bulk composition indicate that the rock type is alkaline and was classified as nepheline troctolite [5]. Calculated parent melt (PM) composition was considered based on i) the field relations and the compositional trends of the highland rocks to define the syn-crystallization assemblages, ii) equilibrium relation with co-existing olivine, and iii) comparison of elemental oxides with different highland rocks [5].

In this study petrogenesis of the Na-rich rocks of the Moon has been interpreted. Occurrences of these alkali-rich rocks require a revision to the lunar magma ocean (LMO) composition, which is capable to shade light on the Moon forming and early evolution processes.

Revised LMO composition: Similarities in several isotopic (O, Mg, Si, K, Ti, Cr, Fe, Mo, Ru, W) characteristics between Earth and the Moon along with the volatile enrichment in deeper mantle of the Moon put a serious constraint on the giant impact origin hypothesis, which requires realistic thermodynamic models of geochemistry and petrology at high temperature (T = 2500-3500 K; [6]). Further, petrogenetic models for lunar troctolites are heavily constrained by the high Mg# (Fo$_{83-92}$) values of olivine. This model study solves most of the above-mentioned complexities to understand the highland crustal vis-à-vis LMO compositions. Based on the above considerations and selected PM composition a new LMO composition (LMO$_{a}$) have been calculated. The silica content is lower in LMO$_{a}$ than that in LMO-LPUM (by 2.9 wt% SiO$_2$) and LMO-TWM (by 1.3 wt% SiO$_2$). Alkali (Na$_2$O+K$_2$O) content in LMO$_{a}$ is 0.3 wt% more than in LMO-LPUM and LMO-TWM. Calcium content in LMO$_{a}$ is similar to that in LMO-TWM, however CaO is ~ 1.5 wt% more in LMO$_{a}$ than in LMO-LPUM. Al$_2$O$_3$ in LMO$_{a}$ (4.9 wt%) is in between that of LMO-LPUM (3.9 wt%) and LMO-TWM (6.1 wt%). Although used a canonical value, the possibility of an Al-enriched (> 4 wt% Al$_2$O$_3$) Moon was not ruled out in the model of thermal and chemical evolution of the lunar interior [7]. Mafic (FeO+MgO) content and Mg# in all three LMO compositions are more or less similar. Perhaps the major difference in LMO compositions are in TiO$_2$ content, which is 3.5 (w.r.t. LMO-LPUM) to 7 (w.r.t. LMO-TWM) times higher in LMO$_{a}$ (1.12 wt%). Crystallization calculation from the LMO$_{a}$ has successfully yielded the early to intermediate stage of crystal settlement at the bottom of the LMO.

Implication to the Moon-Forming Processes: The leading hypothesis for the formation of the Moon, the giant impact model, is questioned by several researchers in their recent studies. If there had abundant volatiles in its early history of the Moon then the giant impact hypothesis must be revised. Sodium is a volatile element; high Na-content indicates crystallization in protracted condition in the solidifying LMO. This might suggest that the global-scale circulation of the magma in LMO was hindered in certain domains with entrapped high volatile and low-Si content.

The upper crustal layers both at the lunar highlands and mare regions of the Moon are dry because the Moon is an airless body, the volcanic and surface or shallow sub-surface magmatic materials of the Moon got degassed before solidification. The nepheline troctolites of Tycho and the associated rocks are not the result of late stage magmatism, rather are crystallized from the LMO in a maximum time span of ~ 500 Ma [8]. This means that the crust building event of the Moon was accomplished in a time-scale of at least first 500 Ma after separation from the proto-earth. It can also be concluded that the Moon has formed much cooler than that by the giant impact and with high volatile content similar to the earth. Much of the volatiles are retained in deep inside of the Moon.

NASA’S HUMAN EXPLORATION AND OPERATIONS MISSION DIRECTORATE’S LUNAR ACTIVITIES. D. B. J. Bussey1 NASA HQ, 300 E Street SW, Washington DC 20546 USA, ben.bussey@nasa.gov

Introduction: NASA’s Human Exploration and Operations Mission Directorate (HEOMD) has a number of ongoing lunar-related activities, relating to both robotic and human exploration.

ISECG Science White Paper: Space agencies participating in the International Space Exploration Coordination Group (ISECG) are discussing an international approach for human and robotic space exploration to achieve the social, intellectual and economic benefits. The status of this work is documented in ISECG’s Global Exploration Roadmap (GER). The GER reflects a coordinated international effort to prepare for collaborative space exploration missions beginning with the International Space Station and continuing to the lunar vicinity, the Moon, asteroids and Mars. While scientific research is not necessarily the main driver for human exploration, space agencies of the ISECG acknowledge the explicit stakes of scientific discovery in space exploration. Therefore, the agencies chartered the production of a Science White Paper that describes the scientific opportunities represented by near-term human exploration beyond low-Earth orbit (LEO). Specifically(111,655),(977,665)

Deep Space Gateway Concept Science Workshop: Following on from the ISECG science white paper, NASA is holding a workshop in February 2018 to discuss the science that could be enabled by the presence of a deep space gateway concept in the lunar vicinity. This workshop is jointly hosted by HEOMD and NASA’s Science Mission Directorate (SMD). The workshop aims to encompass a wide range of science disciplines including Earth Sciences, Heliophysics, Astrophysics, Fundamental physics, Lunar & Planetary Sciences, Life Sciences, and Space Biology. One of the goals of the workshop is to discuss what resources the gateway would have to provide in order to facilitate the types of science investigations that are proposed. To aid these discussions, there will also be crosscutting sessions covering topics such as External Payloads, Planetary Samples, Internal Payloads, Telerobotics, and use of the gateway as communication infrastructure for cubesats of lunar surface payloads.

Lunar CATALYST: Since 2014, NASA’s Lunar Cargo Transportation and Landing by Soft Touchdown (Lunar CATALYST) initiative has been accelerating the development of U.S. private-sector robotic lunar landers that can enable commercial payload transportation services to the lunar surface for both public and private customers. NASA competitively selected three industry partners (Astrobotic Technology, Masten Space Systems, Moon Express), and entered into no-funds-exchanged Space Act Agreements (SAA) with each of them. With NASA’s support through these highly collaborative technical partnerships, each of the industry partners has made substantial progress in developing their lunar landers, while managing their respective businesses with complete autonomy. Through these government-industry partnerships, NASA has provided in-kind contributions including technical expertise, access to test facilities, software, and the loaning of equipment. Based on the significant progress each partner has made, NASA announced in November 2017 that the agency would extend and update the no-funds-exchanged Space Act Agreements with the goal of seeing the first commercial cargo deliveries to the Moon over the next few years.

Korea Pathfinder Lunar Orbiter (KPLO): HEOMD is collaborating the Korean space agency (KARI) on their KPLO lunar mission. As part of this collaboration NASA is flying the ShadowCam instrument on the KPLO spacecraft. ShadowCam is a very sensitive camera that uses light scattered from the illuminated inner rims of polar impact craters to image the floor of these craters. The expected spatial resolution of ShadowCam is better than 2 meters. ShadowCam goals include searching for spatial and temporal distribution of volatiles, monitoring movement of volatiles within permanently shadowed regions, and revealing the geomorphology, accessibility, and geotechnical characteristics of cold traps. KPLO is scheduled to launch in 2020.

Cubesats on EM-1: The first launch of SLS will send an Orion spacecraft around the Moon. NASA is leveraging this launch to also fly 13 cubesats, several of which were selected to increase our understanding of lunar resources. Lunar Flashlight will use multiple lasers to search for volatiles in permanently shadowed craters. Lunar IceCube will look for water in sunlit regions using a spectrometer. And LunIR, by Lockheed Martin, will fly a Mid Wave Infra red sensor to study the lunar surface.

**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 of 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 of Lyman-α on 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) Discernible 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.](image-url)
ISPACe'S POLAR ICE EXPLORER: COMMERCIALLy EXPLORING THE POLES OF THE MOON
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Introduction: ispace is a company whose vision is to expand and sustain humanity’s presence in space by utilizing resources available on the Moon. ispace manages Team Hakuto, a front-running team in the now closed Google Lunar XPRIZE (GLXP). ispace developed and flight qualified Team Hakuto’s SORATO rover, which won the $500K mobility milestone award. As Team Hakuto originally only planned to develop a rover, the team needed to partner with another GLXP team developing a lander in order to be transported to the Moon. Team Hakuto signed a partnership in 2017 with Team Indus, which had a validated launch and became a finalist for the $20M Grand Prize. Unfortunately, neither Team Indus nor any other remaining team was not able to raise enough funds to pay a launch contract and Google official declared the end of the contest on January 23, 2018 [1].

ispace has a vision that expands beyond the GLXP. The company intends to build-upon two fundamental transport focused technologies, a rover and a lander, in order to enable the commercial exploration of the lunar surface and prepare for the establishment of in-situ resource utilization (ISRU) on the Moon. ispace plans to partner with space agencies, scientists, and the mining community for sensor and technology development to better detect water ice deposits. In addition, ispace will offer transportation opportunities so the international community can develop and test its own technology to explore the lunar surface.

Polar Ice Explorer (PIE) Project: The Polar Ice Explorer mission is an ISRU exploration mission that aims to identify and define the extension of the hydrogen and potential water ice deposits in lunar polar regions. This mission also will obtain valuable information on the geotechnical and trafficability properties of the polar regolith.

Four scientific mission objectives were established to address during this project:
1. To determine the local distribution and abundance of H in the subsurface regolith.
2. To characterize the form in which volatiles species containing hydrogen are present in the subsurface regolith.
3. To assess the volatile-rich contamination produced by lander exhaustion plume.
4. To obtain soil mechanics and trafficability information.

Payload: Three criteria are used to identify potential instruments for the PIE: The instrument fulfills at least one of the science objectives, its design is mature and the instrument can be easily procured.

Based on these conditions several instruments have been reviewed and considered as potential payload: (1) A Neutron Spectrometer (NS) to detect areas with enhanced hydrogen signatures, which may indicate the presence of subsurface water ice. (2) A Ground Penetrating Radar (GPR) to can detect, localize and characterize homogeneous stratigraphic units, such as segregated ice. In combination with the NS, the GPR facilitates more accurate mapping of the subsurface water ice deposits. (3) Mass Spectrometer (MS) to characterize the form in which the H-rich species are present in the polar regolith.

Mission Concepts: From the combination of several of the previously described payloads, several missions concepts have emerged (Table 1). Each concept fulfills at least two of the science objectives. In addition to the scientific aspects, programmatic, management and business considerations have to be taken into account in order to select the concept that provides the best cost/benefit ratio.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Goldcrest</th>
<th>Rose</th>
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</table>

Table 1: Mission concepts for the PIE.

Landing Site: The targeted landing sites for this project are regions characterised by sufficiently low annual temperatures to maintain permafrost layers. These regions would receive some direct solar radiation for short amounts of time, but would still remain cold enough to avoid water loss via sublimation [2,3].

Mission Funding: As a private company, ispace must consider new and innovative approaches to cover the costs and even make revenue from its mission. These approaches include selling access to the lunar surface for other scientific and non-scientific payloads, as well as selling the data generated by this mission. ispace intends to market its scientific and engineering data to space agencies, research institutes, and scientists interested in the most up-to-date data on the lunar surface.

**IMPACT HISTORY OF THE MOON.** B. A. Cohen¹, W. F. Bottke², M. D. Norman³, C. H. van der Bogert⁴, C. I. Fassett², H. Hiesinger⁶, K. H. Joy⁵, S. Mazrouei⁵, A. Nemchin⁵, G. A. Neumann⁵, N. E. B. Zellner⁵, ¹NASA Goddard Space Flight Center, Greenbelt MD 20771 (barbara.a.cohen@nasa.gov), ²Southwest Research Institute, ³Australian National University, ⁴Westfälische Wilhelms-Universität Münster, ⁵NASA Marshall Space Flight Center; ⁶University of Manchester; ⁷University of Toronto, ⁸Curtin University; ⁹Albion College.

**Introduction:** Establishing an absolute lunar impact chronology has important ramifications for understanding topics across planetary science, from the early structure of the solar system, to the dynamics, geologic evolution, and composition of planetary bodies. The possibility of a “cataclysm,” or “late heavy bombardment,” has been a central concept in planetary science since the 1960s. The cataclysm posits that between about 3.8 and 4.1 Ga ago, the rate and size of impacts increased to create the nearside basins in a short period of time. The concept is based on detailed geological observations of the Moon and the discovery of petrochemical and geochemical evidence for intense shock metamorphism at ~3.9 Ga in many Apollo samples, although an alternative interpretation is that evidence of earlier impacts is masked in the available samples by the relatively late Imbrium basin forming event. Variable and often poorly constrained crystallization ages of the rocks and/or incomplete resetting of different chronometers may contribute to the scarcity of reported ages of impact-affected rocks older than the proposed timing of the late heavy bombardment.

Dynamical models for lunar bombardment also encompass the gas-dust dynamics of forming disks and giant planet migration, that now may be invoked to understand not only our Solar System, but systems of exoplanets around other stars. Such bombardment would also have affected the Earth at a point when other evidence shows that continents, oceans, and perhaps even life already existed. Numerous community-generated reports recognize the importance of the lunar impact history in understanding the timing of delivery of volatile, organic, and siderophile elements, the possible role of impact stripping of atmospheres, and the geologic evolution of surfaces.

Key tests include understanding whether the putative cataclysm was a global phenomenon or an artifact of Imbrium contamination at the Apollo landing sites, the age distribution of the oldest basins, and whether the terrestrial planets and asteroid belt experienced a relative “lull” in impacts between early and late bombardment episodes. Establishing the stratigraphic relationship of the nearside basins to one another, based on either cross-cutting relationships or visible crater statistics, is challenging because Imbrium basin’s ejecta influenced the surrounding region so profoundly. Therefore, improvements to orbital remote sensing are unlikely to provide closure on this topic. Addressing these issues will require a combination of modeling of the composition of basin impact melt, petrology and geochemistry of samples to tie them to specific basins, and detailed geochronology of multiple samples. Such studies could be accomplished by landing and in situ dating, sample return to orbit, and/or sample return to Earth.

As the oldest stratigraphically recognizable basin on the Moon, the SPA age would anchor the early flux curve. The composition of the SPA interior is well-preserved in orbital remote sensing, providing a means to establish provenance for such samples. Impactites from younger basins such as Apollo, Poincaré, Planck, Inge-nii, Orientale and Schrödinger, as well as other large impact craters, would also contribute to establishing an impact chronology far from Imbrium [1]. Other sites with high potential to contribute to impact history are remnants of the impact-melt sheet filling the Nectaris and Crisium basins [2], young mare basalts and key stratigraphic craters such as Copernicus and Kepler [3-7].

Future work directed toward understanding the sources of projectiles bombarding the Moon may include systematic searches in lunar material for intact meteorite fragments, surface investigations of surface geochemical or physical anomalies that have been proposed to be possible concentrations of surviving impactor debris, and returning samples from known basin impact melt deposits to constrain highly siderophile element signatures. A better understanding of the mechanisms by which meteoritic material is incorporated into impact melts would also assist interpretation of siderophile element data for fingerprinting impactor types. The best temporally constrained records of regolith age are likely to be preserved in trapped ancient “paleoregolith” horizons found sandwiched between layers of radiometrically detectable geological units.

Investments in communications, landing technology, and sample acquisition would be enabling across many landed mission concepts. Additional infrastructure at the Moon related to human exploration activities, such as a communications network or orbital outpost, may also be utilized to enable further understanding of the Moon’s impact history.

REGOLITH OVERTURN DUE TO SECONDARY IMPACTS. E. S. Costello1,2, R. R. Ghent3,4, P. G. Lucey1
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Introduction: The model by Gault et al. (1974) [1] has had significant and ongoing influence on the development of regolith evolution models [e.g. 2, 3, 4, 5] and analyses of the reworking depth of surface exposure effects in Apollo cores [6, 7]; however, key parameters such as impact flux and the relationship between crater size and meteorite and target material properties have not been updated since the 1974 study.

Building on the legacy of the Gault et al. (1974) model, we have reproduced the probabilistic approach of Gault et al. 1974 and built on the model, extending its inputs to include newer data and generalizing the target and impactor properties. We use the updated model to describe gardening on the Moon and have demonstrated its use with updated input values and cratering efficiency laws and validating the results [8]. Most importantly, we include the effects of secondary impactors on regolith overturn as had been suggested but not included by Gault et al. Largely due to the inclusion of secondaries, we calculate a rate of mixing that is orders of magnitude higher than that predicted by Gault et al. (1974).

Results: Using the core concepts presented by Gault et al. (1974) [1] we use the cratering efficiency laws presented by Holsapple (1993) [9] to present a generalized model that describes the rate and probability a point at depth experiences overturn as a function of time. By using material parameters consistent with lunar regolith [9] and flux of primary and secondary impacts [10, 11], we calculate the rate and probability of overturn in the lunar case. Compared to the overturn rate driven by the modern flux of primaries, overturn due to secondaries is in much better agreement with the Morris (1978) [6] reworking rate and the depth-distribution of 26Al measured in Apollo cores [12, 13]. This is especially true at short timescales and shallow depths. Further, overturn due to secondaries better describes the rate at which surface features such as splotches [14], cold spots [15], and rays [16] are re-worked into the background. We conclude from these comparisons that secondaries are the dominant driver of overturn in the top meter of lunar regolith.

Future Work: The ease with which the model can be deployed makes it a useful tool in the exploration the Moon and beyond. A particular strength of the generalized approach presented here is that it allows the opportunity to describe the impact gardening rate on any airless body and the modeling of multiple aspects of regolith evolution. In future work we plan to adapt the model to describe the rate of regolith growth, compaction and the breakdown of surface rocks, with implications for lunar chronology.

Figure 1: The mixing due to secondaries calculated by this model is consistent with the thorough reworking of the top 3 cm of regolith reasoned by Speyerer et al. (2016) [12] from observations of splotches in LROC temporal pairs, the elimination of 20 cm deep cold spots over one to two hundred thousand years, and the erasure of 1 m deep rays over about a billion years.

THE MAFIC COMPONENT OF THE LUNAR HIGHLAND CRUST: NEW INSIGHTS FROM KAGUYA MULTIBAND IMAGER AND ROCK TYPE MODELS. S. T. Crites1, M. Lemelin2, P. G. Lucey3, M. Ohtake1
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Introduction: Since the lunar magma ocean hypothesis (e.g. [1]) was proposed, the lunar highlands crust has been understood as the remnant of the Moon’s primary crust, formed by plagioclase flotation on the magma ocean. However, this primary crust has been heavily processed by impacts since its formation, added to by intrusive and extrusive volcanism, and space weathered, leaving many questions open in understanding the lunar highlands we see today, including: How much did magma ocean processes concentrate plagioclase during flotation? How can GRS measurements revealing ~5 wt% FeO [2] or ~15 vol% mafic minerals in the lunar highlands be reconciled with this process? How much did highlands volcanism and intrusions contribute to the formation of the crust? Did large impact penetrate into the lunar mantle or a mafic lower crust, and is there evidence for lunar mantle material excavated at the lunar surface today?

We utilize improved, high resolution mineral maps [3] to investigate these questions using mixing models of three representative endmember rock types of the lunar highlands: (1) inherently mafic lunar anorthosites [4]; (2) mafic post-magma ocean intrusive or extrusive igneous material [5]; and (3) mafic lower crust or mantle material excavated by large basins [6].

Methods: We use the quantitative mineral maps of Lemelin et al. [3], based on Kaguya Multiband Imager Data and radiative transfer modeling, as inputs to mixing models following the approach of Crites et al. [7]. We model the abundances of various types of lunar rock types representing different sources: mantle ejecta (dunite, pyroxenite); post-magma ocean highlands igneous activity (troctolite, norite, gabbro); and mare basalt and base the compositions of each endmember on average lunar sample compositions. We model 29 different combinations of endmembers and assumptions to fully explore the possible sources of material to the lunar highlands crust.

Results: The result of each mixing model is a series of rock type abundance maps showing the distribution of primary magma ocean anorthosite, igneous rocks, and/or mantle material for a given set of assumptions. Individually, the high resolution (60 m) of the base mineral maps [3] means that the modeled rock abundances can be investigated at a highly local scale. Taken together, the results of the mixing models provide insights into the relative importance of the large-scale processes that formed the lunar highlands crust.

Fig. 3. Summary of mixing models showing the range of mafic contaminant to the highlands crust from different sources. Dots show range covered by the 29 models calculated in this work; diamonds show selected models; lined region shows range covered [7].

The new, higher-resolution mineral maps of [3] reveal more plagioclase-rich regions and mixing models based on these maps strongly support a relatively pure anorthositic endmember, with all scenarios incorporating “mafic anorthosites” (15% mafics) encountering no solution over 90% or more of highland pixels. The average abundance of anorthosite in the highlands is relatively constant, in the range of 60-80%. The remainder of the highlands crust is made up of either ejected mantle (15-20%) or igneous material (30-40%). These results are in overall agreement with the conclusions of [7], indicating that between 15-40% of the highland crust is made up of non-primary magma ocean products, and also places strong constraints on the excavation depths of lunar basins, with a maximum of 20 vol% mantle material permitted.

SPACE WEATHERING – OUTSTANDING QUESTIONS AND WHAT’S NEXT. Brett W. Denevi¹, Sarah K. Noble², David T. Blewett¹, Roy Christoffersen³, Ian Garrick-Bethell⁴, Jeffrey J. Gillis-Davis⁵, Timothy D. Glotch⁶, Benjamin T. Greenhagen¹, Amanda R. Hendrix⁵, Dana M. Hurley¹, Lindsay P. Keller¹, Georgiana Y. Kramer¹, Michelle S. Thompson³, and David Trang⁴. ¹Johns Hopkins University Applied Physics Laboratory, Laurel, MD, ²NASA Headquarters, Washington, DC, ³NASA Johnson Space Center, Houston, TX, ⁴University of California, Santa Cruz, Santa Cruz, CA, ⁵University of Hawaii, Honolulu, HI, ⁶Stony Brook University, Stony Brook, NY, ⁷Planetary Science Institute, Tucson, AZ, ⁸Lunar and Planetary Institute, Houston, TX.

Introduction: What happens to a surface left exposed to the space environment, protected by neither an atmosphere nor a magnetic field? The Moon has shaped our understanding of this question, and provided the foundation for our understanding of the ways that the solar wind and impacting micrometeoroids create a mature regolith. We have made large advances in understanding how physical and chemical changes to the surface affect observations of the Moon from far-ultraviolet through thermal-infrared wavelengths. But what are the major outstanding questions in lunar space weathering, and how can we set about answering them? Here we present our consensus view, reached as we synthesized the last decade of advances in space weathering for our New Views of the Moon 2 chapter.

Key Outstanding Questions: 1. Solar Wind vs. Micrometeoroids. Many space weathering studies, whether based primarily on analysis of remote sensing data, laboratory simulations, or examination of samples, focus on understanding the role(s) of the solar wind vs. micrometeoroid bombardment. A fundamental outstanding question is whether, in the aggregate, one process dominates (e.g., results in more rapid changes or changes that have larger spectral effects), or whether both are required to produce a “typical” mature soil (e.g., solar wind implantation aids in reduction of iron during micrometeoroid bombardment).

2. Lunar Swirls. Crustal magnetic anomalies provide some degree of shielding from the solar wind, and host lunar swirls that by many measures appear immature. Is the lower flux of solar-wind ions responsible for the presence of swirls, providing an opportunity to gauge the relative importance of solar-wind vs. micrometeoroid bombardment? Is another process responsible for their formation? Can one mechanism explain the anomalous spectral properties from UV through mid-IR wavelengths while leaving the topographic and thermophysical properties unchanged?

3. Rates. What do laboratory space weathering experiments tell us about space weathering rates and how do these compare to observations made of returned samples? Can we accurately simulate solar wind irradiation in the laboratory using fluences much higher than the solar wind? Can the energy deposition from laser experiments easily be translated to micrometeoroid energy deposition amounts and rates?

How do we translate these into rates of maturation of the lunar surface, where gardening and larger impact events complicate a straight path to maturity by burying and re-exposing soils?

4. Across the Solar System. How does space weathering on the Moon differ from that on airless silicate bodies closer to and farther away from the Sun? Can the differences in weathering on various airless bodies inform us about the relative importance of the range of processes responsible for maturation?

5. Other Processes. What role does dielectric breakdown play in the maturation of the lunar surface? Do other processes exist that may have ramifications for space weathering and maturation, that we have, thus far, failed to appreciate?

What’s Next: These questions may be addressed in a variety of ways. High-resolution images from the Lunar Reconnaissance Orbiter Cameras have revealed striking details of fresh impact craters, but many such features are smaller than the scale of a pixel in other multi- and hyperspectral observations; meter-scale multispectral images would provide critical new information. Hyperspectral imaging (from UV through mid-IR wavelengths) of the Moon, started by the Moon Mineralogy Mapper, should be completed in order to provide a more complete view of maturity differences across the globe. Also of importance are future in-situ observations of mature and immature regolith in the vicinity of a lunar magnetic anomaly/swirl. A mission with a suite of spectral, plasma, and magnetic field sensors would do much to improve our understanding of the relative roles of solar wind and micrometeoroid bombardment in surface maturation, as would returned samples of swirl regolith. Even more realistic laboratory simulations of space weathering also continue to be fruitful. Transitioning from nanosecond pulsed laser experiments to femtosecond lasers or dust impact experiments could prove beneficial, as could low-flux irradiation experiments. Coordinated TEM, synchrotron X-ray, and UV–mid-IR spectral analyses of experimentally weathered samples will remain crucial for improving our understanding of space weathering. Refining radiative transfer models of the absorbing and scattering properties of nanophase and microphase iron will also provide a critical theoretical basis for the interpretation of remotely sensed data.
ASTRONOMY FROM THE MOON AND INTERNATIONAL LUNAR OBSERVATORY MISSIONS. S. Durst1 and Y. D. Takahashi1, 1International Lunar Observatory Association (Kamuela, Hawai‘i; info@iloa.org).

Introduction: Astronomy from the Moon has been proposed since at least the 1960s, and two telescopes have already operated on the lunar surface, on Apollo 16 and Chang‘e 3. With numerous lunar missions being planned in the coming years, many astronomy proposals are being considered around the world. The International Lunar Observatory Association (ILOA) is one organization advancing missions to the Moon for astronomy and communication.

History: The advantage of the Moon for astronomy was first brought up in 1964 by S. Gorgolewski, pointing out that the far side would be the best for radio observations avoiding terrestrial interference [1]. Since then, 100s of publications have discussed lunar astronomy. The pioneering astronomical telescope was on Apollo 16 in 1972, a far-ultraviolet camera/spectroscope operated by astronaut John Young [2]. In 1990, American Institute of Physics held a conference on “Astrophysics from the Moon”. In 1997, ESA conducted an in-depth study on “Very Low Frequency Array on the Lunar Far Side” [3]. Since a mission to the far side was not likely in a timely manner, a more realistic concept for a radio observatory at the lunar south pole was proposed in 2002 [4]. In 2003, NASA also sponsored an engineering study on “Astronaut-Aided Construction of Large Lunar Telescopes”, investigating infrared telescopes in permanently-shadowed craters.

Current Projects and Proposals: Currently one telescope is operating on the Moon and numerous projects are ongoing for realization in the next few years.

Chang‘e-3 LUT. China’s first Moon lander Chang‘e 3, which landed in 2013, has a 15-cm aperture Lunar-based Ultraviolet Telescope that continues to operate today [5]. ILOA has collaborated with National Astronomical Observatories of China (NAOC) to image the spiral galaxy M101 in 2014 (Fig. 1b).

Chang‘e-4 LFS. Chang‘e-4 lander and rover are expected to carry Low-Frequency radio Spectrometers to operate on the far side. LFS will consist of 3 orthogonal antenna elements operating below 10 MHz to survey the Galactic low-frequency radio waves for the first time [6].

NASA LUNAR. NASA currently funds Lunar University Network for Astrophysics Research (LUNAR), led by Jack Burns and Joseph Lazio. LUNAR has published over 100 peer-reviewed papers since 2008 [7].

LRX / Lunar LOFAR. A Europe-based team has been working on Lunar Radio Astronomy Explorer (LRX) to examine the suitability of a future 33-element interferometer, Low Frequency Array (LOFAR) on the Moon [8].

Figure 1: (a) M101 spiral galaxy image taken by LUT-ILOA, 2014 (Credit: NAOC/ILOA); (b) ILOA Moon South Pole astronomy vision by M. Carroll, 2015.

ILO Missions: ILOA is a non-profit enterprise based in Hawaii to expand human understanding of the cosmos through observation and communication from our Moon (Fig. 1b).

ILO-X. ILOA has developed the ILO-X telescope for Milky Way Galaxy first light imaging from the Moon, awaiting launch on a Moon Express spacecraft possibly onboard the Rocket Lab Electron launcher.

ILO-1. The flagship ILO-1 mission is being developed through prime contractors Moon Express at Cape Canaveral and Canadensys Aerospace Corp in Toronto. Moon Express is working on landing and hazard avoidance technologies, with ILO-1 spacecraft development to begin NET 2018. Canadensys completed the Lunar Electronics Program in 2017 and is now working on Lunar Optics Program to deliver a flight-ready optical payload for ILO-1, ruggedized for the Moon. ILO-1 may be serviced by a future human mission.

Conclusion: Astronomy from the Moon provides a promising new frontier for 21st century astrophysics and related science activity.


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Introduction: Enabling science return on future lunar missions that exceeds the Apollo missions will require significant coordination between the science community defining the science objectives, the engineers who will design and build the hardware and spacecraft, and the mission operations personnel who will ultimately operate these missions. To be useful and to minimize costs from mission re-designs, this interaction will need to begin early and continue for the life of the program. To that end, our chapter in the New Views of the Moon 2 is based on developing first level systems engineering input and operations requirements for use by future lunar mission design engineers and operators. A critical part of this activity will focus on the open science questions as springboards to define mission design elements that enable future science return. Failure to engage the engineering community early can have significant consequences; for instance, the present Orion vehicle will have less sample return capability than the Apollo Command Module, largely due to miscommunications and incorrect historical data used early in the systems engineering process.

Mission Concepts: The mission concepts for future lunar science missions have been discussed in earlier workshops [1], [2]. Concept 1 missions involve simple robotic sample return or monitoring package emplacement based off a stationary lander. Concept 2 missions involve a highly mobile and dexterous robot, similar to the Robonaut Centaur, to do a detailed robotic investigation of a site of interest (e.g., Compton-Belkovich silicic volcanics) and return samples after a mission duration ≤1 lunar day. Concept 3 missions involve extended human sortie missions similar to an Apollo J-Mission, with unpressurized rover capability for all crewmembers, ≤10-20 km radius of exploration and surface stays ≤1 lunar day. Lastly, Concept 4 missions involve extended stays at a large, complex field site (e.g., Aristarchus Plateau, SPA Basin) with pressurized roving capability ≥100 km and stay times of ≥1 lunar day.

Chapter Progress: At present, the first draft of the chapter is completed, detailing the overall implications of the individual mission concepts with respect to sampling and curation, in-situ measurement needs, surface science operations approaches, information management needs and crew training approaches. The second half will be an engineering and operations analysis of the open science questions derived from other chapter teams.

Analyzing Science Questions – Developing a Systems Engineering Framework: One perennial issue with mission development is that engineering design and operational concept development often proceed in the absence of desired science community goals. Often, the only time the three communities come together is after the preliminary engineering designs and operational concepts have been completed. This often results in mission designs that do not meet science mission needs, and either cannot be changed or can be changed only after significant dollar expenditure. We propose that this chapter, in addition to defining basic mission concepts and their implications, should develop the basic science requirements that can be integrated into preliminary engineering design and operations concept development. The majority of this talk, and hoped for discussion at the NVotM2-Asia, is a consideration of which parameters need to be specified to answer these questions, and to put limits on requirements that will need to be met. For instance, if sample return is required, engineers will need to understand the size of the sample, target sampling locations, the character of the sample (bulk regolith, rake samples, cores, etc.) and sample return conditioning and handling. Also, the operations personnel will need to understand the types of locations from which samples are desired and steps need from acquisition through in-situ analysis and final storage for return to Earth. Similar questions can be asked for any open science question, and the appropriate systems engineering analysis must be applied to ensure that the science community receives the needed data and samples to inform the open science questions, and to set the stage for New Views of the Moon 3.

ROLE OF FLUIDS IN LUNAR VS. TERRESTRIAL GABBROS DURING LATE-STAGE AND POST-MAGMATIC CRYSTALLIZATION, A CASE STUDY. T. J. Fagan¹, A. Fujimoto¹ and D. Kosaka¹, ¹Department of Earth Sciences, Waseda University, Tokyo, Japan (fagan@waseda.jp).

Introduction: Water plays an important role in the formation of igneous rocks of the Earth’s crust by (among other processes): (1) lowering crystallization temperatures, changing mineral stabilities and compositions when H₂O is dissolved as a component in silicate liquid; and (2) causing recrystallization of original igneous minerals when H₂O is present in a fluid phase in hot rock [e.g., 1,2]. In the Apollo view of the Moon, water had no comparable role during the formation and alteration of igneous rocks on the Moon [see review by 3]. Subsequent, post-Apollo SIMS analyses of lunar igneous glass andapatite have shown that some igneous rocks on the Moon formed with some water [e.g., 4,5], raising multiple questions regarding the abundance of water in the Moon and role of water during lunar petrogenesis.

In this study, we (1) characterize enrichment of incompatible components, including H₂O (if present), in late-stage magmatic pockets in olivine cumulate gabbro (OC) of the Northwest Africa 773 clan of lunar meteorites [e.g., 6,7], and (2) compare late-stage pockets of the OC with pockets in a terrestrial gabbro, the Murotomisaki gabbroic sill, Shikoku, Japan [8]. We focus on zoning of plagioclase feldspar near and in the pockets, because feldspar can act as a recorder of both crystallization from igneous liquid and recrystallization in the presence of aqueous fluid [1,2].

Methods: Late-stage magmatic pockets were identified in a polished thin section (pts) of NWA 2977, a member of the NWA 773 clan composed entirely of OC [7,9], and in a pts (labelled Muro-14) of the coarse gabbro unit in the central portion of the Murotomisaki gabbroic sill [8]. The coarse gabbro is the last unit of the sill to crystallize and therefore is likely to host magmatic pockets enriched in incompatible components, including H₂O. The pockets were found by a combination of petrography and elemental mapping of the pts. Elemental X-ray maps and analyses of minerals were collected using a JEOL JXA-8900 electron probe micro-analyzer (EPMA) at Waseda University. Quantitative analyses of feldspars and other minerals were conducted using 15 kV and 20 nA. Ab-rich feldspar in Muro-14 was sensitive to loss of Na under a focused beam, so analyses in Muro-14 were collected while rastering a focused beam at 20,000x for a spot size of 6x8 μm. Plagioclase in NWA 2977 is more anorthitic and less sensitive to beam-induced variations in composition, so we used a 100,000x beam with spot size of <2 μm.

Results and Discussion: Murotomisaki gabbro. Five pockets were found in the Muro-14 pts. All of the pockets contain the water-rich silicates prehnite and chlorite. In some pockets, chlorite is texturally replacing biotite. Plagioclase feldspar adjacent to the pockets is Ab-rich (An⁻¹⁰) and often exhibits porous textures characteristic of albitized feldspar [2]. Smooth textured albite occurs in some places and probably recrystallized from porous albite. More An-rich feldspar occurs farther from the pockets and exhibits normal zoning (An-rich cores, relatively Ab-rich rims). The boundaries between albitized and original igneous feldspars have discontinuous breaks in composition (e.g., An₁₅ vs. An₃₅). Albitization appears to be superimposed on feldspars with normal igneous zoning.

NWA 2977. Seven pockets were found in the pts of the NWA 2977 OC. All of the pockets contain Ca-phosphates and ilmenite, and all but one contain K,Ba-feldspar. Plagioclase feldspar crystals adjacent to the pockets have compositions near An₀₀ and show no/little zoning over distances from 100 to 600 μm from the pockets. Closest to the pockets (<50 μm) plagioclase contents show discontinuous changes in composition to An₉₀.

We have not determined the origin of the discontinuous decreases in plagioclase An-contents with proximity to the pockets. Possibilities include: (1) exsolution; (2) a thermal maximum in the An-Ab liquidus at An₁₀₀ (azetoite; see [10]); (3) recrystallization in the presence of an H₂O-poor fluid.

Previous work shows that H₂O was present in at least some late-stage magmatic pockets of the OC [5]; the Murotomisaki pockets, however, were engulfed with post-magmatic H₂O-rich fluid. It is apparent that the Murotomisaki gabbro crystallized and recrystallized at higher P(H₂O) than the NWA 773 clan OC.

LUNAR PYROCLASTIC DEPOSITS: OUTSTANDING QUESTIONS. L.R. Gaddis¹, B. Horgan², M. McBride³, C.K. Shearer⁴, J. Stopar⁴, and S. Lawrence⁴. ¹Astrogeology Science Center, U. S. Geological Survey, Flagstaff, AZ; ²Purdue University, W. Lafayette, IN; ³Institute of Meteoritics, Univ. New Mexico, Albuquerque, NM. ⁴Lunar and Planetary Institute, Houston, TX; ⁵NASA Johnson Space Center, Houston, TX. (lgaddis@usgs.gov)

Introduction: Lunar pyroclastic deposits have been recognized as dark, rock-free, glass-rich units that mantle underlying terrain, often at the margins of lunar maria [e.g., 1]. A major component of the sampled pyroclastic deposits at Apollo 17 (Taurus Littrow) and 15 (Hadley Rille) landing sites are picritic glass and crystallized beads [2, 3]. These primitive materials were likely derived from depths up to 400 km and they provide clues to the nature of the early lunar interior, especially regarding endogenic volatiles [3-5] and the locations of potential resources [6, 7]. The concentration and source of such volatiles may have major implications for the interior structure, composition, and origin of the Moon [e.g., 8]. Here we describe major outstanding questions to be addressed to further understand these deposits and their value for future lunar exploration.

Resources: Indigenous magmatic water was found in melt inclusions in sampled lunar pyroclastic glasses [e.g., 9-11]. The mapped abundance and distribution of lunar indigenous water [12] show a striking correlation with the sites of many large lunar pyroclastic deposits, with local enrichments of up to 300-400 ppm H₂O. Also, mafic minerals in pyroclastic deposits can provide Fe, Ti, and O₂ [13], and pyroclastic glasses and beads have surficial vapor-deposited coatings of volatile-element compounds that may be valuable resources [e.g., Au, Ag, Cu, Cd, F, S, Zn; 14]. Finally, the enrichment in iron and titanium oxide (typically in ilmenite) of glass and devitrified beads [6] also allows them to retain solar wind-implanted volatiles, including H and He isotopes [e.g., 15]. Helium-3 (³He) in mature lunar regolith has been proposed as a possible fuel for nuclear fusion reactions [16].

Outstanding Questions: Where are pyroclastic glasses found? Do all volcanic vents have pyroclastic glasses? Why don’t pyroclastics at Sinus Aestuum have mapped water? How do volatiles behave during an eruption? How much water was present in source regions and how much variability is observed at different locations?

Landing Site Suitability: Lunar pyroclastic deposits are not only resource-rich, they are often accessible and relatively safe for landing site selection. All of the larger lunar pyroclastic deposits [e.g., Aristarchus (26.7⁰N, 52.3⁰W), Sulpiicius Gallus (21.7⁰N, 9.4⁰E), Sinus Aestuum (6.6⁰N, 5.9⁰W) and Rima Bode (11.9⁰N, 3.4⁰E)] are on the lunar near side [1] and are accessible for landing sites and traverse science. The small pyroclastic at Schrödinger crater (75⁰S, 132.4⁰W) supports selection of a South Pole landing site [17].

Site characterization must include assessment of local and regional slopes at the 10-cm level, and mapping of the location and position of sub-scale rocks and boulders associated with impact craters and outcrops. The 2016 LEAG update of the strategic knowledge gaps [18] highlighted the need for in-situ measurements of geotechnical properties (particularly soil grain-size distribution and penetrability) as well as understanding the thickness of large pyroclastic deposits as key measurements for human exploration scenarios. Such detailed characterization and mapping of lunar pyroclastics is supported by high-resolution image data from the NASA LROC NAC [19] and the JAXA Kaguya Terrain Camera [20] and Multiband Imager [21]. Preliminary assessments point to numerous safe landing sites near pyroclastic deposits, making these prime destinations for future missions.

Outstanding Questions: Are all pyroclastic deposit sites equal for communications to orbiters or Earth? Are some sites more rugged than others (e.g., because of a high number and density of vents, impact craters, etc.)? Are other potential resources nearby?

SPACE WEATHERING IN THE THERMAL INFRARED: LESSONS FROM LRO DIVINER AND NEXT STEPS. B. T. Greenhagen1, P. G. Lucey2, T. D. Glotch3, J. A. Arnold4, N. E. Bowles5, K. L. Donaldson Hanna6, and K. A. Shirley7, 1Johns Hopkins Applied Physics Laboratory, 2University of Hawaii at Manoa, 3Stony Brook University, 4Carnegie Institute of Washington, 5University of Oxford, Email: benjamin.greenhagen@jhuapl.edu

Introduction: Before the launch of the Lunar Reconnaissance Orbiter (LRO), it was suggested that thermal infrared (TIR) spectroscopy would be a unique tool for lunar compositional remote sensing in part because evidence indicated that 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.

Discussion: Observable TIR 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. Features such as interiors, ejecta and ray deposits of Copernican craters show CF positions at systematically shorter wavelengths than their more space weathered surroundings. Lunar swirls (Figure 1), 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].

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 (Figure 2), 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.

However, the CF position is only one TIR indicator of space weathering; both the shape of CF and depth of absorption features at longer wavelengths are also affected. Therefore it is critical that future TIR instruments should be designed to more fully characterize the spectral properties. In this presentation we will describe the most critical space weathering spectral characteristics to be observed by future TIR instruments.

Figure 1. Diviner CF shows systematic differences between on- and off-swirl terrains. [from 6].

Figure 2. Demonstrating the use of OMAT to correct space weathering effects from Diviner CF data.

Introduction: The Earth has a fluid core and it can rotate around an axis independently from that of the mantle. If the axis of rotation of the fluid core deviates from that of the mantle for some reason, two different rotations around different axes begin. This phenomenon is called the Free Core Nutation (FCN). In case of the Earth, the period of FCN is about 460 sidereal days, and when seeing on the rotating coordinate fixed to the Earth, the period becomes $2\pi/\Omega (1-1/460)$, which is very close to 1 sidereal day. There are a lot of components of diurnal Earth tides near the period of 1 sidereal day, and the amplitudes of these components are magnified due to the resonant, which is called fluid core resonance.

Lunar Core: Whether the Moon has a fluid core or not is still unclear although it is an important issue which is related to existence or non-existence of paleo magnetic field and thermal history of the Moon. Williams et al. [1] suggested energy dissipation inside of the Moon from the analysis of Lunar Laser Ranging data, and Harada et al. [2] suggested partial melting inside of the Moon from the theoretical estimation of tidal heating. The results of re-processing the Apollo seismic data and give its size [3,4]. Arkani-Hamed & Boutin [5], on the other hand, suggested the existence of core dynamo reversal from analyses of magnetic data. However there has been no direct observation which shows the existence of the fluid core.

Free Core Nutation: The period of FCN is estimated to be from several to 20 decades according to lunar model and the amplitude is less than 16 arc seconds [6]. Astronomical observations of FCN might be very difficult because its period is long. Barkin et al. [7] made a comparison of the semi-empirical series of ephemeris [8] with the analytical theory of librations of the Moon having a fluid core, and estimated the FCN-period be 206 years, and obtained the amplitude and the phase of FCN for the first time. According to Barkin's analyses the amplitude is equal to 0.0395 arc seconds. Observations of deformation or gravity variation affected by resonance of FCN appear on the lunar surface, on the other hand, might be more practical like the Earth. Supposing the mean angular velocity of the Moon be $\Omega_c$, angular velocity of FCN relative to inertia space be $\omega_c$, then FCN is observed on the Moon as the angular velocity of $\Omega_c-\omega_c$. It becomes $0.0366-1/(200\times365)\approx0.03660099-0.00001370\approx0.03658729$ (the 27.331 days) for the FCN period of 20 decades.

Fluid Core Resonance: Because there are a lot of components of lunar diurnal tides around the 27.3 days, there is possibility that the amplitudes are magnified by the resonance of FCN. Not only the tidal variations but the forced physical librations which are caused by the same forces must be affected by the resonance. Actually there are some evidences of resonance in the result of analyses of Lunar ephemeris DE421 expanded to over 1000 years [8]. There are, on the other hand, free modes such as the precession (about 24 year period), the Chandler like polar-motion (about 75 years), the free librations (about 100 years for latitudinal mode and 2.9 years for longitudinal mode) as well as FCN [6], and the resonance effects must be complicated.

Concluding Remarks: We propose to observe variation of deformation and gravity on the lunar surface in order to detect the effect of resonance of FCN.

DEVELOPMENT OF THE LUNAR POLAR HYDROGEN MAPPER MISSION. C. Hardgrove¹, J. Bell¹, R. Starr³, A. Colaprete¹, D. Drake¹, L. Lazbin⁴, S. West¹, E. B. Johnson¹, J. Christian¹, L. Heffern¹, A. Genova², D. Dunham², B. Williams³, D. Nelson³, S. Puckett⁶, N. Struebel⁶, A. Babuscia², P. Scowen¹, H. Kerne³, R.J. Amzler¹,¹Arizona State University, Tempe, AZ, ²Jet Propulsion Laboratory/CalTech, Pasadena, CA, ³Catholic University of America, Washington, DC, ⁴NASA Ames, Moffett Field, CA, ⁵Techsource, Los Alamos, NM, ⁶Arizona Space Technologies, LLC, ⁷Radiation Monitoring Devices, Watertown, MA, ⁸KinetX, Simi Valley, CA.

Mission Overview: The Lunar Polar Hydrogen Mapper (LunaH-Map) is a 6U CubeSat flying on the Space Launch System (SLS) Exploration Mission 1 (EM-1) and was selected for flight in the first call for proposals in NASA’s Small, Innovative Missions for Planetary Exploration (SIMPLEX) program. The LunaH-Map spacecraft is equipped with gimbaled solar arrays, 3 reaction wheels, a star tracker, an X-Band radio, a command and data handling system, power control system, neutron spectrometer array, and a low-thrust propulsion system [1, 2]. Spacecraft operations, telemetry and science data analysis will be conducted at the Mission Operations Center at Arizona State University. After deployment from SLS EM-1, LunaH-Map will maneuver and perform a lunar flyby targeting the Earth-Moon L2 point and eventual capture by the Moon within two months [3]. Upon lunar capture the spacecraft will spiral down to an elliptical low-altitude science orbit with perilune at the South Pole. During the science phase, a miniature neutron spectrometer (Mini-NS) will measure neutron counts about the perilune of each orbit to enable the mapping of hydrogen enrichments within permanently shadowed regions (PSRs) at spatial scales less than 15 km². Mini-NS is an epelositel scintillator based neutron spectrometer with 200 cm² of detection area and gadolinium shielding to filter out thermal neutrons with E < ~0.3 eV [4, 5]. A mean perilune altitude between 10 to 15 km above terrain poleward of 85°S is targeted throughout the science phase, but will vary depending upon the final SLS EM-1 launch date and trajectory [3].

Science Mission: There is substantial evidence for small-scale (<10km) hydrogen enrichments within south pole lunar PSRs [7, 8]. Several studies of Lunar Prospector Neutron Spectrometer (LP-NS) data have also revealed that hydrogen enrichments are not uniformly distributed across all south pole PSRs [8, 9, 10]. There remains uncertainty about the bulk (non-surficial/frost) abundance and distribution of these enrichments. Placing constraints on the bulk hydrogen abundance within PSRs will point to specific processes and delivery sources for polar volatiles, and can help resolve mechanisms operating over long time scales (e.g. solar wind) from other, much shorter time scale delivery mechanisms (e.g. passing asteroids or comets) [11]. Small-scale bulk hydrogen abundance maps can also be correlated with other polar datasets (i.e. temperature) to help untangle the relationship between volatile distributions and other surface properties. Hydrogen enrichments between 500 to 600 ppm at a spatial scale of 5-15 km could provide robust evidence for discerning hypotheses regarding transport processes of polar hydrogen enrichments [9, 12]. The orbit of the LunaH-Map spacecraft, and perilune altitude, will determine the ultimate spatial resolution of the Mini-NS. The current science phase orbit achieves 282 orbits over two lunar days and preliminary analysis of the Mini-NS sensitivities shows the mission will be capable of identifying small-scale (<15 km²) regions of hydrogen enrichments on the order of 600ppm +/- 120ppm. [4]

POSSIBLE LUNAR LAVA TUBE AND ITS SKYLIGHT HOLE AS RESOURCE FOR LUNAR SCIENCE AND EXPLORATION. J. Haruyama1, 1Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency :Haruyama.junichi_at_jaxa.jp (change “_at_” to @).

In 2009, the Japanese lunar explorer SELENE (nicknamed KAGUYA) discovered three large holes in the lunar maria at the Moon's Marius Hills region1, at Mare Tranquillitatis, and at Mare Ingenii2). Each of these holes has near vertical or overhanging walls, tens of meters in both diameter and depth. Several photos with different solar elevation angle conditions by SELENE Terrain Camera and Multiband Imager, and higher resolution imaging and additional excellent oblique observation imaging by LRO Narrow Angle Camera indicate the existence of subsurface voids, probably lava tube caverns that seem associated with the holes 2-4).

Recently, developing methods of gradiometry and cross correlation to isolate the target signal of mass deficits from the twin GRAIL gravity data, Chappaz et al. (2017)[5] detected many locations of horizontally extended mass deficits. They concluded some of them could indicate the existence of large and long intact lava tubes. One of the mass deficits is an area at Marius Hills in which a skylight hole had been discovered. Kaku et al. (2017)[6] investigated radar data from Lunar Radar Sounder (LRS) onboard SELENE (Fig.1) for the mass deficit area and found an echo pattern suggesting the existence of an intact lava tube. Kaku and his colleagues have been expanding research area to find similar echo patterns, and they have found many ones [7].

The existence of intact lunar lava tubes has become more realistic. A group of Japanese scientists and engineers are considering missions to enter and explore lava tubes of the Moon via their skylight holes. The mission program is named UZUME, after a Japanese goddess in historical literatures.

In this presentation, we will summarize recent studies on lunar lava tube and its skylight hole as resource of science and exploration with an introduction of the UZUME project.


Fig. 1. An image of SELENE Lunar Radar Sounder experiment.
SUPPLIES AND STORAGE OF VOLATILES ON MOON. K. Hashizume, Faculty of Science, Ibaraki University (ko.hashizume.sci@vc.ibaraki.ac.jp).

Introduction: Detection of water and other volatile compounds on Moon’s surface is now considered to be a hot topic, both in scientific and practical aspects. I would like to review the current situation of volatile studies of Moon, particularly on the origin and behaviors of volatiles at the lunar surface. This study is aimed at contribution in establishing attractive scientific goals, as well as in the estimation of volatile resources, toward expected international lunar exploration programs.

Water Planet and Moon: One of the most important scientific goal ultimately expected from volatile studies on Moon is to acquire the residence time of these compounds on small planets. Precise knowledge of the process that determines the residence time will contribute in providing generalized information to predict emergence of water planets among the exoplants currently being eagerly searched.

Behaviors of Volatile Compounds on Moon: The volatile behaviors on Moon could be sub-divided into several stages that require different methodologies and disciplines to understand: (1) supply/generation of volatiles; (2) migration of volatiles; (3) volatile storage on/in lunar regolith; (4) volatile escape from lunar regolith, and from the lunar gravity. Studies reviewed here mostly belong to stages (1) and (3), which must be connected with the remaining parts to approach a total view of the volatile behaviors on Moon.

Volatile supplies on Moon: Volatile compounds on present Moon’s surface could be supplied from several sources, such as solar wind (SW), micrometeorites (MM), lunar rocks through ion-sputtering and/or comets. Regarding water, it is important to estimate the flux of water, which does not necessarily correspond to the flux of hydrogen. SW is deemed to be the most important source of hydrogen to the lunar surface. However, the dominant fraction of hydrogen that are implanted to lunar regolith minerals exist in the form of elemental hydrogen. Though part of the implanted protons could react with rock-forming oxygen, resulting in formation of hydroxyl-ions and/or water molecules [1], the conversion rate of protons to OH/H2O-forms is probably less than 1%, which is estimated from SW studies of Apollo regolith samples with a variety of proton concentrations. Meanwhile, MM, the most important mass-flux of extraterrestrial material to Earth [2] and probably to Moon, could be a competing source of water, if not of elemental hydrogen. MM, known with their primitive natures, are expected to contain abundant volatiles, equivalent to those in primitive carbonaceous chondrites. Based on the contemporary SW flux, MM flux to Earth, and the sputtering/reduction rate of ions in lunar regolith minerals, I estimate that the proportion of water on Moon with the two origins, SW protons+oxygen sputtered from lunar rock, and water vaporized from MMs, is comparable.

To obtain a full list of volatile sources on Moon, cometary fluxes must be known, although this is reserved to our future task. Note that degassing from the water-rich lunar lithosphere [3] may also be considered as an important volatile source to the Moon surface, if the residence time of volatiles is long enough to expect that an important part of the volatiles present on contemporary Moon was sourced upon the now diminshed lunar volcanic activities.

The generation/accretion rates of volatiles with different origins could be locally/temporally different depending on the natures of these sources. For instance, larger SW flux is expected at the lower latitude, particularly at the far side, whereas MM flux is probably rather homogenous on the entire Moon. Cometary contribution could be heterogenous owing to their sparse accretion nature, both in spatial and temporal sense. Difference in the localities and generation processes of these sources could be reflected in the efficiencies of migration to the cold high-latitude region, and/or to the storage in/on the cold regolith layers. I consider that deciphering the origins of lunar volatiles is important both in scientific and practical aspects. The sources of water on Moon could be distinguished by the isotope compositions of hydrogen and oxygen.

Storage of volatiles on Moon: Part of the volatile molecules supplied to bulk Moon is probably migrated to the polar region, being trapped on/in the regolith. A couple of storage forms are proposed, with different concentrations and locations. By the first mode, volatiles are trapped in the permanent shadowed region [4]. The second one is the broad area of the polar region, at some depths of the lunar regolith [5]. By this mode, vapors of volatile compounds, trapped during night and vaporized upon dawn, possibly diffuse into the regolith by a process so-called the pumping effect [6].

CHARACTERIZATION OF POTENTIAL LANDING SITES FOR UPCOMING LUNAR MISSIONS. H. Hiesinger1, J. Flahaut2, M. Ivanov3, C. Orgel4, L. Xiao5, J. Huang5, C. H. van der Bogert5, J. W. Head2, 4Institut für Planetologie, Westfälische Wilhelms-Universität Münster, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany, Hiesinger@uni-muenster.de; 2CNRS/CRPG/UL, Vandoeuvre Les, Nancy, France; 3Vernadsky Institute, Moscow, Russia; 4Department of Planetary Sciences, Freie Universität Berlin, Germany; 5Planetary Science Institute, China University of Geosciences, Wuhan, China; 6Department of Geological Sciences, Brown University, Providence, USA

Introduction: In the last decade, lunar science has become increasingly more important because it has been realized how crucial the Moon is for an accurate understanding of the Earth-Moon system, the other planets, as well as the history and evolution of the entire Solar System. Numerous recent space missions to the Moon and universities can participate in lunar research with small-scale cubesat-type missions. The European Space Agency (ESA) is collaborating with China and Russia on their upcoming lunar missions and we are supporting our Russian and Chinese colleagues with the characterization and evaluation of potential landing sites.

Chinese lunar activities: As indicated by numerous scientific reports (e.g., NASA decadal survey, NRC), the South Pole-Aitken Basin (SPA) on the lunar farside is high on the priority list of scientific human and robotic exploration [e.g., 1]. By the end of 2018, Chang’e-4 will be the first landed mission on the lunar farside to explore this region with a Yutu-heritage rover and an orbital relay satellite [2]. The scientific objectives of Chang’e-4 include: (1) studies of the interaction between the solar wind and lunar surface, (2) investigation of the formation mechanism of lunar regolith and dust, (3) evaluation of the lunar-based VLF astronomical potential, (4) determination of the regional geochemistry and subsurface structure, and (5) characterization of the recent impact flux of the Moon [2]. Before the selection of Von Karman crater in western SPA [3], a potential landing site for the Chang’e-4 robotic mission was the 538 km-diameter Apollo basin in the NE quadrant of the SPA basin. Thus, we compiled all relevant data for the assessment of the scientific potential, as well as landing site safety for this region. We have prepared a regional geologic map of the northern portion of the SPA basin, including the Apollo basin for which we prepared two higher resolution (1:50,000) geologic maps of the central and southern parts [4,5]. Several regions of interest (ROIs) within these portions of the Apollo basin were examined in greater detail. These studies indicate that their relatively high FeO (~14-20 wt%) and TiO₂ (~1-7 wt%) contents make them favorable candidates for in situ resource utilization (ISRU) demonstrations [5]. In addition to the study of the Apollo basin, we are also investigating the Von Karman landing site, as well as the potential landing zone of the Chang’e-5 mission on the lunar nearside, north of Mons Rümker [6]. This is a particularly interesting area because previous crater size-frequency distribution (CSFD) measurements indicate the exposure of very young (~1.3 Ga) lunar basalts [7]. Thus, radiometric ages from rocks returned from this region would allow us to define a new calibration point of the lunar chronology in a time interval that has not been covered by Apollo and Luna samples.

Russian lunar activities: The Luna-Glob (LG) mission will be the first mission of a series of Russian lunar missions with increasing involvement of ESA. The potential landing zone that we studied in detail is located close to the rim of the South Pole-Aitken (SPA) basin between 0° and 60° E and 65-85° S [8-10]. In the landing zone, predominantly ancient terrains of pre-Nectarian and Nectarian ages are exposed [8]. In particular, the origin of pre-Nectarian stratigraphic units is mostly related to the emplacement of SPA ejecta, although post-SPA basins also transported materials across large distances to the landing zone [10,12-14]. We assess the potential contributions of several individual lunar basins (e.g., Australe, Nectaris, Schrödinger, Imbrium) to the regolith at potential landing sites in order to facilitate interpretation of the results of the LG in situ analyses. We used the model of [15] to calculate the ejecta thicknesses contributed to the landing zone by various remote basins with a 1x1° grid resolution. On the basis of these calculations, we find that the SPA basin is by far the main source of materials that constitute the megaregolith [3,16,17] of the potential landing area. According to the applied ejecta emplacement model, the average SPA ejecta thickness is ~3.2 km, ranging from ~1.8-5.5 km, depending on the distance from SPA. All other considered pre-Nectarian basins only contributed ~3.6% to the total ejecta thickness in the landing zone, with Australe being the most important source, which contributed ~70 m (mean) of ejecta. Nectarian and Imbrian basins delivered only a few meters of ejecta to the landing zone. Among those basins, Serenitatis and Nectaris are major contributors.

Future work will include investigations of regions of interest in the vicinity of the South Pole for the Luna-Resurs landers and other upcoming missions to very high latitudes [e.g., 18].

GROUND-BASED LUNAR SURFACE WATER: LATITUDE, LONGITUDE SYSTEMATICS AND DETECTION AND ABUNDANCES AT SMALL GEOLOGIC TARGETS. C. I. Honniball1, P. G. Lucey1, H. M. Kaluna2, S. Li1, L. Sun1, and E. Costello1, 1University of Hawaii at Manoa, Department of Geology and Geophysics, 1680 East-West Rd, Honolulu, HI 96822, cih@higp.hawaii.edu, 2University of Hawaii at Hilo Department of Physics and Astronomy, 200 W Kawili St, Hilo, HI 96720.

Introduction: Detection of 3 µm absorptions on the lunar surface by three spacecraft, Cassini, Chaandryaan-1, and Deep Impact, created a new paradigm for the presence of water on the surface of the Moon [1-3]. These observations established that a 3 µm absorption attributable to water or hydroxyl is present on the surface and has three characteristics; 1) the 3 µm absorption feature is present at high latitudes and away from the subsolar point at low latitudes; 2) it varies with lunar time of day; and 3) it varies in strength with local geology on the Moon.

The measurements of [1-3] were groundbreaking, but existing data have limitations in resolution and coverage. Ground-based spectroscopy however offers access to the entire earth facing hemisphere at 1-2 km resolution with full coverage of the 3 µm feature excepting a small window from 2.5-2.9 µm.

Using the SpeX infrared cross-dispersed spectrograph [4] at the NASA InfraRed Telescope Facility (IRTF) at Mauna Kea Observatory we obtained data from 1.5 to 4 µm of small targets on the lunar surface. Our goals were to: 1) verify that 3 µm absorptions could be detected using terrestrial observatories, 2) collect data similar to previous spacecraft observations to verify those measurements and validate our technique; and 3) derive estimates of water abundances independent of M3 measurements.

Data: On February 19, July 15 and November 9 and 10 2017, observations of the lunar surface were obtained. Data from February were collected along the equator with varying longitude and lunar time of day similar to the Deep Impact equatorial profile [5]. July data were acquired along the terminator with varying latitude in approximately 10 degree increments from the equator towards the north pole to seek latitude variations in water abundances. Lastly, data collected in November were of small geologic sites that show anomalous enhancements of water [6,7].

Methods: Data in this spectral region contain very significant thermal contamination that must be accounted for. Thermal corrections used the algorithm of [8] that explicitly includes the wavelength dependent effects of spectral emissivity via application of Kirchoff's Law. Data were converted to radiance from target/star ratios by application of appropriate photometric normalizations, and scaling to reflectance factor data from Kaguya Multiband Imager data [9].

Water/hydroxyl abundances were estimated using the methods of [10] assuming a grain size of 60 µm.

Results: A strong 3 µm absorption feature is observed both at high latitudes and in local geologic features. The strongest 3 µm bands have depths on the order of 10 percent or more, confirming that groundbased telescopic observations can detect lunar water at high spatial resolution.

In our latitude scan, with data obtained near the terminator to limit thermal contamination, water abundances were found to rise sharply and non-linearly with increasing latitude, with over 200 ppm detected in Goldschmidt crater at 75N.

In contrast, data collected along the equator from the terminator to the subsolar point only showed hints of water absorptions near the terminator and none at local times nearer noon.

The small geologic targets called out by [7,8] that we were able to observe all show strong water bands. At the pyroclastic sites, high water abundances are derived similar to those reported by [7].

Finally, while atmospheric compensation is preliminary, some of our spectra appear to have band minima near 3 µm, consistent with the presence of molecular water.

Conclusions: Our observations showed latitude and time of day systematics consistent with measurements by Cassini [3] and Deep Impact [2]. Observations of localized 3 µm anomalies identified using M3 data [7,8] confirmed the presence of a 3 µm band using our greater wavelength coverage, and in the case of the pyroclastic deposits, we derived similar water/hydroxyl abundances using entire independent observations and thermal corrections. Finally, our data may indicate the presence of molecular water at these very small locations, conclusions not available from existing spacecraft data.

HERACLES MISSION LANDING SITE CANDIDATES AND ITS SCIENCE WITH POSSIBLE RETURN SAMPLES DISCUSSED IN JAPANESE SCIENCE COMMUNITIES. Y. Karouji, M. Abe, J. Haruyama, M. Ohtake, Japan Aerospace Exploration Agency (JAXA) (karouji.yuzuru@jaxa.jp).

The space agencies of the international Space Exploration Coordination Group (ISECG) are discussing a next step of international partnership of International Space Station (ISS), and how they proceed post-ISS activities, which is proposed in the Global Exploration Roadmap (GER).

Japan Aerospace Exploration Agency (JAXA) is studying a Human-Enhanced Robotic Architecture and Capability for Lunar Exploration and Science (HERACLES) concept that is an international coordination program, which is described in the GER (see Fig.1) and led by European Space Agency (ESA). The objectives of the HERACLES study is to provide a concept of coordinated precursor architecture for future lunar missions, and set top-level technology requirements as a goal of a robotic precursor mission. Based on previous study, it is decided that the concept of HERACLES focuses on demonstrations of critical technology and risk mitigation for a future human lunar mission. HERACLES mission is going to demonstrate safe vehicle operations in cis-lunar space, in low orbit, during descent, landing, on the surface, during ascent, as well as on the surface in conditions closely representing a human surface mission. Among these architecture, a baseline concept of the HERACLES lander system is composed of a lander module, an ascent module, and a surface rover.

HERACLES mission aims a robotic sample return from the lunar surface. After placing a sample container with the collected sample in the ascent module, the ascent module carries the sample container to the Deep Space Gateway which is a concept for a crew-tended cis-lunar space station led by the ISS partners. Then, the sample container is planed to bring back to the Earth by astronaut using crew vehicle.

As an activity of the Science Working Group (SWG), which is one of the subgroups of the HERACLES study team, we are discussing mission objectives, landing areas, requirement for the sample (mass, chemical composition and so on), requirement for in-situ observational instruments etc.. As a reference mission, which is used for identifying required technology to achieve this type of mission, Schrödinger crater has been used as a landing area. From now on, we are planning to prioritise mission objectives suitable for this mission with landing sites suggesting that can contribute to the progress of the lunar science by discussing international lunar science community.

In this presentation, we present previous activities related to the HERACLES SWG and planned discussion within Japanese lunar science community of study in the HERACLES SWG.

![Fig. 1 A concept of HERACLES Mission](from GER3, 2018)
Introduction: Main differences with formed processes of the Apollo lunar minerals (including feldspar minerals of crust rocks) compared with Earth minerals are less answered completely by many scientists. Main purpose of the present paper is to elucidate comparative differences with formed processes (including volatile components) of terrestrial and extraterrestrial minerals [1-12].

Minerals and rocks defined on water planet Earth: Main differences with rocks between Earth and other planets (including the Moon and Asteroids) are existence of global water fluids only on Earth [2-3]. Therefore Earth’s mineral and rocks reveal larger crystals and wider geological layers. Earth’s shock-wave events of volcano, earthquake and asteroid impact are used to produce extreme condition with rapid high temperature and pressure abruptly, where quenched grain aggregates are formed through global systems separated to the water and atmospheric layers above the rock layers.

Rocky minerals formed on extraterrestrial condition: Main differences with rocks between Earth and other planets (including the Moon and Asteroids, called as Exo-Earth) are existence of global water fluids only on Earth [1, 4-6]. Therefore Exo-Earth’s minerals and rocks reveal small crystals and regional geological layers as follows:

The Exo-Earth’s shock-wave events of asteroid impact and volcano (near Equator) are used to produce quenched grain aggregates abruptly and locally, where there are no global ocean water system as follows:

Younger minerals on Earth’s circulation system: The latest and younger minerals are progressively formed among global air-water and rocky solid systems. This is mainly because global and successive separation to evaporated ions and molecules of gas and liquid phases from rocky surface are active and progressive changes among three state systems triggered by major geological activities, though first formation of water planet Earth is not such stable circulation, but very complicated and trapped water system through global impact event which is discussed on other paper in this meeting. This is main reason for younger and the latest minerals with larger crystalline minerals and wider rocks on water-Earth, which are used for Earth’s standard database [2-3]. If there is no global water and active air-water system on Exo-Earth (including the Moon and Mars), rocky minerals and surface outcrops show waterless-Earth type process with primordial rocky minerals [1, 4-6].

Accumulated information for Exo-Earth explorations: Rocky images (by camera and beam analyses) and surface outcrop information are significant descriptive data. However, fine and mixed data (with analyses) can be explained by regional melting and evaporation processes (mainly triggered by meteoroid impacts on rocky surface) [6-12]. Therefore, characteristic mineral aggregates and surface outcrops on Exo-Earth (including the Moon, Mars and Asteroids) are considered to be explained by non-global water system.

Regional fluid formation on Earth and Exo-Earth: Local formation at abrupt process at geological events (including volcano, earthquake and asteroid impact) can be observed on water Earth (including water-bearing and clay minerals) and on Exo-Earth (including short-time generation at meteoritic impact and volcanic eruption near Equator area) [2-3]. This suggest that regional fluid formation is not global-water system (on Exo-Earth) but local fluids within global air-water-rock system on planet Earth.

Application to the next human space exploration: The present result is applied to the next space exploration and landed habitable bases as follows [11-12]:

1) Ready-made fluid system (including shallow interior) cannot be found on any Exo-Earth’s surface, because there are no global and active circulation system on present surface based on the previous and present space exploration image data [11-12].

2) Local fluids (including mixed water, not pure water) can be formed on any Exo-Earth surface by using old fine rocks mixed with volatile [11].

3) Local storage of fluid water on landed surface can be planned and obtained used surface stones naturally, though pure water required for life activity should be used industrial compact design for next exploration largely [11].

Summary: The present study is summarized as follows:

1) Main differences with rocks between Earth and other planets (including the Moon and Asteroids) are existence of global water fluids to form large crystals and wide rock layers mainly on water planet Earth by separation of air-liquid and rocky solid systems with progressive activity (including volcano, earthquake and asteroid impact).

2) Extraterrestrial (called as Exo-Earth) minerals are formed without active global air-water systems evaporated and circulated systems to produce small crystals and abrupt layers as quenched grain aggregates abruptly and locally, where there are no active global ocean water system.

3) Characteristic mineral aggregates and surface outcrops on Exo-Earth (including the Moon, Mars and Asteroids) are considered to be explained by non-global system (including water system).

4) The present mineral differences can be applied to fluid-water formation on the next space exploration and landed habitable bases.

New Views of the Moon 2 – Asia 2018 (LPI Contrib. No. 2070)

NEW VIEWS OF THE MOON’S SPIN. J. T. Keane1, B. C. Johnson2, I. Matsuyama3 and M. A. Siegler4,5; 1California Institute of Technology, Pasadena, CA 91125, USA (jkeane@caltech.edu); 2Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912, USA; 3Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA; 4Planetary Science Institute, Tucson, AZ 85719, USA; 5Southern Methodist University, Dallas, TX 75275, USA.

Today, the Moon rotates placidly—tidally locked to the Earth, with a small obliquity (and other relevant angles and variations thereof) set by the balance between tides from the Earth and Sun. However, the Moon’s rotation has not always been so simple; the young Moon experienced large scale variations in its spin. Tidal and orbital evolution resulted in episodes of potentially very large (~90°) obliquities [1]. Impacts knocked the Moon off of its axes, causing it to tumble [2]. Asymmetric thermal evolution of the interior resulted in the slow gradual reorientation of the Moon [3]. Our previous New Views of the Moon abstract [4] summarized these slower reorientation processes. In this work, we will new results regarding some of its more dramatic episodes of rotational motion in the aftermath of large impacts. These perturbations of the Moon’s spin with time have had a variety of important consequences for the geology of the Moon, including unlocking it from synchronous spin [5], stirring up the core dynamo [6], and altering the stability of water and other volatiles in permanently shadowed regions near the Moon’s poles [3].

Impacts perturb the spin of the Moon in several ways. Most previous studies only considered the effect of the torque imparted from impactor. Torques from larger impacts can unlock the Moon from synchronous spin [2, 5]. However, most previous studies have neglected, or greatly simplified, how the Moon’s moments of inertia change after an impact basin forms [2, 5, 7-8]. Our understanding of the impact basin formation process has dramatically improved in the past decade thanks to new geophysical measurements from NASA’s GRAIL and LRO missions [9], and new numerical simulations of the impact process [10]. Here, we leverage these recent advances and reexamine the rotational dynamics of the Moon in the aftermath of large impacts.

To investigate the rotational dynamics of the Moon after impact, we couple state-of-the-art iSALE hydrocode simulations [11-13] with classical rotational dynamics to evaluate how the Moon’s spin evolves after impact. This unique combination of techniques enables us to accurately track the spin of the Moon in the aftermath of large impacts. We find that basins significantly perturbed the moment of inertia of the Moon. In the case of the South Pole-Aitken basin, the basin’s moment of inertia perturbations far exceeded the dynamical oblateness of the present-day Moon. All large impact basins induce a period of non-principal axis rotation (“tumbling”), and in some cases, the redistribution of mass unlocks the Moon. Fig. 1 shows examples of how the spin of the Moon evolved in the aftermath of the Orientale and South Pole-Aitken impacts.

In the coming decade, we anticipate it will be possible to construct the first comprehensive chronology of lunar spin dynamics. Furthermore, while our work focuses on the Moon, the dynamical processes explored here are completely general, and applicable to a variety of solar system worlds. Once again, the Moon can be our cornerstone to understanding the dynamics of other planetary bodies.

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Fig. 1. Dynamics of the Moon in the aftermath of impacts

Introduction: Images returned by the Kaguya and Lunar Reconnaissance Orbiter missions revealed deep pits exposing tens of meters of layered stratigraphy in their walls [1-3]. Moon Diver (Fig. 1), a Discovery class mission to a mare pit, would address numerous top-priority lunar science goals laid out in community reviews [4], the Decadal Survey [5], and the Lunar Exploration Roadmap [6] by examining: (1) intact lava layers in the context in which they were emplaced, (2) the regolith-bedrock interface, and (3) possible ancient paleoregolith layers preserved between lava flows. Payload capability would include: morphologic measurements and layer thicknesses (provided by a camera system), mineralogy (provided by a reflectance spectrometer), texture (provided by a microimager), and elemental chemistry (provided by an X-ray spectrometer).

Figure 1. A representation of the Axel rover rappelling into a lunar pit as part of the Moon Diver mission. This mission’s exploration of mare pits with potential subsurface void spaces would address numerous top-priority lunar science goals.

In some cases, lunar mare pits may open into subsurface void spaces or lava tubes [1-3]. Human settlements located in lava tubes would benefit from a stable, benign temperature, and would be protected from cosmic rays and micrometeorites.

For these reasons, lunar pits provide an exciting new target for lunar exploration. Before now, the desire to send a mission to these targets was tempered by the difficulty of reaching them given limitations of the vertical mobility of traditional rovers. The Axel Extreme Terrain Rover [7], developed by the Jet Propulsion Laboratory in collaboration with Caltech, has the mobility necessary to approach and rappel into this type of pit, revolutionizing our capability to access and explore in-place stratigraphy on the Moon.

The Axel Rover: The Axel rover consists of two wheels connected by a thick axle containing a winch and a tether [7]. Scientific instruments are housed inside eight deployable bays housed in the wheel wells (Fig. 2), which rotate independently of the wheel.

Figure 2. The Axel rover taking spectroscopic measurements on a slope of 40º (figure from [14]).

Axel communicates through its cable, alleviating common communication problems facing other cave exploring robots. The rover can also receive power through its tether, meaning that it can use a solar panel on the surface to power its exploration in the dark cave below [7]. Once at the bottom of the pit, the rover could continue to explore up to the length of its tether (currently 250-300 m, potentially up to 1 km [7]).

References:

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INTEGRATING EXISTING DATA TO UNDERSTAND THE NATURE OF THE LUNAR MANTLE. Rachel L. Klima1, Jordan M. Bretzfelder1,2, Benjamin T. Greenhagen1, Debra L. Buczkowski1, Carolyn M. Ernst1, and Noah E. Petro1. 1Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA., 2University of Southern California, Los Angeles, CA 90007, USA., 3NASA/Goddard Space Flight Center, Greenbelt, MD, USA.

Introduction: Lunar missions in the last decade and the advancement of sample analysis techniques have resulted in a wealth of new information about the lunar surface. Integration of data across different sub-disciplines is critical for addressing the outstanding science and exploration questions and identifying, as a community, what missions or advances would conclusively answer such questions. Recent studies [e.g., 1, 2], have shown the strength of integrating different remote sensing data sets with one another, or with sample studies. We here focus on a joint analysis using data from the Moon Mineralogy Mapper and the Diviner Lunar Radiometer.

Searching for Lunar Mantle: The Moon has experienced over a dozen impacts resulting in basins large enough to have excavated mantle material. With many of those basins concentrated on the lunar near side, and extensive regolith mixing since the lunar magma ocean crystallized, one might expect that some mantle material would have been found among the lunar samples on Earth. However, so far, only a small number of candidate mantle samples [e.g. 3] have been identified, and their provenance is still debatable [4].

From orbit, a number of olivine-bearing localities, potentially sourced from the mantle, have been identified around impact basins [5]. Based on analysis of near-infrared (NIR) and imaging data, Ohtake et al. [6] suggest that roughly 60% of these sites represent olivine from the mantle. If this is the case and the blocks are coherent and not extensively mixed into the regolith, these deposits should be ultramafic, containing olivine and/or pyroxenes and little to no plagioclase. In the mid-infrared, they would thus exhibit Christiansen features (CF) at wavelengths in excess of ~8.5 µm, which has not been observed in global studies using Diviner [7].

We are in conducting an integrated study of the massifs surrounding the Imbrium basin, which, at over 1000 km wide, is large enough to have penetrated through the lunar crust and into the mantle. These massifs are clearly associated with the Imbrium basin-forming impact, but existing geological maps do not distinguish between whether they are likely ejecta or rather uplifted from beneath the surface during crustal rebound [8]. We examine these massifs using visible, NIR and Mid-IR data to determine the relationships between and the bulk mineralogy of local lithologies. NIR data suggest that the massifs contain exposures of four dominant minerals: olivine, Mg-rich orthopyroxene, a second low-Ca pyroxene, and anorthite. Mid-IR results suggest that in the Montes Alpes region, the Mg-rich mafic material is present with substantial amounts of plagioclase. However, in the southeastern portion of Mare Imbrium, near Wolff Mons, the higher (~8.15 µm) CF values of these exposures suggest that these are more likely candidates for pyroxenite or very pyroxene-rich norite [9].

Fig. 1. Diviner sites analyzed around Mare Imbrium. Low CF values (cool colors), consistent with anorthosite-dominated lithologies, while higher CF values (warm colors) are found among the mare deposits and in some of the massifs.

Implications and Recommendations: For the specific example of our search for candidate mantle material on the lunar surface, integrated analyses suggest that perhaps the upper mantle is dominated by orthopyroxene instead of olivine. Analyses of these and other data sets will continue around Imbrium and other basins. Multidisciplinary investigations using the wealth of recent lunar data have the potential to test and revise numerous hypotheses to zero in on those that are in most critical need of a future lunar mission.


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Mare Orientale: widely accepted large impact or a regular tectonic depression?
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The Mare Orientale – one of the principal features on the lunar surface origin of which was almost never put in doubt. Many publications are devoted to the impact origin of this large multy-ring circular object. Nevertheless, a simple tectonic analysis of the lunar surface shows that this giant ring belongs to the regular structural net of the satellite joining two its hemispheres-segments. Let us consider two structural positions where the Mare Orientale acts as a principal tectonic element of endogenous origin, not a random impact.

Two tectonic lunar and terrestrial triads are analogous nevertheless drastically different masses of respective cosmic bodies. They determine their global wave tectonics and are as follows: Pacific Ocean – Malay Archipelago – Indian Ocean and Procellarum Basin – Mare Orientale – SPA basin. In the wave sense they are $2\pi R - \pi R/2 - \pi R$ structures, where $R$ is the bodies’ radius [1].

Two lunar tectonic lines in both hemispheres (Fig. 4) are very impressive They are a sequence of Marea: Moscoviense – Freundlich-Sharonov – Dirichlet-Jackson – Hertzsprung – Orientale in the far side and Imbrium – Serenitatis – Crisium – Smythii in the near side. The second line is characterized by sharply outlined mascones due to uplifted mantle masses. The lunar lay-out reflects a position of the ancient axis of rotation that was inclined about 30 degrees from the present one [2]. The same is evident comparing the above tectonic triads. Two tectonic triads of two very different by masses cosmic bodies are remarkable also by their very different by ages basalt infillings. The lunar basalts are mainly 4.5-3 billion y. old, the terrestrial oceanic basalts are MZ-Cz in age. The mantle source of basalt melts requires its melting. It happened much earlier in the Moon than in Earth. The ages are in proportion to their masses according to the first Newton’s law. The heating and melting require a heat source that is most probably transition of the orbital energy of movement to the heat [2].


Fig. 1. Earth. Tectonic triad: Pacific Ocean (2$\pi R$ structure) – Malay Archipelago ($\pi R/4$-structure) – India Ocean ($\pi R$-structure).
Fig. 2. Moon. Tectonic triad: Procellarum Basin (2$\pi R$) - Mare Orientale ($\pi R/4$) – SPA (South Pole-Aitken) Basin ($\pi R$).
Fig. 3. Schematic presentation of both (terrestrial, Fig. 1; lunar, Fig. 2) triads.
Fig. 4. Gravity map of the Moon (Japan) and tectonic lines (black).
STUDIES BASED ON LUNAR GLOBAL SUBSURFACE RADAR SOUNDING DATA OBTAINED BY SELENE (KAGUYA). A. Kumamoto1, Y. Yamaguchi2, A. Yamaishi3, S. Oshigami1, K. Ishiyama2, N. Nakamura1, J. Haruyama5, H. Miyamoto6, T. Nishibori3, F. Tsuichiya1, and M. Ohtake3.1Tohoku University, Aoba, Aramaki, Aoba, Sendai 980-8578, Japan. (kumamoto@stpp.gp.tohoku.ac.jp), 2Nagoya University, Nagoya, Japan, 3Kyoto University, Kyoto, Japan, 4National Astronomical Observatory of Japan, Mitaka, Japan, 5Japan Aerospace Exploration Agency, Sagamihara and Tsukuba, Japan, 6University of Tokyo, Tokyo, 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. In the operation period from October 29, 2007 to 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 buried 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 units 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. Ishiyama (2016) [3] investigated the inclinations of the subsurface reflectors in the Mare Imbrium, and discussed the evolution of the lithosphere in it.

Volcanic activity in the maria: Based on the depth of the buried regolith layers, Oshigami et al. (2014) [4] 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. 5]. 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: Pomerol et al. (2010) [6] 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) [7] 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) [8] 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.

Lava tubes: Kaku et al. (2017) [9] identified lava tubes below the surface around Marius Hills Hall (MHH) by finding characteristic echo patterns in LRS data. The locations of identified lava tubes were consistent with those of mass deficits reported by GRAIL, and also suggested that the extension from rille to underlying lava tube.

Comparison with GPR data: After the SELENE mission, subsurface radar sounding from the lunar surface was also performed by Lunar Penetrating Radar (LPR) onboard Yutu Rover in the Chang’E-3 mission [10]. The data from orbiter’s radar and rover’s radar can be complementary: Orbiter’s radar can detect deeper reflectors in wide area but with low resolution. Rover’s radar can measure the shallow subsurface structures in limited area with high resolution. In the comparison between SELENE/LRS and CE-3/LPR data, we found some difference in detectability of echoes from multiple layers and single layer. Such comparison and complementary analyses will be useful in planning GPR observation in future missions.

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 JAXA/DARTS SELENE Data Archive (http://darts.isas.jaxa.jp/planet/pdap/selene/), which will be useful for researchers to apply them to wider Lunar sciences.

CORE SUPERCOOLING AND HIGH MAGNETIC FIELD ON THE EARLY MOON. M. Laneuville1 and D. Cébron2, 1Earth-Life Science Institute, Tokyo Institute of Technology, Japan (mlaneuville@elsi.jp), 2CNRS, ISTerre, Université Grenoble Alpes, France.

Introduction: Recent analyses of lunar samples have helped constrain the history of the magnetic field. The existence of a long lasting dynamo is well established between 4.2 [1] and 3.56 Ga ago [2]. A new study presents an even younger magnetized sample ~1-2.5 Ga ago [3]. Paleointensity estimates suggest an early high field epoch for several 100 million years, with magnetic fields up to 100 μT (i.e., similar or larger than on present day Earth), followed by a low field epoch of several billion years and fields on the order of 1 μT or less [4].

While several processes have been studied to explain the duration and amplitude of the low field era [4], how to generate the high amplitude fields remain uncertain. In this contribution, we investigate the influence of inner core nucleation and subsequent growth. We use arguments from metallurgy developed by Huguet et al. [5] to investigate the effect of supercooling: onset of nucleation does not occur when the temperature reaches the liquidus, but after an additional supercooling of several 10 K.

Supercooling: When the inner core nucleates as the core reaches the melting temperature, an implicit assumption is that there is no nucleation energy barrier to form the first stable crystal. In practice, the first crystal forms when the volume free energy balances the interfacial free energy cost. This happens at a given ΔT/Tm, which is about 20% for pure iron [6] (and up to 30% using molecular dynamics calculations [7]).

The lunar core is not pure iron, so more work needs to be done to constrain ΔT/Tm but the concept of supercooling itself is robust. Even if the level of purity of the lunar core seems important, at slow enough cooling rate any ‘dirty’ water can be supercooled by as much as 5 K [8]. We propose a proof of concept for the implications on nucleation and subsequent evolution of supercooling of about 10 K, as suggested by [5].

Inner core nucleation and growth: To test the effect of supercooling, we use an energy balance in the outer core between latent heat generated at the crystallization front, heat conducted in the inner core and the core-mantle boundary heat flux. We assume that the transport timescale in the liquid outer core is short and that the core-mantle boundary heat flow is constant for the duration of the model (~100 million years). The melting curve is that of an Fe-S alloy [9] and the adiabat is parameterized using the scale height defined in [10]. We then integrate forward in time for each set of model parameters and compute the power released at the ICB available to drive the dynamo.

Preliminary results: The degree of supercooling required to start nucleation is still poorly constrained and therefore test a range of values. Figure 1 shows inner core growth for those scenarios. A key result is that when considering supercooling, growth is several orders of magnitude faster than without (~104 vs ~108 years). A direct consequence is a several orders of magnitude increase in power available to drive the dynamo (same energy released, but over a much shorter time period). The magnitude of the magnetic field depends on dissipation with the power 1/3, therefore we expect a factor 20 to 400 increase compared to usual predictions (i.e., a surface field ~10-100 μT, comparable to the observations).

Discussion and conclusion. We recognize that the concept of supercooling for planetary cores is still in its infancy, but we show that if it does play a role, the surface magnetic field generated during that period would be much larger than usually expected. Once the power source is no longer strong enough, the field decays on the ohmic timescale (1/3rd per ~104 years), therefore the high field can only be maintained for a short time compared to the observed 100 million years.

LRO LAMP PHOTOMETRIC CORRECTIONS AND FAR-UV INVESTIGATIONS OF NEW IMPACT CRATERS, COLD SPOTS, AND SPACE WEATHERING ON THE MOON. Y. Liu1, K. D. Retherford2,3, T. K. Greathouse4, K. E. Mandi5, J. T. S. Cahill6, A. R. Hendrix2, U. Raut2, C. Grava2, D. M. Hurley7, B. Byron1,2, L. O. Magaña1,2, A. F. Egan5, D. E. Kaufmann5, M. W. Davis5, G. R. Gladstone2,3, W. R. Pryor7; 1Lunar and Planetary Institute, Houston, TX, USA (liu@lpi.usra.edu), 2Southwest Research Institute, San Antonio, TX, USA, 3University of Texas at San Antonio, San Antonio, TX, USA, 4Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, 5Planetary Sciences Institute, Tucson, AZ, USA, 6Southwest Research Institute, Boulder, CO, USA, 7Central Arizona University, Coolidge, AZ, USA.

Introduction: The Lunar Reconnaissance Orbiter (LRO) Lyman Alpha Mapping Project (LAMP) provides global coverage of both nightside and dayside of the Moon in the far ultraviolet (FUV) wavelengths between 57 and 196 nm [1]. The innovative nightside observations use roughly uniform diffuse illumination sources from interplanetary medium Lyman-α sky glow and UV-bright stars. The dayside observations use the more traditional photometry technique with the Sun as the illumination source which are very complementary.

Global albedo maps are produced at Lyman-α, on-band and off-band, which are used to constrain the abundance of water frost based on the strength of the on and off the water frost absorption edge at ~165 nm [1]. The nightside FUV albedo measurements over a few PSRs in south pole indicate 1-2% water frost abundances [2]. The dayside data reveals a distinct diurnal variations in hydration level across the surface of the Moon [3]. The spectral images cubes with 2 nm resolution are created to characterize lunar swirls for several regions of interests by the reddened FUV spectra of immature materials [4].

In this work, we introduce photometric corrections for LAMP dayside observations. We investigate the spectral properties of a few new impact craters detected by LROC and several cold spots identified by DIVINER, using LAMP FUV data. We also discuss the enhanced Lyman-α albedo at crater equator-facing slopes that are possibly consistent with enhanced space weathering due to high solar wind flux.

Photometric Corrections: LAMP dayside observations use sunlight as the illumination source where bidirectional reflectance is measured. The bidirectional reflectance is dependent both upon the observation geometry and the soil properties. To compare the same area covered from multiple observations with different viewing geometries, photometric corrections are needed to normalize the reflectance as if it is measured in the same observation geometry. In this work, we use a simplified Hapke’s bidirectional reflectance distribution function (BRDF) to simulate LAMP’s reflectance [5]. By modeling the lunar phase curve (i.e., reflectance as a function of phase angles) at FUV wavelengths, we retrieve the wavelength-dependent Hapke parameters by using the Levenberg-Marquardt regression analysis algorithm. The retrieved Hapke parameters are then used for photometric corrections of LAMP data using the Hapke BRDF model.

FUV Investigations of New Impact Craters, Cold Spots, and Space Weathering: The FUV reflectance spectra are sensitive to maturity of the lunar regolith, therefore allowing us to investigate space weathering effects on the Moon. For example, LAMP nightside Lyman-α albedo is relatively low for less space weathered regions and has been used to survey lunar swirls [6]. The dayside spectra show redder slopes for the less space weathered areas [4]. Numerous new craters have been detected by LROC camera [7]. These new impact events excavate materials from the subsurface of the Moon, and these materials are potentially immature and should have very different spectral characteristics (i.e., redder slopes) in FUV wavelengths from the regolith present before the impacts occurred. A class of anomalous cold surfaces (termed “cold spots”) has been identified by Diviner radiometer [8]. These “cold spots” are mostly associated with fresh craters with unique ejecta morphology and possibly have different spectral characteristic in FUV wavelengths as compared to their surroundings. Also, numerous craters are observed with Lyman-α albedos distinctly enhanced along their crater rims, which is consistent with the enhanced space weathering there as first identified using Apollo 17 UVS measurements [9]. For craters observed at high latitudes these Lyman-α albedos are distinctly enhanced along their equator facing walls, in agreement with relatively higher rates of solar wind incident on these regions.

Here we report the initial results of FUV investigations of new impact craters, cold spots, and space weathering along crater rims and walls with the photometrically corrected LAMP data.

MULTISPECTRAL POLARIZATION MEASUREMENTS OF EIGHT LUNAR SOILS. P. G. Lucey1, C.I. Honniball1,2, R. Brennan2, L. Burkhard2, E.S. Costello1,2, M. Sandford1,2, L. Sun1,2, 1Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, HI, USA, lucey@higp.hawaii.edu; 2Dept. of Geology and Geophysics, University of Hawaii, Honolulu, HI, USA; 3Dept. of Chemistry, University of Hawaii, Honolulu, HI, USA

Introduction: Polarization is a fundamental property of light that can provide new insight into the surfaces of planetary objects. Separation of polarized components can shed light on the properties of grain surfaces, now known to be a critical aspect of space weathering, and the interior of grains that may contain more fundamental compositional information. Shkuratov and co-workers [1-4] have shown in a series of papers the unique contribution of polarization to lunar studies using laboratory measurements of lunar samples, lunar analog materials and telescopic observations of the Moon. Recently, Jeong et al. [4] reported extensive multispectral polarization telescopic observations, deriving hemispheric grain size distribution maps and drawing conclusions regarding the differential effects of space weathering on the mare and highlands.

The Korean Pathfinder Lunar Orbiter, a lunar satellite in development by the Korean Aerospace Research Institute, will carry POLCAM, a multispectral imaging polarimeter to lunar polar orbit that will provide unprecedented global and high resolution polarimetry measurements.

These advances led us to conduct imaging polarization measurements of a series of lunar soils for which we have extensive chemical and mineralogical analysis. The eight samples cover the entire range of lunar iron and titanium contents, and for each composition we include a very mature and a very immature sample. Our measurements were collected at a phase angle of 90 degrees, near the largest excursion of linear polarization. At this angle the differences between surface scattering and internal scattering enhanced by polarization is at its maximum[4].

Methods: We constructed an imaging polarimeter to collect data in three wavelengths, 430, 656, and 750 nm, near wavelengths used by POLCAM or Shkuratov et al. [4]. The instrument consists of an unpolarized illuminator, a sample stage, a continuously adjustable linear polarizer, a filter wheel, reimaging optics, and a CCD camera. Data were normalized to a Spectralon target. The Spectralon reference shows weak polarization in raw data, so we removed this effect from the final polarized reflectance data.

Results: For each soil and wavelength, data were collected at ten polarization angles. These data were then fit with a cosine to ensure the maximum and minimum polarizations were captured. Data were then reduced to percent polarization by the ratio of the difference between the maximum and minimum reflectance, to the sum of the maximum and minimum reflectance. The average polarization for the soils ranges from a low of 1.2% in the immature highland soil 67711 at 760 nm to 25.6 percent for the mature high titanium basaltic soil 10084 at 430 nm.

Polarization was measured on a pixel by pixel basis, specular reflectance glints of grain surfaces are common, and are highly polarized; the remainder of the soil shows polarization near the average will little variation.

Discussion: A fundamental property of particulate materials in general and the Moon in particular is an inverse correlation of polarization and albedo, known as Umov’s Law [6]. Our data do show such a correlation, but it is not entirely linear. Given that the highest albedo soils are immature, some deviation is to be expected as surface coatings evolve with space weathering. Space weathering effects are also discernable in spectral data. We observed spectral differences with maturity and polarization angle. The angle of polarization perpendicular to the plane of the source, sample and observed is most sensitive to specular, surface reflection, and 3-point spectra of the sample at this angle are somewhat redder than the parallel angle that emphasizes internal scattering, consistent with strong surface-correlated space weathering effects.

PROSPECTS FOR NEAR ULTRAVIOLET ASTRONOMICAL OBSERVATIONS FROM THE LUNAR SURFACE- LUCI. Joice Mathew¹, Binu Kumar², Mayuresh Sarpotdar³, Ambily Suresh¹, Nirmal K¹, A.G Sreejith⁴, Margarita Safonova⁴, Jayant Murthy³ and Noah Brosch⁴. ¹Indian Institute of Astrophysics, Bangalore, India (joice@iiap.res.in). ²Space Research Institute, Austrian Academy of Sciences, Schmiedlstrasse 6, Graz, Austria. ³M. P. Birla Institute of Fundamental Research, Bangalore, India. ⁴The Wise Observatory and the Dept. Of Physics and Astronomy, Tel Aviv University, Israel.

Introduction: Observations from the Moon provide a unique opportunity to observe the sky from a stable platform far above the Earth atmosphere [1, 2]. This is especially relevant in the ultraviolet (UV) field. Hence we have explored the prospects for UV observations from the lunar surface, mainly the feasibility, scientific outcomes and possible configuration of UV telescopes [3]. To realize this, we have been in collaboration with TeamIndus, Axiom Research Labs, (an aerospace startup), to put a UV telescope (LUCI-Lunar Ultraviolet Cosmic Imager) on the Moon as a piggyback payload. LUCI is an all-spherical near UV (pass-band: 200-320 nm) telescope with a field of view of 0.46° x 0.34° [4].

Figure. 1. LUCI on the TeamIndus lunar lander

LUCI will be mounted on the lunar lander (Fig. 1) as a transit telescope and will perform the survey of the available sky from the surface of the Moon. Here we will present the design and development of the instrument. We will also briefly explain the assembly, integration, and calibration of LUCI.

Science Objectives: A UV/optical transit telescope that uses the slow lunar sidereal rate was by Nein and Hilchey [5]. It was suggested that a large 20-m liquid mirror telescope [6] with UV imaging capability has the potential to surpass the sensitivity of HST and even JWST by orders of magnitude. The primary science goal of LUCI is the detection of transients such as, for example, Tidal Disruption Events (TDEs), or SNe in distant galaxies as a probe for cosmological distant scale. As we perform survey of the sky, we will also pick up other transients such as near-Earth asteroids, as well as produce an NUV catalog of the sky.

Instrument Overview: The instrument is an all-spherical UV telescope, with a weight of 1.2 kg. It will be used to study the variability and environment of bright UV sources by acquiring photometric timeseries in the 200–320 nm wavelength range. The events will be processed and stored on-board, and send back to Earth whenever the radio link is available. The fully assembled payload in class 1000 room is shown in Fig. 2.

Observation Strategy: LUCI will be mounted as a transit telescope, where it will look at zenith to scan the sky in the NUV domain. The apparent motion of the celestial objects will allow the telescope scan a portion of the sky, and the observation will continue until the object moves out of the available sky region of the telescope. The required power for the detector will be provided by the lander, where solar panels are the primary source of electrical energy during the lunar day surface operations, therefore LUCI will only operate in the daytime.

**Introduction:** Despite all of the new data generated on endogenous lunar volatiles since the publication of New Views of the Moon, many important questions remain unanswered or only partially resolved. This abstract looks to the future and discusses several of those important remaining questions on the topic of endogenous lunar volatiles.

**Volatile-bearing minerals on the Moon:** Many of the volatile-bearing minerals (exclusive of apatite) that have been reported in lunar rocks remain “unverified” (e.g., amphibole) and a recent effort to reexamine some of these samples with modern techniques could yield additional important mineral systems through which one can utilize in order to understand lunar volatiles. A substantial effort has been put forth to investigate apatite, but that wealth would be greatly enhanced by information about volatile abundances and isotopic compositions of coexisting amphiboles or biotite, which could potentially move the field forward much further than with apatite alone. Samples from evolved crustal terranes that have been identified by orbital data (e.g., Compton-Belkovich) would be ideal places to look for additional volatile-bearing mineral phases in lunar samples.

The abundance and distribution of magmatic volatiles in the mantle, crust, and bulk silicate Moon: Estimates of the abundances of H$_2$O, F, and Cl in the lunar mantle, crust, and bulk Moon vary substantially depending on the samples used [1], which either indicates a highly heterogeneous distribution of volatiles in the lunar interior, or it represents an incomplete understanding of the origin and petrogenesis of the various lunar rock types. Consequently, these observations highlight the importance of using a diverse set of samples to try and estimate the volatile abundances of the lunar mantle, but it also highlights the importance of investigating the petrogenetic history of each sample beyond the information obtained directly for the magmatic volatiles. We advocate continued research on volatiles in lunar samples for which little work has been reported, including high-Ti basalts, high-Al basalts, and Luna samples. Additionally, any samples collected outside the PKT will be very important for determining whether there are differences in the volatile abundances between rocks within and outside the PKT.

**Development of accurate lunar hygrometers:** The estimates of the volatile abundances of urKREEP, the lunar mantle, and bulk silicate Moon (BSM) could be further refined with future experimental efforts that constrain the mineralogy and mineral composition of the entire LMO using appropriate BSM starting compositions as well as experimental work on mineral-melt partitioning of H$_2$O, F, and Cl between LMO minerals (olivine, pyroxene, Fe-Ti oxides, and anorthitic plagioclase) and silicate melt under reducing conditions relevant to lunar magmatism.

**Origin of δD variations in lunar rocks and minerals:** It is still unclear whether or not the isotopic variations in H observed in lunar samples are being driven by fractionation processes, mixing of various reservoirs, or both. H isotopes were likely affected by secondary processes and mixing of multiple reservoirs, which preclude straightforward interpretations of the existing data. From the plethora of data on lunar soils, it is clear that there is a very light (~ -1000 ‰) reservoir of solar wind and a fairly heavy reservoir of spallogenic D at the lunar surface, and nearly all data lay between these two extremes and may represent primary lunar H, H that was delivered late, or mixtures of the two extremes [1].

UNIQUE MOON FORMATION MODEL: TWO IMPACTS OF EARTH AND AFTER MOON’S BIRTH.
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Introduction: The models of the Moon formation reported by many scientists previously are based on descriptive models mainly based on obvious evidences for scientists from many academic fields theoretically and academically. The present model of the Moon formation and development is applied new aspects of Earth and the Moon from impact-related processes as the main purpose in this paper [1-10].

Problem of previous astronomical views: The previous model from astronomical viewpoint which is used to the relative relations of the Moon and Earth by using well-known astronomical units of the Moon and Earth is based on main units of astronomical body as minimum unit [1]. This is easily understood the relation of two bodies as unchanged units. The problem of its stable-like unit method is shown as outline aspects but difficult to show the detailed process including impacted materials of rock and mineral remained on the present Moon. In other words, the astronomical understanding is postulated as fundamental units (especially numbers 0 to 9 etc.) in stable-like units (even in macro- to micro-scales) during the any change process, which cannot be applied to materials changes from solid, liquid to vapor (as discarded units due to its disappeared processes).

Problem of relation of old Moon and young Earth: Previous scientists have reported formation stages of the old Moon and active Earth (continuous change from old to young age) by radioactive aging methods precisely, which are explained as relative relation of the Moon by stable astronomical viewpoints [1]. The problem of its stable aging relation method is shown as astronomical aspects which are explanation on stable rock data remained now. The aging data are obtained by this method, but material changes of three states are difficult to show the detailed process including the impacted materials of rock and mineral remained (and discarded liquid and vapor data). This consideration of aging data make the following relation in the present model:

1) The Moon as satellite position is located astronomically next to active planet Earth with younger rocks and continuously changed rocks. This suggests in this study that the Moon might be close relation with the planet Earth’s formation which is not normal, but special situation (including formation of water-planet Earth finally) of the Moon formation in the Solar System. This is additional condition to form water-planet (with life system) next to present Moon.

2) The present Moon is not normal satellite for planet in the Solar System relatively. Dark and impacted rocks on the Moon suggests the possible mixtures of old ejected blocks from active Earth and old Moon’s surface impacts [1,6].

Problems of materials evidences of two major impacts: Possible materials evidences of two major impacts are difficult to be obtained previous studies. The present model includes new aspects of differences in two major impacts events of the first on Earth and the later on Moon as follows:

1) Impact glass with various voids-bearing texture is considered to be evidences of impact melting and quenching during air-planet Earth because of global system required to be formed. In fact, fusion-crust of glassy melting-and-quenching glassy layers of fallen meteorites can be found on air-planet Earth, which are remnants of some of active planet Earth, but similar bubble- and voids -rich textures have been reported on the Apollo lunar regolith and agglutinates [1,11].

2) Water-planet Earth produces ocean-plates with crust layers (including enriched elements of silica and feldspar mineral compositions and heavy elements of Fe and Ni etc.) as evolved final products on Earth’s crust, can be reported on the Moon’s brecciated rocks (as mixture of the Earth).[1,9].

Mixture model of the Moon’s impacted rocks: The present model can be applied mixture processes as follows:

1) First source of the impacted mixture is considered to be originated from planet Earth (by major planetary impact followed by smaller impacts). This rejected glassy blocks are formed passing atmospheric system (to be formed quenched glass with bubbles) to be remained around the Earth planets which are concentrated to the Moon with various blocks with voids-rich interior [1]. The bubble-rich blocks on the Moon might be triggered by cave-existing interior in the shallow interior discovered recently on the Moon (and Mars?).

2) Second source of the impacted mixture is considered to be originated from the Moon after birth (by major satellite smaller ad slower impacts around Earth’s orbit). This rejected impacted glasses on the Moon (called as agglutinates) are obtained various impacts craters on the Moon. Airless Moon might be formed less voids or bubble glassy breccias (on airless Moon surface) [1-11].

Summary: Present study can be summarized as follows:

1) Previous Moon-formation models are summarized as various analytical data with astronomical unit- viewpoints, which are difficult relatively to be changed body and material changed model precisely.

2) The Moon rocks are mixed with two impact-processes of Earth’s impact breccias and airless Moon’s impact breccias.

3) The present impact mixture are considered to be proved void-rich glassy texture, crust-rich elemental mixtures, from air-fluid-bearing Earth and airless Moon relatively.

4) The present model might be explained cave-rich interior on the airless-and waterless Moon

Acknowledgements: Author thanks for many scientists to discuss present model from the first preparation model.

GEOCHEMICAL AND PETROLOGICAL INVESTIGATIONS OF LUNAR METEORITES TELL US NEW INSIGHTS OF LUNAR CLUST. H. Nagaoaka1, Y. Karouji2, N. Hasebe1,3, Makiko Ohtake1, 1Research Institute of Science and Engineering, Waseda University, Shinjuku, Tokyo 169-8555, Japan (hiroshi-nagaoaka@asagi.waseda.jp), 2Space Exploration Innovation Hub Center, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa 252-5210, Japan, 3Schools of Advanced Science and Engineering, Waseda University, Shinjuku, Tokyo 169-8555, Japan, 4Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa 252-5210, Japan

Introduction: The geochemical and petrological investigations of pristine anorthosite samples returned by the Apollo missions, told global Lunar Magma Ocean (LMO) model to form the massive anorthosite crust. The early lunar crust formed by the crystallization by flotation of plagioclase from evolved magma with Fe-rich compositions e.g., [1,2], which was assumed to consist of f erroan anorthosite (FAN) with Mg#40-70 (= molar 100 × Mg/(Mg+Fe)) e.g., [3]. The Apollo samples were recovered from several regions around geochemically anomalous region restricted in the central nearside, which locate within or around the Procellarum KREEP Terrane [4]. On the other hands, the Mg# (>70) of bulk compositions and mafic minerals in feldspathic lunar meteorites are partly higher than those in FAN e.g., [5,6]. The differences imply that feldspathic lunar meteorites originate from different regions from the Apollo landing sites, which could include the farside of the Moon.

Our recent knowledge and understanding of formation processes and geological features of global lunar crust have been promoted by global remote sensing data and lunar meteorite studies. They have provided global information of lunar crust lithology. Compositional dichotomous distributions of Mg# [7] and Th abundances [8] observed by the first large-scaled lunar orbiting explorer, Kaguya (SELENological and ENgineering Explorer, SELENE), indicate that the central farside highland has more primitive aspects because of the highest Mg# and lowest Th abundance. Kaguya observation also reported the presence of rocks (Purest Anorthosite, PAN) with high plagioclase abundances (>98% plagioclase) at some large craters by reflectance spectroscopy. Kaguya observation has provided new insight of lunar crustal lithologies because of the improved observational precision of each science instrument.

Feldspathic lunar meteorites with low incompatible element abundance originate from the highland crust, which are all brecciated by impacts on the lunar surface e.g., [9]. And these brecciated anorthosites are observed in regolith breccia or impact-melt breccia or granulitic breccia among the meteorites, they contain mafic minerals (~10-30%). These brecciated anorthositic samples present the evidence that they have experienced complex impact histories on the surface, and reflect mafic-rich compositions of feldspathic crust. On the other hand, several large pure anorthosite (>98% plagioclase) clasts were found in the feldspathic lunar meteorites, Dhofar 489 group [10]. These anorthosite samples are thought to be identified as pure anorthosite. Their mafic minerals have large chemical variation in Mg#60-85.

The brecciated anorthosites which are abundant among feldspathic lunar meteorites could originate from mafic-rich mixing layer of feldspathic crust implied by remote sensing data e.g., [11], while the pure anorthosite could be from PAN layer below the mafic-rich mixing layer [12].

Objectives: In this work, geochemical and petrological features of lunar crust are reported and discussed on the basis of recent geochemical and petrological studies of lunar meteorites and returned samples. Furthermore, the research data are compared with the remote sensing data to discuss formation process of crust, and provide new implication for future lunar missions.

References:
GLOBAL MAP AND CLASSIFICATION OF LARGE-SCALE EXTENSIONAL STRUCTURES ON THE MOON. A. L. Nahm1, M. B. Johnson2, E. Hauber1, T. R. Waters2, and E. S. Martin2, 1Institut für Planetenforschung, German Aerospace Center (DLR), Rutherfordst. 2, 12489 Berlin, Germany, (amanda.nahm@dlr.de, ernst.hauber@dlr.de); 2Center for Earth and Planetary Studies, National Air & Space Museum, Smithsonian Institution, Washington, DC 20560 (watterst@si.edu, martines@si.edu).

Introduction: Tectonic structures visible on the surface of a planetary body provide records critical for understanding the temporal and spatial changes in stress states. They also provide information regarding formation mechanisms, which in turn have implications for the body’s internal and surficial evolution and geologic processes. Basic information about tectonic structures, such as spatial distribution, orientation, potential clustering, association with certain landforms (like mare filled basins) is easily displayed via global maps.

A global map of large-scale extensional structures using the high-resolution LRO datasets has not yet been published. Recently, however, two maps of large-scale extensional structures on the Moon have been compiled [1, 2]. The map by [1] was restricted to the lunar nearside and was produced at a scale of 1:500,000, while the map by [2] shows the global distribution of all structures with negative relief (including non-tectonic sinuous rilles). The global map presented here represents a compilation of both of these maps. Additionally, a classification scheme for large-scale extensional structures on the lunar surface is presented.

Mapping: A global map of extensional tectonic structures at a scale of 1:250,000 has been produced. The base map used for mapping was the LRO Wide Angle Camera (WAC) global mosaic at 100 m/px (http://wms.lroc.asu.edu/lroc/view_rdr/WAC_GLOB_AL). LRO Narrow Angle Camera (NAC) images and WAC stereo-derived topography supplemented this basemap where necessary. In general, graben are identified by their negative relief and are accompanied by parallel scarps that generally bound long, relatively narrow troughs. Individual scarps are also observed and are again characterized by negative relief, though only one scarp is observed.

Distribution and Tectonic Setting: Graben and other extensional structures are concentrated on the nearside and in association with most of the margins of mare basins. Extensional landforms are also found within impact basins not completely flooded by mare basalt, e.g., Orientale and Schrödinger. Not an insignificant number of graben are located on the farside highlands away from mare basins. In addition, many extensional structures are located in floor materials of impact craters commonly referred to as floor-fractured craters [3]. Notably, there is a dearth of extensional structures in and around Mare Crisium, as well as in the northern parts of Oceanus Procellarum and Mare Imbrium.

Some structures show distinct radial orientations relative to the western portion of Oceanus Procellarum as well as in the central-eastern nearside south of Mare Imbrium. Concentric structures are also observed outside of Mare Serenitatis and Mare Humorum.

Length statistics: A total of 4366 structures were mapped, with lengths varying from ~952 m to 519 km. The vast majority of structures (4313, or 98.7%) have lengths between ~952 m and 110 km, while the length bin with the highest number of structures is ~6.1 to 11.3 km, with 1194 segments.

Classification: The 6 categories of extensional structures identified here are scarp, elliptical trough, catena, flat floored trough, narrow-deep trough, and subdued trough. Scarp structures consist of an individual or non-paired scarp. An elliptical trough is an elliptical to elongate rimless depression that does not occur in association with a sinuous rille or extensional structure; some structures are long and narrow, while others are short and wide. Narrow-deep troughs are deeper than they are wide and are identified by two visible scarps, though the floor may be in shadow. Subdued troughs are linear to curvilinear narrow depressions. Their walls appear to converge, creating the appearance of a line along the floor; wall crests appear rounded or subdued. Their morphology may be subdued due to overlying deposits, such as crater ejecta or pyroclastic deposits, or surface degradation. A catena is composed of an aligned series of circular to elliptical rimless depressions or pits; pits may be distinct or separate from each other, or may connect. These structures may or may not be associated with single scarp structures or graben, either continuing along trend of graben or contained within graben. Flat floored troughs are wider than they are deep with flat floors, have clearly delineated paired antithetic scarps, and are often segmented.

Outlook: The next step is to assign each mapped structure a classification and to get orientation statistics.

Improved Lunar Iron Map Obtained by the Kaguya Gamma-ray Spectrometer. M. Naito, N. Hasebe, H. Nagaoka, E. Shibamura, M. Ohtake, K. J. Kim, C. Wöhler, and A. A. Berezhnoy. School of Advanced Science and Engineering, Waseda University, Shinjuku, Tokyo 169-8555, Japan (m.naito@aoni.waseda.jp). Research Institute for Science and Engineering, Waseda University, Shinjuku, Tokyo 169-8555, Japan, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa 252-5210, Japan, Korea Institute of Geoscience and Mineral Resources, Yuseong-gu, Daejeon 305-350, Korea, Image Analysis Group, TU Dortmund University, 44227 Dortmund, Germany, Sternberg Astronomical Institute Moscow State University, Leninskie Gory Moscow 119991, Russia.

Introduction: The iron distribution in the lunar surface is essentially important for the development of lunar magma ocean theory [1]. Its global distribution has been studied using Clementine spectral data [2] and Lunar Prospector Gamma-ray Spectrometer (LP GRS) data [3, 4]. The Apollo and Luna returned samples have provided local information at the source regions as well as lunar meteorites. In this work, the global distribution of iron was determined by the observation data of Kaguya Gamma-ray Spectrometer (KGRS). The KGRS employed a high-purity germanium (HPGe) detector and a BGO scintillator for main and anti-detectors [5]. The excellent energy resolution of HPGe (7.1 keV at 1.46 MeV) enables to obtain accurate counts of individual gamma-ray lines in the complex energy peaks such as an iron gamma-ray line at 846 keV.

Methods: Peak fitting of the iron gamma-ray lines emitted by inelastic scattering at 846 keV and neutron capture at 7.631 and 7.646 MeV are conducted to obtain iron gamma-ray count rates. The contents of inelastic gamma-ray are corrected by the fast neutron flux derived from sawtooth peak, which is produced by the injection of fast neutron [6], and those of capture gamma-ray are corrected by the thermal neutron flux obtained by Lunar Prospector neutron spectrometer [7]. Therefore, the iron distribution obtained by the inelastic gamma-rays is determined without any other instrument dataset. Elemental determination only by KGRS observation is conducted for the first time.

To confirm the data accuracy, statistical error of gamma-ray counts are estimated and compared between the inelastic and capture gamma-ray. The two gamma-ray lines by neutron capture were summed in order to increase statistics. Calibration of gamma-ray counts to FeO concentration is conducted by using ground truth of the Apollo-Luna returned samples and meteorites from lunar feldspathic highland terrain.

Results and discussion: The counts of inelastic gamma-ray were statistically superior to those of capture gamma-rays in spite of some contamination peaks around the inelastic gamma-ray line. According to Reedy (1978) [8], the emission rates of iron inelastic gamma-ray and sum of capture gamma-rays are comparable. The higher detection efficiency of low energy gamma-ray causes this superiority in inelastic gamma-ray. On the other hand, the gamma-ray counts was lower than the detection limits with 1σ at some low iron regions in highlands. The lower limit of detection was ~ 3 wt%. This value is superior to that of the LP GRS. The lunar FeO map obtained by inelastic gamma-ray is shown in Fig. 1. The areas with iron content below the detection limits are filled by black. The KGRS map shows similar trend to the LP GRS iron map. However, some differences in the area with low-middle FeO content (3-15 wt%) such as around the South Pole-Aitken basin and the Tycho crater were observed. By the use of HPGe detector with excellent energy resolution, the production of high quality lunar FeO map is achieved.

Detail estimation and discussion of FeO distribution map by the KGRS are shown in Naito et al., (2017) [9].

Fig. 1 Lunar FeO distribution map (wt%) [9].

References:
NEW VIEWS OF THE MOON, 2: THE FUTURE. C. R. Neal¹ and S. J. Lawrence², ¹Dept. Civil & Env. Eng. & Earth Sciences, University of Notre Dame, Notre Dame, IN 46556, USA (neal.1@nd.edu), ²ARES, NASA-Johnson Space Center, Houston TX 77058, USA (samuel.j.lawrence@nasa.gov).

Introduction: There have been 11 missions to the Moon this century from 5 different space agencies. ten of these missions have been orbital. Significant global datasets thus derived now show our lunar sample collection is not representative [1]. The results from these 21st century missions were not included in the original New Views of the Moon book [2]. Therefore, the New Views of the Moon 2 project has summarized the progress made since the original NVM book was published in 2006. NVM-2 will be different in that it has 21 chapters instead of 7, and an electronic deposit for large data files that will be housed at the Planetary Data System Imaging Node at the USGS in Flagstaff, Arizona.

In looking to the future, it is our belief that getting to the lunar surface is an imperative as all but one of the missions since Apollo have been orbital, although the global data from these now allow intricate planning of surface operations. A recent Landing Site Workshop for Lunar Science [4] demonstrated there is much that can be done for lunar science both in situ and through sample return [4] and representative landing/investigation sites are shown in Fig. 1a,b.

Future Lunar Science & Exploration: The proposed future investigations highlighted in Fig. 1 would benefit many chapter subjects in the NVM-2 project. Assuming that landed missions, including robotic sample return, are possible in the next 5 years through commercial providers (e.g., [5,6]), visiting any of the sites proposed here will add future avenues of research to the following chapters:


Young Igneous, Farside Mare Basalt: Magmatic Evolution 2; Lunar Interior; Volcanic Features & Processes.

Pyroclastic Deposits: Magmatic Evolution 2; Volcanic Features & Processes; Edogenous Volatiles; Resources.

Olivine-rich (Mantle?) Deposits: Lunar Interior, Magmatic Evolution 1; Evolution of the Lunar Crust.

Polar H Deposits: Surface Volatiles; Endogenous Volatiles; Resources; Surface Processes; Space Weathering & Exosphere-Surface Interactions.

Pure Anotrohostic (PAN): Evolution of the Lunar Crust; Magmatic Evolution 1 & 2; Impact Features and Processes.

Farside Crust: Lunar Meteorites; Evolution of the Lunar Crust; Surface Processes; Space Weathering & Exosphere-Surface Interactions.

Undertaking landed missions to the types of sites depicted in Fig. 1 will also yield information regarding the origin of the Earth-Moon system, and samples will help understand the origin and evolution of the lunar dynamo. Small detectors on landers would also inform us about the dust and plasma environment. Conclusion – we need to get to the lunar surface for the next era of scientific exploration of the Moon.


Fig. 1: Proposed landing sites for in situ science & sample return based upon orbital data gathered since Apollo.
ABSTRACT:

Our purpose here is to show and promote the importance of science causes and the synergistic engineering, operational and commercial consequences of movements of fine dust (MOFD) on the Moon. We show qualitative and measurement-based quantitative evidence of MOFD impacts (i) on cost effectiveness of lunar missions, both human and robotic; (ii) on success or failure of a mission or task; and (iii) unexpected opportunities of commercial interest. The only quantitative and fungible in situ measurements of MOFD were made by the 270g Apollo Dust Detector Experiment (DDE) we invented in 1966. A DDE played key roles in measurements of MOFD explaining each of the two major operational crises of lunar expeditions which bookend lunar expeditions (i) 1969 failure of the active Apollo 11 EASEP the first active observatory placed by humans on another world, and (ii) 2014 immobilisation of Chang'e-3 Yutu, the first lunar rover in almost half a century.

Planning of future missions is based on testing of simulated dust under simulated lunar environments in Dirty Thermal Vacuum Chambers (DTVCs). Vigorous debate continues about relative merits of various simulated dusts. Accordingly, we recommend and offer a tranche of Ground truth data published in GRL 2009 for an historic challenge to a double-simulation laboratory to match this measured behaviour of dust in situ on the Moon. The tranche is for Apollo 12 DDE vertical East-facing solar cell shielded by silicon, of 25 hours of data from deployment to just before the Lunar Module ascent. Collateral dust on the cell progressively fell off as solar elevation increased from 10 to about 20 degrees. Fungible digital measurements at 54 second intervals can be made available to registered participants. This unique in situ tranche of measurements of adhesion to vertical surfaces is important for structural designs on the Moon. Its causes are not analysed yet. Even if the challenge has no takers, perhaps theorists may be interested.

International knowledge of MOFD comes chiefly from Apollo. Astronaut debriefings gave skilled but qualitative assessments of problems caused by dust. Gaier spoke for the silent experiments and hardware in 2005, giving many more examples of problems from MOFD. In 2015 an International Space Exploration Coordination Group assessed technology gaps for dust mitigation for the Global Exploration Group and included an example of 4 layers of layered engineering defence plans. The International Space Exploration Coordination Group (ISECG) charged the group to publicise the report, duly presented publicly at AIAA Space 2016 Forum and available on the Web. Yet a curious and unresolved feature about MOFD is that remnants of the 1964 culture of "dismissal" of the importance of lunar dust still appear, squelching real information and thus funding of its use.

Post 2014 discoveries from Apollo 12 Dust Detector Experiment (DDE) measured Sunrise-driven levitation of dust to 100cm height resolving the 50-year mystery of Horizon Glow phenomena, which was sought but not found by lunar-orbiting LADEE LDEX at altitudes of 2 to 250km.

Commercial ventures are already making significant changes to established views. We add an unexpected commercial bonus from MOFD, because the sunrise-driven movements of dust measured by Apollo 12 DDE have positive implications for mining on the Moon and large airless asteroids, In Situ Resource Utilization (ISRU) and naturally-occurring rehabilitation of a mined site.

This presentation adds to New Views high-level considerations of the historical development of the knowledge of lunar science by introducing the Kuhn cycle. We populated it with (i) a "crisis" in 2014 (Yutu immobilisation), (ii) "a revolutionary discovery" in 2015 (publication about sunrise-driven dust storms) and (iii) a "paradigm change" in 2016 (announcement at ELS2016 of revised priority of lunar dust in Chang'e-4 in 2018). The Kuhn cycle gives the first sense of continuity and a rational progressive increase in scientific understanding of MOFD, potentially a pragmatically useful tool in presentations to communities, decision-makers and Treasuries.
The initial condition-dependence of the history of the lunar magmatism inferred from numerical models.

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To discuss how the history of magmatism on the Moon depends on the initial thermo-chemical state of the mantle, I present two-dimensional numerical models of magmatism in convecting mantle internally heated by incompatible heat producing elements (HPEs) [1]. Mantle convection occurs beneath a stagnant lithosphere that inhibits recycling of the HPE-enriched crustal materials to the mantle. Magmatism is modeled by a permeable flow of magma generated by decompression melting through matrix. Migrating magma transports heat, mass, and HPEs: Case (1) When the deep mantle is initially hot with the temperature at its base $T_D$ around 1800 K, magmatism starts from the beginning of the calculated history to extract HPEs from the mantle. The mantle is monotonously cooled, and magmatism ceases within 2 Gyr, accordingly; Case (2) When the deep mantle is initially colder with $T_D$ around 1100 K, HPEs stay in the deep mantle for a longer time to let the planet be first heated up and then cooled only slightly. If, in addition, there is an HPE-enriched domain in the shallow mantle at the beginning of the calculation, magma locally continues ascending to the surface through the domain for more than 3 Gyr; Case (3) If the mantle is initially layered with a compositionally dense layer enriched in HPEs at the base of the mantle, magmatism occurs more extensively to extract the HPEs from the basal layer, and ceases earlier. The model of Case (2) fits in with the thermal and magmatic history of the Moon inferred from spacecraft observations. However, it is not clear if the initial thermo-chemical state of the mantle assumed in this case is consistent with the single giant impact hypothesis for the origin of the Moon. The history of magmatism imposes an important constraint on the origin of the Moon.


Figure 1. (a) The average temperature plotted against time. (b) The upward flux of magma across the depth levels $d$ indicated by the dotted lines in the snapshots of (c), plotted on the plane of the horizontal coordinate $x$ and time. (c) Snapshots of the distribution of temperature (color) and magma (contour lines) taken at the time indicated in the figure. The contour interval is 5%.
OVERVIEW OF A JAPANESE LUNAR POLAR MISSION. M. Ohtake¹, T. Hoshino¹, Y. Karouji¹, and H. Shiraishi¹, ¹Japan Aerospace Exploration Agency (JAXA) (ohtake.makiko@jaxa.jp).

Introduction: In addition to the scientific interest, the Moon is considered as the next destination of human activity. The Japan Aerospace Exploration Agency (JAXA) identified lunar landing exploration as the next step for technology development in space exploration after the successful lunar orbiter SELENE (Kaguya) mission. It is carrying out a mission called Smart Lander for Investigating Moon (SLIM). The SLIM mission [1] is a technology demonstration mission targeting a pinpoint landing, which is mandatory for future lunar and any planetary explorations.

In parallel, the International Space Exploration Coordination Group, organized by the space agencies of 15 countries and regions, is discussing future space exploration plans based on international collaborations. Planning of manned lunar surface exploration via a manned cislunar space station and precursor robotic (unmanned) missions prior to the manned mission is being studied in this framework.

Lunar polar exploration is an intensely studied candidate missions of the precursor robotic mission by many countries. In this presentation, we discuss an overview of the lunar polar mission studied in Japan.

Mission objectives: Recently, it has been suggested that water ice might be present in the lunar polar region based on spectral measurements of artificial-impact-induced plumes in the permanently shadowed region, and remote sensing observation of the lunar surface [2]-[4]. In addition to the scientific interest about the origin and concentration mechanism of the water ice, there is strong interest in using water ice (if present) as an in-situ resource. Specifically, using water ice as a propellant will significantly affect future exploration scenarios and activities because the propellant generated from the water can be used for ascent from the lunar surface and can reduce the mass of the launched spacecraft of lunar landing missions.

However, currently it is unclear if water ice is really present in the polar region because of the currently limited available data. Therefore, we need to learn that by directly measuring on the lunar surface. If there is water ice, we also need to know it’s quantity (how much), quality (is it pure water or does it contain other phases such as CO₂ and CH₄), and usability (how deep do we need to drill or how much energy is required to derive the water) for assessing if we can use it as resources. Therefore, JAXA is studying a lunar polar exploration mission that aims to gain the above information and to establish the technology for planetary surface exploration [5]. JAXA is also studying possibility of implementing it within the framework of international collaboration.

Spacecraft configuration: The spacecraft system comprises a lander module and rover system. The launch orbit is a geostationary transfer orbit (GTO), and the spacecraft system is transferred from GTO to lunar orbit (or the spacecraft is directly transferred to the lunar transfer orbit (LTO)) using a propulsion module. After landing onto the lunar surface, the rover is deployed using a descending ramp. The rover then prospects for water ice using observation instruments on board.

Landing site selection: Considering the mission objectives and condition of the lunar polar region, we listed the following parameters as constraints.
1) Presence of water
2) Surface topography
3) Communication capability
4) Duration of sunshine

As a first trial of the landing site selection, sunshine is simulated using digital elevation models to obtain the sunlight days per year and the number of continuous sunshine periods at each site. Also, slope and the simulated communication visibility map from the Earth are created. These conditions can be superimposed to select the landing site candidate.

Technology Development: We currently focus on developing technologies required for the exploration of polar regions and are promoting the following research and development.

- Sunshine in the polar region is from the horizontal direction, and it is affected by the local topography. Solar panels therefore need to be deployed vertically in a tower.
- Normal image based navigation is difficult in the polar region. Therefore shade image collation navigation using images of shadows created by the terrain is being studied.
- A prototype model of a rover equipped with a 1.5 m drill is being developed to examine basic functions.
- Currently, for rover deployment, we plan to develop ramps in forward and backward directions to secure redundancy. It is therefore important to develop a lightweight ramp structure.


Introduction: APPROACH [1] is a future lunar science mission which aims to clarify the internal structure of the Moon. In this mission, a penetrator will be deployed on the Moon, and observe the seismic activities and heat flow. It is important for almost all landing missions to evaluate the environment of their landing sites for a successful touchdown. In the case of the Moon, recent lunar missions (e.g. SELENE and LRO) obtained high-resolution imagery of lunar surface, and these data enabled us to understand the surface environment of the Moon. In this study, we measured rock size-frequency distribution (RSFD) of the landing-site candidate using LROC Narrow Angle Camera (NAC) image data. And then, we estimated the probability of success of deployment based on the RSFD we measured.

RSFD of Landing-Site Candidate: Figure 1 shows the rock abundance map deduced from Diviner data [2][3]. Yellow circle represents the uncertainty of the deployment. Its radius was assumed to 10 km. To measure the RSFD in the candidate site, we collected LROC NAC image data and counted the number of boulders at two different rock abundance areas (the highest and lowest rock abundance regions) within the error circle. Figure 2 represents the comparison of RSFDs of the selected areas shown in Figure 1 and those of previous missions compiled by [4]. Each solid circle corresponds to the RSFD of the areas in Figure 1. Each solid line shows the exponentially fitted function of the RSFD.

Probability of Success of Deployment: We simulated the deployment of the penetrator based on our results. In this simulation, about 1 million rocks were randomly located on the surface and at sub-surface (1 m depth). Rock size distribution was given by the exponentially fitted function in Figure 2. Although cumulative number of rocks seems to saturate at smaller diameter at any landing sites in Figure 2, we adopted the exponential function to consider the pessimistic case. Because there are few RSFD models for sub-surface, we assumed the similar RSFD at 1 m depth. Also, locally high rock abundance areas were set to simulate the candidate site. Under these conditions, penetrator was dropped 1000 times. Deployment sites were given randomly. Random pattern obeys normal distribution (average = 0 m, standard deviation = 2000 m respectively from the candidate site) (Figure 3). This series of operation was carried out 100 times and the average and standard deviation of the probability of success was calculated. As a result, the average and standard deviation of the probability of success were 99.408 %, 0.244 % respectively. Although we assumed the pessimistic case for RSFD at the candidate site, more than 99 % success was shown through this simulation.


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Figure 1. Rock abundance map inferred from Diviner data
Rock abundance map near the candidate site (0.8 deg square) is shown. Center of the map corresponds to the position of the candidate site (lon, lat) = (346.2926 deg, -5.53612 deg).

Figure 2. Comparison of RSFD X-axis shows diameter of rocks. Y-axis shows cumulative number of rock for 1km².

Figure 3. Deployment sites Center coordinates (0 m, 0 m) correspond to the candidate site (346.2926 deg, -5.53612 deg). Black plots show the deployment site of penetrators. These plots are randomly located obeying normal distribution.
INTRODUCTION OF JAXA LUNAR AND PLANETARY EXPLORATION DATA ANALYSIS GROUP: LANDING SITE ANALYSIS FOR FUTURE LUNAR POLAR EXPLORATION MISSIONS

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Introduction: JAXA established JAXA Lunar and Planetary Exploration Data Analysis Group (JLPEDA) at 2016. Our group has been analyzing lunar and planetary data for various missions. Here, introduce one of our activities.

Recently, the lunar polar region has received attention as one of the most attractive exploration targets because remotely sensed observations reveal that valuable resources are likely to exist in the lunar polar region. Due to the long-duration of preferable illumination and volatiles captured in the cold trap, the polar region will be useful for future crewed space exploration missions in the deep space.

However, there still remain many questions about volatiles. In order to investigate these resources, some agencies, such as NASA and ESA currently plan landing missions around the poles of the Moon. JAXA is also considering a Moon polar exploration mission to investigate lunar resources and to study their potential usage. In such a landing mission, we must select a landing site with the possible existence of water ice [1], desirable sunlight, communication with the Earth, slope, and hazards. Landing site selection is critical for mission accomplishment in the polar region, so a great deal of previous work has analyzed various conditions using remote-sensing data on the Moon polar region [2, 3, and 4].

In this paper, we present detailed analysis results for one of the candidates, “de gerlache rim” (GR1), by simulating the sunshine, communication with the Earth, and slope conditions. In this analysis, we used Digital Elevation Models (DEMs) created from the observation data of Lunar Orbiter Laser Altimeter (LOLA) of LRO and the Terrain Camera (TC) of SELENE.

Landing Site Analysis: In order to select landing sites for the mission, we simulated the conditions mentioned above using the LOLA DEM with a grid resolution of 40 m and the orbit of the Sun relative to the Moon from SPICE data. The resulting candidates satisfy the following restrictions. 1) The number of sunshine days exceeds 100 in two years. 2) The ratio in which Earth-Moon communication can be conducted exceeds 25%. The sunshine and communication simulations’ duration is two years, from April 1, 2022 to May 31, 2024. 3) The slope angle is less than 10 degrees. Here, a sunshine and communication threshold is defined as 50% of the sun disk at 1 m altitude. (For the definition of the sun disk, see [5].)

As an example, we present the simulation result for GR1 using a DEM with a grid resolution of 2 m. Figure 1 presents the simulations for a 1 km square region of GR1. Using these analysis results, we decide the way points for the exploration such as the Permanently Shadowed Region (PSR), which is one of the interesting regions.

Conclusions: This paper presents the analysis results as for the landing site selection using previous remote-sensing data. After the landing site is determined, we simulated the illumination, communication, and slope. We will simulate these conditions for other candidate landing sites and plan the exploration trajectory.


Figure 1 These images represent a 1 km square region which is the vicinity of GR1 (88.6952S 68.2846W). (a) Orthorectified LROC Narrow Angle Camera (NAC) image (M143000050). (b) Sunshine ratio [%]. The black region indicates the Permanently Shadowed Region (PSR), which has no sunshine for 20 years in the simulation. (c) Communication ratio with the Earth [%]. (d) Slope condition [deg]. Red indicates the region with more than 25 degrees slope angle.

Introduction: NASA’s Mini-RF instrument on the Lunar Reconnaissance Orbiter (LRO) is currently operating in concert with the Arecibo Observatory (AO) and the Goldstone deep space communications complex 34 meter antenna DSS-13 to collect bistatic radar data of the Moon. These data provide a means to characterize the scattering properties of the upper meter(s) of the lunar surface, as a function of bistatic angle, at S-band (12.6 cm) and X-Band (4.2 cm) wavelengths. These data are being collected to address driving questions for the current LRO extended mission.

Background: The transmitters for Mini-RF bistatic observations are AO (S-band) and DSS-13 (X-band). The data returned provide information on the structure (i.e., roughness) and dielectric properties of surface and buried materials within the penetration depth of the system (up to several meters for Mini-RF) [1-4]. The bistatic architecture allows examination of the scattering properties of a target surface for a variety of bistatic 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 [5-7].

Operations: Collecting data in the Mini-RF bistatic architecture requires significant advance planning with both the LRO operations team and ground-based facilities. As a result, no more than a few collects per month are feasible. The first Mini-RF bistatic campaign (2012-2015) included 28 AO S-band observations of the lunar surface, polar and nonpolar. Those observations provided data used to suggest the presence of water ice within floor materials of the crater Cabeus [8] and to characterize the weathering of Copernican crater ejecta [8,9].

The current bistatic campaign (2017-present) includes an additional 4 AO S-band observations and 23 DSS-13 X-band observations of the lunar surface. A variety of lunar terrains are being targeted to address science objectives for the ongoing LRO extended mission. They include collecting data of: the floors of south pole craters to search for signatures indicative of the presence of water ice [10]; Copernican crater ejecta blankets to characterize rates of regolith breakdown/weathering [11,12]; the ejecta of newly-formed craters to characterize the size-distribution and density of wavelength-scale scatters as a function of distance from the impact [13]; mare materials within the Imbrium basin to provide important information on the locations, extents, and depths flow units and deposits [14]; and irregular mare patches (IMPs) and pyroclastic deposits to characterize their radar properties [15,16]. In concert with the collection of these data, modeling work is being conducted to characterize the response of surface materials to variations in incidence angle [17] and to address LRO science objectives with Mini-RF monostatic data [e.g., 18,19].

Results: Initial analysis of south polar targets acquired at X-band [10] do not appear to show the possible water ice signature detected at S-band [8]. This would indicate that, if water ice is present in Cabeus crater floor materials, it is buried beneath ~0.5 m of regolith that does not include radar-detectable deposits of water ice. Observations of Copernican crater ejecta materials at S- and X-band wavelengths continue to show variations that can be attributed to the age of the crater [11]. Differences between S- and X-band observations of the same crater are also present, providing new insight into the size-distribution of radar scatters within the ejecta [11,12]. Two craters that formed during the LRO mission have been identified in X-band Mini-RF data acquired in the current bistatic campaign. Analysis of these data suggest enhanced wavelength-scale surface roughness to radial distances of 100s of meters from the crater centers [13]. S- and X-band observations of mare materials in the Imbrium basin and pyroclastic deposits in the Montes Carpatus, Aristarchus, and Taurus Littrow regions have been acquired and, combined with ground-based P-band observations, are providing important information on the locations, extents, and depths to individual flow units and deposits [14-16].

WHAT IS NEXT? THE LUNAR CRUST PROVIDES KEYS FOR UNDERSTANDING SOLAR SYSTEM ISSUES AT 1 AU. C. M. Pieters¹ and J. W. Head¹, ¹DEEPS Brown University, Providence, RI 02912 (Carle_Pieters@brown.edu).

Introduction: The Moon provides a unique opportunity for integration of remote sensing, in-situ, and sample analyses that will address broad and important Solar System issues in the years ahead. The multi-national activities planned and envisioned to explore the Moon with modern technology on orbiters, landers, and rovers as well as with new samples returned from key targets provide the basis for the next level of understanding about the character and history of the innerSolar System shared by the Earth and Moon.

The record of the first billion years has essentially been lost on Earth through active plate tectonics and constant erosion and weathering. Although forged ~4.5 Ga ago during the same violence at 1 AU as Earth, the Moon retains a full record of subsequent events after its crust and mantle formed a few 10s to 100 Ma later. A serious and multi-faceted exploration program directed at this early record promises to not only provide enormous geologic insight about the Moon, a nearby differentiated cousin of Earth, but it also provides the only opportunity to understand fundamental processes (and their timing) that shaped the character and habitability of the Earth/Moon system. We provide a few (highly incomplete) examples of opportunities and progress envisioned with different tools and approaches to be implemented exploring the Moon, probably prior to expanded exploration involving a human/robotic partnership.

Remote Analyses: As for the Earth, we are never finished exploring surface geology, composition, regolith, and potential resources of the Moon from orbit. This is because new information is always sought and welcomed using capabilities across several dimensions from advanced instruments that continue to improve in accuracy and precision: spatial and spectral resolution, extended measurements of the electromagnetic spectrum and spectral range, global and targeted coverage, repeat measurement capturing temporal variations. Coincident with these improved capabilities are collection, storage, and accessibility of large data volumes.

Recent observations: Hydrated materials are now detected from orbit. Global plagioclase (PAN/FAN) was confirmed to form a magma ocean cumulate primary crust. The megaregolith is globally dominated by noritic plagioclase breccia. SPA exposes low-Ca pyroxenes, suggesting a mantle dominated by Mg-pyroxene. Localized exposures of olivine, pyroxenite, and Mg-spinel near or within feldspathic inner rings of basins suggest these components are linked to the lower crust.

Issues to be addressed: Document and understand the lunar ‘water cycle’. Identify local source areas for ‘Mg-suite’ crustal components. Characterize and distinguish properties of the lower crust from the lunar mantle and map their distribution. Identify-characterize-map potential localized resources. Provide iterative context analyses for landers and sample return.

In-Situ Analyses: Multiple special areas recognized for their high scientific value have been identified as targets for detailed in situ analyses. These are globally distributed, and when several are linked for simultaneous operation they can provide a network of geophysical stations to probe the interior. Precision landing, long-term (diurnal) operations, global communication, and compact advanced payload are key challenges.

Recent observations: Only one robotic lander/rover (Chang’E-3) has recently soft-landed on the lunar surface (the productive Apollo and Luna programs ended more than 40 years ago). Several challenging robotic landers and rovers are planned for the next decade to restart this essential form of exploration.

Issues to be addressed: Identify and map variations of diverse local geology and composition at lunar targets of interest. Characterize and confirm resources. Initiate geophysical stations to address crustal thickness variations, magnetics, heat flow, interior structure, shape and sharpness of crust-mantle boundary, etc.

Sample Analyses: Lunar samples returned 40-50 years ago continue to be analyzed world-wide with constantly improved capabilities that provide exquisite data used to address diverse geochemical and petrographic problems. The samples provide an invaluable resource, but are known to be highly incomplete (biased) for addressing major science issues.

Current observations: The documented returned lunar samples are from PKT and nearby terrain of the nearside. All else (FHT, SPA, polar, young basalts, etc.) remain unsampled but are known to be highly diverse.

Issues to be addressed: Resolve planet-wide nearside/farside differences. Establish Solar System chronology by dating basin and crater events. Determine the composition and origin of the lower crust and mantle. Evaluate timing and diversity of secondary volcanism.

Summary: Acquisition and integration of modern data from the next decade of lunar exploration will certainly lead to new understanding of and fresh insight into the evolution of the Earth-Moon system. All of humanity benefits.
CRITICAL LUNAR ROBOTIC MISSIONS. J. B. Plescia \(^1\) \(^1\)Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723.

**Introduction:** Data from an array of orbital mission and a landed mission over the last decade have significantly advanced our understanding of the Moon. Many questions have been answered and many more have been raised. Looking forward, the issue is which objectives are the most important and how they influence our understanding of the lunar origin and evolution. Here, I argue that the two most important missions are a geophysical network and a mission to conduct in situ dating in support of the cratering chronology.

**Network:** The Apollo seismic experiment as well as orbital geophysical data (e.g., GRAIL) have providing insight into the interior structure of the Moon [1, 2].

The Moon consists of a core, mantle and crust. A core consists of an inner solid and a liquid outer core. Extending from 350 km to the base of the anorthositic crust is the mantle, consisting of a lower, partially molten mantle, a middle and an upper mantle. Crustal thickness, based on seismic and gravity data [3], averages 30-40 km, although thickness of 50-60 km occur on the far side and 20-30 on the near side (excluding basins). Moon quakes indicate that the interior is seismically active. Seismic events can be divided into: impacts and surficial thermal events; and shallow and deep quakes. Shallow quakes, as recorded by Apollo, make up a small fraction (0.2%) but are the largest events. Deep quakes make up ~60% of events but are of lower magnitude. Many deep quakes occur in clusters and are temporarily associated with tidal stress.

**Constraining Cratering Chronology:** The lunar impact cratering rate [4] has been estimated on the basis of the returned, radiometrically dated samples and the number of superposed impact craters on the dated surfaces (Fig. 2). Whether an early distinct period of intense bombardment occurred or whether the early higher cratering rate was just the tail of accretion remains unclear. The post-mare basalt rate shows a decline with time. However, dated surfaces are limited to period >3.2 Ga. Ages for Copernicus and Tycho are based on samples collected during Apollo and considered to have come from those craters. However, the crater frequencies for the ejecta of Copernicus and Tycho may not reflect a production population. Thus, the rate for the period 0 to 3.2 Ga is at best poorly constrained (or unconstrained). Crater counts for mare areas have absolute model ages that extend to perhaps 1 Ga [5], suggesting that significant mare volcanism extended well beyond the end of the Imbrian Period. If it did, it would have important implications for the thermal history of the Moon and the timing of a possible intrinsic magnetic field.

**Discussion:** A network mission with an array of stations operating continuously would allow the interior structure and seismicity to be determined. While an active experiment would be best, the occasional large impact can suffice to inject seismic energy into the interior. In order to constrain the cratering rate over the last 3.2 Ga, radiometric ages must be obtained for surfaces with relatively low crater frequencies. While in situ radiometric dating is not as precise as that of a laboratory, it is sufficient. The question is, are the youngest mare surfaces 1 Ga or 3 Ga?

Understanding lunar interior structure and providing better constraints on the thermal history and chronology of events, accomplished by robotics mission, have the greatest potential to advance our understanding.

**What about volatiles?** Lunar volatiles have attracted considerable attention of late. While they are an interesting problem and are relevant to exploration, it is unclear the extent to which understanding polar volatiles will better reveal the origin and evolution of the Moon.

LUNAR REGOLITH - SURFACE PROCESSES. J. B. Plescia, M.S. Robinson, Johns Hopkins University, Applied Physics Laboratory, Laurel MD, School of Earth and Space Exploration, Arizona State University, Tempe AZ.

Introduction: The regolith is the fragmental layer formed on the surface of the Moon. It is the material that is observed by remote sensing techniques providing information on the bedrock composition and history. It is also the material that interacts directly with space, being bombarded by solar and galactic radiation and the population impact projectiles. In turn, the effects of radiation and impact change the physical properties, chemistry and volatile interaction properties of the regolith. The regolith is also the material on which surface operations are conducted and thus it is important to understand the geotechnical properties.

Considerable data has been collected from orbital and surface missions to the Moon since The New Views of the Moon volume was published in 2006 [1]. Our view of the nature and evolution of the lunar regolith and some of the surface processes has significantly changed since that volume. Here, we report on the newest developing in our understanding of the lunar regolith and lunar surface processes.

Physical Properties: Thermal data provided by the LRO Diviner instrument has revealed that the thermal properties of the regolith are more complicated and spatially heterogeneous than previously discerned. Hayne [2] has used the thermal data to describe the density distribution as a function of depth across the Moon thus providing a more complete understanding beyond the data from the Apollo sites [3]. Data suggest that, in general, the regolith has a higher density than the Apollo data indicated. Those same thermal data have been used to examine the distribution of rocks and the roughness at small scale [4, 5]. Roughness at scales of mm can result in a high degree of anisotermality. A class of young craters display a thermal anomaly in which the surrounding surface (10-100 crater radii) is considerably colder than observed. It has been suggested [6] emplacement of distal ejecta has decreased the regolith density to depths of ~10 cm. However, visual imagery does not show obvious alteration. LRO/Mini RF radar data show that the CRP ratio decreases poleward, an effect that could indicate that the regolith density decreases with latitude [7].

Impact Rate and Regolith Turnover: As a result of micro-macro impact events, the regolith is slowly vertically mixed and matured with time. LROC images have identified a large number of newly formed impact craters and albedo markings. These observations suggest that the regolith gardening rate occurs on a timescale about 100x faster previous estimates [8, 9]. Even these significantly greater gardening rates must be well below the rate that occurred several billion years ago, as the current rates are not sufficient to turn over the regolith to depths consistent with the observed thicknesses.

Regolith Formation: The canonical model for regolith generation is that the rocks exposed on the surface are comminuted over time by micro to macro meteors. These impact events slowly produce a regolith particle size-distribution composed of fine material. Observations that asteroids have surface regoliths, when in some cases modeling would suggest that they would not, has led to the argument that thermal fatigue fracturing of rocks can also contribute to the comminution process [11, 12] and that it could occur at a rate significantly greater than from mechanical impact comminution [13].

Volatile Reservoirs: Volatiles are of interest not only for the scientific aspect of their origin and evolution, but also from the perspective of resources. We have begun to recognize that H distribution is not simply a function of latitude and permanent shadow. Regolith H appears to be spatially variable across the surface [14, 15]. Surface volatiles appear to vary as a function of latitude and time of day [16, 17].

Conclusions: The understanding of the character, formation and evolution of the lunar regolith has substantially changed over the last decade. Heterogeneity is greater, new processes have been considered and rates may be significantly greater than previously recognized. The new insights provide a better understanding of how the regolith forms and evolves. It also has implications for the manner in which the regolith acts as a source, sink and venue for the formation and transport of OH and H2O.

THE LUNAR SPACE ELEVATOR, A NEAR TERM MEANS TO REDUCE COST OF LUNAR ACCESS
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Introduction: A Lunar Space Elevator [LSE] can be built today from existing commercial polymers; manufactured, launched and deployed for less than $2B. A prototype weighing 48 tons with 100 kg payload can be launched by 3 Falcon-Heavy's, and will pay for itself in 53 sample return cycles within one month. It reduces the cost of soft landing on the Moon at least threefold, and sample return cost at least ninefold. Many benefits would arise. A near side LSE can enable valuable science mission, as well as mine valuable resources and ship to market in cislunar space, LEO and Earth’s surface. A far-side LSE can facilitate construction and operation of a super sensitive radio astronomy facility shielded from terrestrial interference by the Moon. The LSE would facilitate substantial acceleration of human expansion beyond LEO.

Overview: The original idea for a Space Elevator was for an elevator from the surface of the Earth up to Geostationary orbit. This idea is attractive since in theory it could greatly reduce the cost of access to space 1,2, however, there are no materials existing or on the horizon which are remotely strong enough to hold their own weight over the distance in the Earth’s gravity field. Theoretically Single-Walled Carbon Nanotubes [SWCNTs] would suffice3, but nobody can manufacture them longer than a few cm. Furthermore, SWCNTs have only been produced in tiny quantities in laboratories, and there is no prospect of industrial scale production happening in the foreseeable future. However, there is another planetary scale tether concept which is almost as valuable, and can be built with existing industrial materials, and that is the LSE.

A LSE is a very long tether, connecting the surface of the Moon to an Earth Moon Lagrange [EML] point, either EML1, between Earth and Moon (nesside), or EML2, behind the Moon as viewed from the Earth (farside). In order for the LSE system to be stationary with respect to the Moon it is necessary that the center of mass of the LSE be located at an EML point. Therefore, the tether must extend further from the lunar surface than the EML point, and be terminated at a counterweight. The Moon orbits the Earth, the LSE is not stationary with respect to the Earth.

In a design by T. M. Eubanks the total length of a nearside elevator is 278,544 km, and the total length of the farside elevator is 297,308 km.5

On average, EML1 is 326,380 km from Earth and 58,019 km from the Moon. EML2 is 448,914 km from Earth and 64,515 km from the Moon. Hence, in the Eubanks design, the distance from the Lagrange point to the counterweight for the EML1 system is 220,525 km and for the EML2 system is 232,793 km.

These distances are unprecedented in aerospace engineering, yet preliminary analysis indicates it is both possible, and affordable, using with existing commercial materials5. In this paper we will show how the lunar elevator is both feasible and affordable, and indeed profitable. Of course, there will be many technical and engineering challenges, but as far as we know today, there are no obvious showstoppers.

The idea of a lunar elevator is not new. The first known writing, where the concept of a lunar elevator was described by Tsander in 1910. Star Technology Inc. studied the LSE concept, for NASA Institute of Advanced Concepts in 2005.

References:
POLAR COLOR MOSAIC OF THE MOON FROM SELENE MI OBSERVATIONS. H. Sato, Y. Ishihara, M. Ohtake, and H. Otake, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Tyuo-ku, Sagamihara, Kanagawa, Japan (satoh.hiroyuki@jaxa.jp).

Introduction: The SELENE (Kaguya) Multi-band Imager (MI) has achieved ~240,000 observations during up to 10 months of its operation period. Due to the relatively narrow field-of-view (11°) and the limited mission period, the areas of repeated observations are limited. The mosaic production from the single observations (one time at each location) often results in sharp color offsets along the image seams due to the emphasized residuals of photometric normalization.

The high latitudes (>60°N/S), however, have certain numbers of repeated observations due to the SELENE’s polar orbit (close to each other toward the pole). Using these repeated observations, we produced the color mosaic that can reduce the photometric artifacts and improve the accuracy of normalized reflectance.

Methodology: We used the MI images (~20 m/pixel) with the center latitudes above 60°N (18,604 images, Fig.1) or below -60°N (18,059 images), acquired from Jan. 2008 to Oct. 2008. First we calculate the photometric parameters using Hapke model [2]. To obtain enough variation in incidence $i$, emission $e$, and phase $g$ angles, we classified the high latitude area (>60°N/S) into five groups and calculated the Hapke parameters for each group. We used the polar Hapke parameter map [3] derived from Lunar Reconnaissance Orbiter - Wide Angle Camera (WAC) to define five regions, each of which has similar photometric properties.

The $i$ and $e$ angles were computed based on the local topography. We used SELENE Terrain Camera (TC) stereo digital terrain model (~10 m/pixel) [4]. From the latitude/longitude of each pixel and the locations of the Sun and the SELENE at the time of observation, we compute the $i, e, g$ angles from the SPICE toolkit [5]. The normalized radiance factor ($nI/F$) [2] of each MI observation are then averaged with other overlapping observations to derive the final mosaic product.

Results and Discussions: The number of repeated observations ranged from 0 to 72 (north, Fig.2) and from 0 to 222 (south). The areas below 70°N/S have significant fraction of the areas with no repeated observations (~80%). The residuals and the image seams in the final mosaic will be discussed in our presentation.

JAXA’s Space Exploration Scenario
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Japan Aerospace Exploration Agency (JAXA) has been studying space exploration scenario including human exploration for Japan since 2015, which encompases goals, knowledge gap assessment, architecture assessment, and technology roadmap.

The overall goal of space exploration is divided into science and habitation. As for the habitation, the goal is assumed to stay 500 days on Mars utilizing local resources. Science goal and roadmap is also investigated. Preliminary gap assessment shows that water abundance on the moon is the critical knowledge gap as well as radiation environment, and regolith characteristics. Based on the overall architecture study, it was found that the transportation will become greatly effective if water abundance on the moon is more than a certain level. Also, the re-usability of the transportation system is the key enabler for the affordability and sustainability of human space exploration. Such an architecture study derived several key technology performance goals. Toward such a technology goals, we also developed technology roadmap. Through these activities, we created a proposal for Japan’s space exploration strategy for the political discussion.

Fig.1 shows the overall vision for space exploration after 20 years from now, which was proposed by JAXA to the political discussion. Also, Fig. 2 shows the overall scenario for the vision.

Because we believe the water abundance is critical for future overall space exploration architecture, the proposed first step is a water ice prospecting mission to lunar pole. In parallel with that, along with the Global Exploration Roadmap (GER) 3rd edition developed by the International Space Exploration Coordination Group (ISECG), it is proposed to participate in the Deep Space Gateway and Robotic Demonstrator for Human Landing Mission (called HERACLES) planned in 2020’s. If enough abundant water was found, it is also proposed to develop fuel production capability and finally to construct fuel plan on the lunar pole.

International Space Station (ISS) is also the key element for the space exploration because it is the most suitable facility to demonstrate key technologies for space exploration such as Environment Control and Life Support System (ECLSS), human health care technologies, rendezvous and docking technologies and so on. JAXA is also planning to use the ISS as much as possible leveraging operation opportunity and the right of ISS utilization.
POST-FORMATION MODERATE VOLATILE TRANSPORT AND LOSS ON THE MOON: LUNAR STRATIGRAPHY AND PALEO-PSR’s

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Introduction: The Moon and Earth are generally similar in terms of composition, but there exist variations in the abundance of certain elements among the two bodies. Previous works have attributed this to conditions during the Moon's formation. We explore the likelihood that the observed depletion in moderately volatile elements in lunar samples may be partially due to post-formation mechanisms. Solar effects, loss from a primordial atmosphere and impacts are some of the dominant mechanisms that we examine. Our past and current modeling efforts indicate that a significant fraction of the observed depletion of sodium in lunar samples relative to a bulk silicate earth composition may have been due to solar activity, atmospheric loss and impacts. Evidence of depletion and transport of moderate volatiles may be recorded in lunar stratigraphy and in ancient permanently shadowed regions. Moderate Volatile Depletion/Transport: Lunar samples indicate the Earth and the Moon are generally very similar in composition, but that there exist significant depletions in elements that possess condensation temperatures less than 1300 K (at a pressure of $10^{-4}$ bar)[1]. For example, sodium appears to be approximately five times more abundant in the Bulk Silicate Earth versus the Bulk Silicate Moon, with significant variation depending on the particular lunar sample chosen. Some of these abundance variations have been attributed to incomplete accretion during the formation of the Moon immediately after a hypothesized giant impact on the Earth. [2] However, processes operating after accretion of the Moon may also have influenced moderate volatile abundance and spatial variation. Post-Formation Depletion and Transport Mechanisms: A Primordial Lunar Atmosphere. Given a canonical Moon formation hypothesis, the Moon may have possessed a short-lived largely hemispheric metal dominated atmosphere immediately after it tidally locked to the Earth. [3] Simple estimates of atmospheric escape from such an atmosphere range from 5-25% of the initial sodium content of the global lunar magma ocean. Additionally, sodium would have been transported rapidly to regions of the Moon near or just beyond its terminator with respect to the Earth, producing depletion from sub-Earth zones while producing significant sodium abundance enhancements on rockbergs [4] that were advected towards the far side. Effects of Past Solar Activity. Sodium may also have been depleted due to solar activity in the past. Recent research based on Kepler observations of solar analogues at different stages in their evolution indicate the Sun may have experienced an enhanced period of flare and CME activity earlier in its history, with a higher frequency of geo-effective high energy CMEs. [5] Using a previously developed exosphere generation model that includes the effect of an incident CME [6], we are able to estimate the potential loss of sodium from the regolith due to solar wind and CME effects. Estimates regarding the total percentage of sodium depletion that can be explained by past solar activity range from ~20 - 80% for a variety of different assumptions. Such loss can explain a significant and measurable portion of the total sodium depletion. Effects of Impacts. Using an impedance matching technique, we are estimating the total delivery and loss of sodium during a variety of different impacts. Current modeling examines the total sodium delivery and loss due to impactors of a range of sizes, velocities and compositions. Due to the greater frequency of impacts during the early history of the solar system, specifically during a period when solar activity may also have been much greater [7], regolith churn that occurred may have left detectable abundance variations in lunar stratigraphy that may help to constrain these early solar system processes. Additionally, impactors of large size and velocity may have vaporized material at depths below the regolith, causing large spatial abundance anomalies. Discussion and Future Work. Post-formation depletion should also then be recorded in the stratigraphy of the lunar regolith. The information recorded in such stratigraphy could be used to connect vertical profiles of sodium abundances in lunar samples to physical mechanisms that modified the lunar surface through history. Connecting these variations in abundance to the effects of these physical processes may allow for constraints on past solar activity, impacts and surface processes on both a global and local level for the Moon. Additionally, potential reorientation of the Moon may mean paleo-PSR’s that would have lost most of their highly volatile elements may still retain moderate volatile signatures that may provide such constraints.

Sampling volatile-rich lunar materials. Collecting, preserving, and reading the volatile record of the Moon. Charles K. Shearer1. 1Institute of Meteoritics, Department of Earth and Planetary Science, University of New Mexico, Albuquerque, New Mexico 87131.

Introduction: Exploring and documenting volatile reservoirs on the Moon (mantle, crustal, surface [e.g., 1-4]) are fundamental to understanding the lunar volatile cycle, deciphering the role volatiles play in the origin and evolution of the Moon, and planning for the use of these reservoirs. The latter is particularly important as the strategy for long term human activity on the Moon will be driven by the accessibility and utilization of these potential lunar resources. There is a logical sequence for exploring these reservoirs: (1) identify character, distribution and environment using orbital missions; (2) in situ examination of their undisturbed characteristics; (3) return samples for a more rigorous examination by humans in terrestrial laboratories. Here, we focus upon previous lunar surface missions, their approach to preserving the volatile record in returned samples, and lessons learned for future sample return missions to lunar volatile reservoirs.

Sampling during the Apollo Program: Although samples returned during the Apollo Program were carefully and strategically collected and well-preserved in a clean environment, in many cases some delicate and perhaps transitory characteristics were significantly disturbed or lost (e.g., volatiles, volatile coatings on mineral surfaces). With great foresight, Apollo mission engineers and scientists devised sample containment protocol and tools that more rigorously attempted to capture these fragile characteristics. A total of 9 containers of lunar materials were sealed on the lunar surface and transported to Earth during the Apollo Program.

Special Apollo Samples: Numerous “special samples” were collected during the Apollo Program on an attempt to preserve their unique and fragile characteristics. Special sample containers included (a) Gas Analysis Sampling Container (GASC), (b) Core Sample Vacuum Container (CSVC), (c) Special Environmental Sample Container (SESC) (Fig. 1), (d) Lunar Environment Sample Container (LESC), (e) Magnetic Shield Sample Container (MSSC) and (f) Contact Soil Sample Container. SESC and CSVC have indium seals (Fig. 1). Current unopened samples include two CSVCs (69001, 73001) and an SESC (15014). For the CSVC, drive tube cores were immediately placed in these vacuum containers on the lunar surface. Upon return to the Lunar Receiving Lab each CSVC was placed in a second vacuum container. The samples were stored in the Pristine Sample Vault. These three unopened samples contain 1.7 kg of pristine and unstudied lunar material.

A Guide for Future Missions: Analysis of Sealed Samples: These special sample containers provide us with important new lunar samples and allow us an opportunity to develop and test methodology for handling volatile-rich samples from the Moon. As these samples must be examined in a very systematic manner, Shearer [5] outlined a potential methodology-protocol for the study of unopened samples in a consortium approach.

Figure 1. The SESC has a length of 21 cm, an outer diameter of 6.1 cm, a volume of 360 cm$^3$ and a weight of approximately 360 g. During their use on the lunar surface, some seals were broken by cables trapped between the indium seal in the lid and the knife edge of the container.

Exploring and sampling lunar volatile reservoirs: During future lunar missions there will be a significant emphasis on the definition of lunar volatile reservoirs and their ISRU potential. In situ analyses will provide information concerning undisturbed volatile reservoirs prior to sampling. For both in situ measurements and sampling, methods and tools must be designed that are cleaner and simpler and that disturbs the soil less drastically. These special samples represent our best chance to evaluate these approaches and to inform future missions on requirements for in situ measurements.

Design of SESC and CSVC containers: The containers used during the Apollo program were a reasonable attempt to preserve many characteristics of the lunar regolith. These types of sample containment should not only be utilized during future human missions to the Moon, but may be applicable to robotic missions to Moon and other planetary bodies. Future SESC and CSVC design should include (1) better, long lasting vacuum seals without the potential for indium contamination, (2) easier to use containers, (3) involve an overall general design that can be modified for specific samples, and (4) enable cryogenic cooling of samples to better preserve initial form of volatile compounds.

**Introduction:** Recent studies utilizing remote sensing data report compelling evidence for relatively abundant sometimes large silicic nonmare volcanism on the Moon [1-3]. On Earth, silicic (or felsic) magma centers are some of the largest volcanic landforms. They often are multivent long-lived complexes found in extensional tectonic setting in grabens and marginal basins of continents (e.g., Long Valley and Yellowstone, USA). The primary eruptive products which characterize rhyolite volcanoes are large explosive ignimbrites and relatively small-volume rhyolite lavas and domes. Underpinning these volcanic rocks are shallow granitic intrusions that are replenished by mantle-derived mafic magmas, e.g., [4].

Lunar silicic materials and surface features have gained wider interest in the planetary and exploration science communities because they are more abundant than previously known [1-3] and may concentrate volatiles [5] and therefore present potentially vital in situ resources for future Missions. Although traditional ideas put forth to explain felsic igneous rocks have been confirmed by individual lunar samples (e.g., silicic liquid immiscibility [6]), generally speaking they fail to explain their size and global distribution, and thus their origin remains poorly understood, cf. [7].

On the Moon, rhyolitic surface features exhibit a range of landforms and are generally found within the Porcellarum KREEP Terrane (PKT), the exception is the Compton-Belkovich complex (CBC) [8]. While silicic “evolved” (i.e., high Th content) volcanic features identified in lunar remote sensing data sets indicate the existence of moderately large and widespread silicic centers, akin to those found in Earth’s continental crust, silicic clast lithologies contained in complex impact breccias and found in regolith are rare and typically small in samples from Apollo sites (e.g., [9]).

To first order, understanding the generation of an evolved rock on the Moon can be understood from basic petrological and geochemical principles, i.e., phase equilibria leading to typical feldspathic mineralogy and element melt-mineral partitioning leading to incompatible element enrichment—including volatile species. In detail, however, terrestrial studies consistently show more complicated formation and evolution histories when chronological constraints are considered (i.e., based on isotopic granitoid ages, e.g., [10]).

**Chronology:** Silicic lunar surface features are ancient, with crater count ages varying from 4.07-3.38 Ga. Hansteen Alpha, the largest of the silicic domes, is composed of several distinct units with surfaces emplaced between ~3.74 and 3.5 Ga [11]. The Gruithuisen Delta and Gamma domes are slightly older, exhibiting ages of ~3.8 Ga. The CBC was active around the same time as the Mairan Domes, with the earliest possible onset of volcanism at ~3.8 Ga [12]. The extrusion of the Lassell Massif, the oldest of the lunar silicic domes, occurred between 3.95 and 4.07 Ga [13].

Laboratory-based ages of felsic samples fall broadly into two groups—an older group ≥4.3 Ga, and a younger group, formed ~3.9 Ga [e.g., 9, 14, 15, and references therein]. It has been suggested that the younger group might represent an origin following the Imbrium event whereby granitic melt formed as a result of heating and melting, and was mobilized and emplaced along an Imbrium-related ring-fraction system [7, 15]. The age of Imbrium basin formation is notably older than the majority of silicic lunar features.

Likewise, it is notable that nearly all isotopically dated silicic samples are systematically older than the crater count dated silicic surface features. Given the apparent age difference, one might question whether the silicic features observed on the lunar surface are the source regions for the silicic lithologies that have been studied in the Apollo samples. It is possible that the samples represent more ancient lithologies that have been destroyed or obscured by younger events.

**Conclusions:** The ages obtained thus far for granitoid rocks from the Moon may reflect the time at which they were originally extruded/intruded, or were partially or fully reset due to later impact event(s). Nevertheless, they are consistently older than the crater counting ages of the lunar silicic surface features. Isotopic ages of samples of the felsic domes and/or of young basaltic lava flows used to anchor the lower end of the crater age counting curve and that have potential to correct any inaccuracy in the absolute calibration of crater counting (e.g., [16]), would confirm or correct this apparent age disparity.

The Moon as Its Own Planet. J.T. Struck, 1A French American Museum of Chicago, NASA, Dinosaurs Trees Religion and Galaxies (PO BOX 61 Evanston IL 60204 sealsrosesandstars@yahoo.com).

Introduction:  The Moon is large enough so that the Moon can be considered its own planet. The Moon can be seen as revolving around the Sun, sweeping out an area, being round, having the characteristics of being a planet according to the International Astronomical Union 2006 formulations.

Discussion:
The idea of the Moon as its own planet would give the area a double planet characteristic.
The idea would mean we have already had manned landings on a planet.
The idea would increase the number of planets.
The idea would alter our understanding of the Solar System as having more planets.

Conclusion:
The Moon as planet could be further discussed and debated.
**Introduction:** The Apollo 17 landing site and sample suite has been intensively studied, including detailed studies of rock and soil samples [1], field geology [2] and remote sensing [3]. While the chemistry of the Apollo 17 regolith is well known [4], its mineralogy has been less extensively reported.

Here, we combine quantitative XRD analysis of 43 Apollo-17 lunar soil samples from 19 sampling stations and 60 m resolution mineral maps [5] from SELENE Multi-band Imager (MI) [6] to illustrate the detailed mineralogy and petrology of this landing area and its relationship to the local geology. Our modal mineral abundances of XRD analysis for six soil samples (25–45 µm fraction) show a good agreement (R² = 0.97) with data from the Lunar Sample Characterization Consortium (LSCC) [7–9], which were obtained by SEM point counting. In addition, the mineral abundances of A17 sampling stations extracted from MI mineral maps also show good correlation with XRD results.

**Results:** The mineral modes of 43 Apollo-17 lunar soil samples are analyzed with the rock classification diagram of Stöffler et al. (1980) [10]. We also extracted mineral abundances from the fresh pixels (OMAT>0.25) on top of the Sculptured Hills and the South and North Massifs from MI mineral maps, then averaged the mineral modes for the three features. Several clusters are observed in XRD-derived mineral abundances, and they appear to correlate with location of the stations. Sculptured Hills (A17-S8, LRV 11), South Massif (A17-S2), and North Massif (A17-S6, S7, LRV 10) are distinct clusters on mineral mode plots. Samples from the South Massif contain the most abundant plagioclase, and the local rock type represented by this composition is anorthositic norite. The landslide (A17-S3, S4, LRV 4–5) located at the north slope of South Massif, and most of the samples from here show similar compositions to South Massif, while some of them are more mafic, which may be the result of mixing with mare basalts from the Taurus Littrow valley floor. Samples from the North Massif are similar to those of the South Massif, except they contain less plagioclase. Mineral abundances on the tops of the massifs from MI maps show somewhat more anorthositic composition. XRD analysis show that samples from Sculptured Hills are mainly gabbroic norite, and MI minerals indicate similar compositions but with more diversity in plagioclase content, which agrees with that suggested by Moon Mineralogical Mapper (M³) data [2].

Mare units include the center Valley (A17-LM, S1, S5, S9, LRV 1–3, LRV 7–9 and LRV 12). The average ilmenite content for samples from the Valley is ~15.7 wt.%, which suggests very high Ti mare basalts [1]. We observed two different kinds of olivine-bearing high-Ti basalt samples, one group has higher olivine content (>8 wt.%), and the other one has relatively lower olivine content (<2 wt.%), consistent with modes of basalt rock samples [1]. No regolith samples show VLT mare basalt compositions known from studies of small basaltic fragments [1, 3] in the Valley.

**Conclusions:** We combined the XRD analysis of A17 lunar soil samples with MI mineral maps to investigate the mineralogy of Apollo 17 landing site. Our results suggest that the North and South Massifs have similar mineralogy, which is consistent with [3]. Samples collected at the base of the Sculptured Hills show less diversity of compositions compared to remote sensing data. We observed low-olivine and high-olivine high-Ti mare basalts in the Valley, but no regolith samples dominated by VLT basalts.

**Future work:** Based on the results of this work, we are able to calibrate the mineral abundances of MI maps with XRD analysis of A17 lunar samples, then develop new rock type maps of Apollo 17 landing area. Armed with this calibration, new global rock type maps can be made by applying this calibration and with samples from all the six Apollo missions.

Introduction: A hard-landing mission using a penetrator has a great advantage, being lightweight compared to a soft landing system. LUNAR-A was first approved as a lunar penetrator mission, however, it was canceled in 2007 due to the delay of the penetrator development. After that, the penetrator technology was refined on the level of ground experiments in 2011. We re-design the mission to optimize small class mission using Epsilon launch vehicle and submitted to the M-class mission of JAXA as APPROACH (Advanced Penetrator Probe Applied for a Challenge of Hard landing) in January 2018. This paper reports science objectives and an outline of mission concept.

Science Objectives of the APPROACH: The objectives we defined are derived from one of the fundamental questions of science; “how and why life exists on the Earth and whether life is universal in the universe.” Today’s remaining questions in lunar science are summarized by Lunar Exploration Roadmap (Exploring the Moon in the 21st century) which was compiled by the Lunar Exploration Analysis Group (LEAG: https://www.lpi.usra.edu/leag/). By referring to this, we define the following three objectives and investigations of this mission;

Objective 1. Understand the physical conditions of the lunar-forming giant impact.
=> Constrain the bulk abundance of refractory elements on the Moon and understand the thermal environment of the lunar-forming disk
=> Investigate the structure of the lunar upper mantle.

Objective 2. Understand thermal evolution of the Moon.
=> Constrain the heat production in the Procellarum KREEP Terrane (PKT) region of the Moon and understand the current thermal environment of the Moon

Objective 3. Understand impact phenomena on planetary bodies.
=> Understand the energy partitioning of impacts
=> Understand the impact environment of the Earth-Moon system.

On the other hand, in order to approach the goal of the planetary technology, we define one objective as;

=> Penetrator development and demonstration in space
=> Penetrator deployment and surface penetration on the Moon, and performance verification

Basic configuration of the APPROACH: As of now, APPROACH is basically a succession of LUNAR-A mission heritage, although the number of the penetrator is reduced to one(Figs. 1 and 2). The science instruments onboard are seismometer and heat-flow measurement respectively to achieve the science objectives described above. In order to determine internal structure of the Moon with one station, we are also planning to deploy an onboard camera to detect impact flash with the aid of ground network observations.
IMPORTANCE OF E/PO ACTIVITY IN LUNAR SCIENCE. J. Terazono¹, ¹The University of Aizu, Tsuruga, Ikki-Machi, Aizu-Wakamatsu, Fukushima 965-8580, JAPAN.

Introduction: All scientists including lunar and planetary science may and should know the importance of E/PO (Education and Public Outreach) activity to widen public interest (and eventually research budget and political recognition of research).

The E/PO activity in scientific region is more important than technology domain as these researches are mainly driven by taxpayers’ money. Recognition of importance of research by public will bring us more research accomplishment.

Rise of the boom of lunar exploration is based on wider scientific research activity. Private companies, not national sectors, will have some functions of the exploration activity in near future, however, they have also obligations for explanation of purpose of investment for their stakeholders. It turns out that, even scientific lunar missions driven by private sectors, we have E/PO importance and, in some content, obligation.

We can take one intensive example of E/PO activity in Google Lunar X Prize [1] which ended with no winners for lunar landing and roving in mid-January 2018. HAKUTO [2][3], Japanese team of GLXP candidate, sorted out series of public outreach campaign from their foundation period to rover completion stage. These activities include naming campaign for their rover and forming and operating “fun team” with closed and privileged events. These activities made interest of lunar exploration, not only their challenge but overall Japanese lunar exploration including ones by JAXA, and eventually assured their business enterprise for future lunar resource development.

Difficulty of E/PO Activity in Lunar Science: However, we should also point out that there are many difficulties and hard point to be getting over. Here are some of them [4]:

- Dense contents of lunar science: many specialized terminology, newly generated scientific and technical concepts and awkward mathematical expressions should be incorporated in proceeding E/PO activity of lunar science. If you start with description of lunar mineralogy, you will have to include enormous background information with plain expression which can be understood by general public, generally with no mathematical expressions. However, most people do not like to read bunch of texts which they have little interest.

- Depletion of human resources in E/PO region: To make public pay attention to lunar science, technical and strategic information dispatch is necessary. Here, the term “technical” means not simple meaning of manufacturing, but well-founded, professional and widely accepted technique of information transmission of expertized category. It needs high skill of academic achievement as well as balancing information choice, deep understanding for overall scientific regions and experience of presentations in public including lectures, events and writings (including digital and paper-based). We need to turn out such manpower strategically as there are very few people working for lunar science E/PO worldwide.

- Few budget for E/PO region: Also, we should seek for appropriate plan and strategy for obtaining enough budget for lunar science E/PO. Many of E/PO programs have been carried out as one of ancillary project for exploration missions. However, we should emphasize that it is time to widen this concept to one which is supported by research community. Many mission-related projects ended after mother mission concluded, and their legacy often did not take over succeeding missions.

- No definite revenue model: To achieve these goals, it is also time to consider E/PO activity as company-based work. Actually, E/PO project of OSIRIS-REx [5], Asteroid exploration, is led by a private company founded by a mission manager. Such “business model” will be common from here on, as this cannot be interfered by political movement.

What We Should Do Now: We should first regard that our research world is now entering “great competition era” to obtain public interest and eventually research budget. The real competitor is not an adjacent project, but different scientific research region.

To promote lunar science research, we need to have an understanding that E/PO activity is its base, not an appendage. First, we should construct solid plan to promote E/PO activity worldwide, including strategy for budget acquisition and human resource allocation and nature. It can be multi-year or decadal project, but now is the time to kickstart. Solid strategy, understanding of decision makers and cooperation of scientists will make lunar science E/PO wider and stronger.

References:
MAGMAS EVOLVED FROM A CRUSTAL-COMPONENT-ENRICHED BULK SILICATE MOON MODEL COMPARED WITH LUNAR METEORITES. S. Togashi, Geological Survey of Japan, AIST (Central 7, Tsukuba 305-8567, Japan; s-togashi@aist.go.jp).

Introduction: We have proposed a new Crustal-Component-Enriched Bulk Silicate Moon Model (cBSM) with sub-chondritic Ti/Ba, Sr/Ba, and Sr/Al ratios [1, 2]. The cBSM is enriched in crustal components (e.g. Al, Ba, and Th) of proto-bodies relative to the bulk silicate Earth, and it is the source of the parental magmas of lunar feldspathic crusts. Furthermore, refractory element concentrations in the host mafic magmas of typical feldspathic crust, estimated from feldspathic lunar meteorites [3], are consistent with those of ferroan anorthosite (FAN)-host magma from the cBSM [1].

In this paper, I compare the more evolved magmas from the cBSM with the compositions of lunar meteorites with intermediate iron concentration [4].

Evolution of magma from the cBSM: A polybaric three-step model was applied by extending the two-step model [1, 2]. In the first step, an initial magma was generated from the cBSM as a 40% equilibrium melt under high pressure (0.8 GPa). In the second step, the magma separated and ascended to a shallow depth (0.3 GPa), where it remained and crystallized in equilibrium to a 20% melt and fractionally with solids to a 10% melt of the cBSM. A part of the 10% melt, the FAN-host magma, mixed with plagioclase to form feldspathic crust [2]. In the third step, the remainder of the 10% melt further evolved fractionally with solids to a 1% melt of the cBSM to form evolved magma at near-surface conditions (0.01 GPa). Evolved magma compositions from the cBSM were investigated by using the Rhyolite-MELTS algorithm [5, 6] and partition coefficients for trace elements between minerals and melts [1, 7, 8, this study]. The C1-normalized patterns of refractory elements in the evolved magmas basically inherited the cBSM patterns for Ba, La, Th, Sm, and Yb (Fig. 1).

Lunar meteorites: Among lunar meteorites randomly sampled from the whole Moon, three extreme types are recognized: 1) brecciated anorthosite, 2) mare basalt and brecciated basalt, and 3) Th-rich (KREEP) impact-melt breccia [9]. Although most lunar meteorites with intermediate iron composition (5–16% FeOt) are mixtures of these extreme types, several are not (e.g. open symbols in Fig. 2, [4]); these have greater Th/Sm and lower Sm concentration than ternary mixtures, suggesting a signature of lower-crustal mafic rocks containing little or no KREEP and a possible origin from the SPA basin [4]. For meteorites with 8–16% FeOt ([4], Fig. 2), sharp Sr and Ba spikes are observed in some weathered meteorites (dashed lines), but other refractory elements show generally similar patterns to those of the evolved magmas from the cBSM (Fig. 1), except with greater Ti and Eu depletion in the meteorites.

Conclusion: Magma evolved from the cBSM [1, 2] would have sub-chondritic Ti/Ba, Ti/Th, Sm/Th, and La/Th ratios, mostly similar to those of lunar meteorites with intermediate Fe concentration [4]. This result supports the addition of a crustal component enriched in Ba and Th to the cBSM from alkali-rich proto-bodies with chondritic refractory element ratios by heterogeneous accretion during impact [1].

LUNAR LAVA TUBES: A POTENTIAL OPTION FOR FUTURE HUMAN HABITATION ON THE LUNAR SURFACE. L. W. TOMBROWSKI\textsuperscript{1} and A. A. MARDON\textsuperscript{2, 1} Antarctic Institute of Canada (Post Office Box 1223, Station Main, Edmonton, Alberta, Canada T5B 2W4, aamardon@yahoo.ca).

\textbf{Introduction:} For the past several years it has been suggested that the next manned mission to the Moon could make use of lunar lava tubes as habitable shelters and/or storage areas. The lava tubes on the moon would provide protection against cosmic radiation, micrometeoroids, meteorites, and other natural hazards while also providing a habitable environment with relatively stable temperatures compared to the wildly fluctuating day/night temperatures on the Moon’s surface.

\textbf{Benefits:} There are numerous potential benefits to building a manned lunar base inside a lava tube. Due to the more stable temperatures in the tube, space suits and base modules would not require as extensive of temperature regulation systems as on the surface of the moon. This would allow astronauts a greater degree of freedom of movement while inside the tube. Eliminating the need for bulky insulation also means a lunar base only requires pressurization, therefore improving the size and portability of base components (this is assuming that the risk of debris falling from the roof of the tube is negligible). The protection from cosmic radiation inside the tubes presents the possibility of a long-term manned lunar mission without the need for as extensive of shielding from radiation. Lunar lava tubes may also provide the opportunity for mining operations and geological study from directly beneath the Moon’s surface. Study of the tubes themselves may provide clues as to how the Moon was formed.

\textbf{Further Study:} More information on the exact structure and location of lunar lava tubes is required. At the present moment, only observational evidence has been found to support the existence of lava tubes on the Moon. Unmanned missions using lunar rovers and/or probes must be conducted in advance of a manned mission in order to determine the suitability of a tube for human habitation. Research must also be conducted in order to determine safe and efficient methods of moving supplies, astronauts, and other equipment in and out of the tube. Due to a lower gravity and absence of atmosphere, lunar lava tubes could be significantly larger than lava tubes on Earth.

\textbf{Seismic Activity:} The exact cause and intensity of seismic activity on the moon is currently unknown. Therefore, study on the seismology of the Moon must be conducted in order to measure the potential risk of a lava tube collapsing or debris falling from the ceiling of a tube. Methods for safely clearing the floor of a tube of debris, boulders, or other potential obstructions must also be looked into.

\textbf{Power:} Considering the scenario where the main base and living quarters are located inside of a lunar lava tube, options for power generation and storage would have to be examined. If the power is generated from outside the tube (e.g. solar panels), an appropriate power transfer system and backup system must be established inside the tube, or vice versa if power is generated inside the tube.

\textbf{Conclusion:} The usage of lunar lava tubes for human habitation and/or storage in future manned missions to the Moon is largely theoretical at this point in time. There are unquestionably great potential benefits to the concept, however a considerable amount of study and further unmanned missions to the Moon will be required before any conclusions regarding the viability of the tubes can be reached.

Astrolife, Astrobiology, Exobiology

Let us begin this abstract with one word - spreading.

Humanity has made many big, huge steps throughout their time, especially in the last hundred years. Steps in science, physics, astronomy, biology, quantum mechanics and more. Everyday we are trying to solve some puzzles, and by exploring the world around us we actually explore ourselves, and unstoppable process of evolution.

Any form of life in core has two lines of code: eat the host and spread around. If we look even further it seems like the whole known universe is doing the exact same thing - spreading, creating space-time from nothingness, and eating some unknown host, but this subject is too philosophical for our topic.

To make big steps, first we have to learn how to walk, how to make small steps. Actually those small steps are something that we are all making every day, everywhere. These are tiny little astrobiological steps.

Introduction: First of all, we do not believe that humans in current form are able to reach any interstellar distances. Probably genetic and cyber biology will come up with the solutions, but until then we still can try to grow plants in space. This could be of benefit for the human interaction and use, as a: food, additional oxygen, energy source and psychological support, but it will create also possibility for new, unknown branch of the plants evolution.

Phases of research and simulation:
1) In the specially created simulation of the Moon soil, which we got from the ESTEC team, we have planted 3 different seeds. Seeds were couted in the mixture of the clay and minerals.

2) Moon soil was treated in the first two weeks only with a water and LED red-blue light in the daily rhythmical way to support and accelerate plants grow.

3) After two weeks on the top of water-light, soil was treated with the additional minerals:
   a. 2.7% nitrogen organic (N)
   b. 1.3% anhydride phosphoric (P2 O5)
   c. 5.9% potassium oxid (K2 O)

Experiment at the Moon Lander:
During the EVA at the Euro Moon Mars – Moon short simulation at the ESA-ESTEC, astronauts have performed spectrometral readings of the plants leaf reflectance [1,2] with the device located at the Moon Lander.

The spectrometer was remotely controlled from the Habitat controlled by Habitat CapCom in the synchronised action and communication with the astronauts outside.

In addition to collecting more data, we performed also remote reading of Moon Lander thermometer and hygrometer.

Data collected in this process first were stored at the Habitat local data server, and then transferred to the Mission Control for the further analyses.

ACTIVE SEISMIC EXPLORATION PACKAGE ON THE MOON. T. Tsuji¹, T. Kawamura², A. Araya³, Y. Nagata⁴, Y. Ishihara⁵, K. Ogawa⁶, T. Kobayashi⁷, S. Tanaka⁸, T. Aizawa⁹, ¹Kyushu University (744 Motoooka, Nishiku, Fukuoka, 819-0395 Japan; tsuji@mine.kyushu-u.ac.jp), ²National Astronomical Observatory of Japan, ³The University of Tokyo, ⁴Institute of Space and Astronautical Science/Japan Aerospace Exploration Agency, ⁵Kobe University, ⁶Ritsumeikan University, ⁷Sunco Consultants

Introduction: Developing a seismic exploration package that is compatible with small to middle size spacecrafts will open a new window to investigate interior of planetary bodies including the Moon. We have been designing and developing an active seismic exploration package (ASEP) with seismometers, active seismic source and anchoring system. Our seismic exploration package was designed to investigate from shallow formation (i.e., ice saturation) to deep formation (i.e., thickness of regolith) of the Moon, by integrating surface-wave analysis, seismic reflection analysis and seismic refraction analysis. Here we present the basic concept of our seismic exploration package and its experimental results. We then discuss the possibilities of future space missions.

Designed active seismic exploration package: The active seismic source is designed so that we can control the generated waveform [1]. We usually use sweep waveform with wide frequency range. By stacking the continuously-generated waveforms, we improve signal-to-noise ratio of the seismic signal. Thus, less-energy waveform derived from small-size motor (or piezoelectric element) could be utilized for exploration of deeper formation. This is a well-developed method in terrestrial seismology and resource exploration known as ACROSS (Accurately Controlled Routinely Operated Signal System) [2].

By recording the source signal by seismometer array, we investigate the subsurface structure and properties. If both lander and rover have active source system and seismic array, we can use multiple seismic exploration methods; (1) surface wave analysis, (2) seismic refraction analysis and (3) seismic reflection analysis. As described in next section, we can explore relatively shallow formation including ice distribution via (1) surface-wave analysis. Using (2) seismic refraction (tomography) analysis, we investigate P-wave and S-wave velocity distribution between lander and rover. (3) Seismic reflection analysis can be used to investigate formation boundary beneath the rover (and lander).

The mechanics of our designed seismic exploration package is relatively simple. Furthermore, even if some devices have trouble on the Moon, we can investigate the lunar subsurface structure by applying other seismic analyses (methods).

The anchoring mechanism should be considered especially on low gravity condition. One of the major problems in planetary observation is the coupling between the instruments and the ground. This will be an important issue especially for active seismic source.

Surface wave analysis to investigate shallow formation: Here we describe method and experimental results of surface wave analysis. To estimate the degree of freezing in sediments, seismic surveys would provide useful information because seismic velocities in porous rocks vary significantly with the degree of pore-fluid freezing [3]. A small amount of frozen water in the voids of a porous sediment rock can lead to large S-wave velocity increases [4]. Therefore, the S-wave velocity distributions derived from surface-wave analysis could provide useful information to reveal ice saturation in shallow formation.

We conducted active-source seismic exploration in the test field in Japan Aerospace Exploration Agency (JAXA). The test field is filled with loose sands of ~50cm thickness. In this experiment, we conducted seismic survey with several acquisition parameters. When we applied the active seismic survey for small-size receiver array, we retrieved clear shot gather (Figure 1a). We further calculated dispersion curve from the shot gather and obtained S-wave velocity profile beneath the array using GA inversion [5] (Figure 1b). The S-wave velocity in shallow formation could be accurately estimated and continuously increases for depth direction, suggesting that ice can be identified as anomalous high S-wave velocity.


Figure 1. (a) Retrieved shot gather of small array. (b) S-wave velocity derived from surface-wave analysis.
LUNAR METEORITES: WHAT’S NEXT? R. A. Zeigler¹, K. H. Joy², F. M. McCubbin³, R.L. Korotev⁴, J. Gross³, T. Arai⁵, M. W. Cahee⁶, and K. Nishiizumi¹. ¹Astromaterials Acquisition and Curation Office, NASA Johnson Space Center, 2101 NASA Parkway Mail Code X12, Houston TX 77058, USA. ryan.a.zeigler@nasa.gov. ²School of Earth and Environmental Sciences, University of Manchester, Manchester, UK. ³Department of Earth and Planetary Sciences, Washington University in St. Louis, St. Louis, MO, USA. ⁴Dept. of Earth and Planetary Sciences, Rutgers University, Piscataway NJ. ⁵Planetary Exploration Research Center, Chiba Institute of Technology, Chiba, Japan. ⁶Department of Physics and Astronomy, Purdue University, West Lafayette, IN, USA. ³Space Sciences Laboratory, University of California, Berkeley, CA, USA.

Overview: Lunar meteorites are fragments of the Moon ejected by impacts into the lunar surface. There are currently 326 lunar meteorite stones with a total mass of 217.7 kg that comprise 138 distinct lunar meteorites. These meteorites come from random locations on the Moon, and after pairing considerations are taken into account, likely represent >40 different sample locations (i.e., source craters) on the Moon. Collectively, the lunar meteorites represent our best average composition of the lunar crust, but their lack of geologic context and terrestrial weathering can limit their applicability to some studies. This is in contrast to the Apollo samples that have excellent geologic context, are relatively pristine, but come from a relatively restricted region of the lunar nearside. Together these two lunar sample suites are complimentary, however the lunar meteorites are the only lunar sample source likely to yield significant new samples for scientists over the next decade. Here we will discuss “What’s Next?” in lunar studies relevant to the lunar meteorite suite.

Discussion: There are two sources of “new” lunar meteorite samples available to scientists that will yield important information about the topics listed below: the identification of new components within the existing meteorite collections, and the discovery of new lunar meteorites. (1) More systematic studies [e.g., 1] of the petrography of the feldspathic lunar meteorites (n=91; 3-7 wt% FeO) and the “mingled” meteorites (n=16; 7-10 wt% FeO) would give a better understanding of the lithologic diversity in lunar highlands. Of particular interest is the identity of the non-mare mafic components in both groups. (2) Although most Apollo anorthosites are ferroan and Na-poor, many FLM contain magnesia or Na-rich anorthosites, and there is orbital evidence for extremely Fe-poor anorthosites [2] as well as spinel anorthosites [3]. Detailed studies of these components would have significant implications for magma ocean crystallization. (3) Lunar meteorite basaltic (n=10) and basaltic breccias (n=14) contain extremes in both age [4,5] and composition [6,7] relative to the Apollo basalts. Thus, continued studies of new basaltic materials in meteorites should contribute to our understanding of the evolution and variability of lunar mantle. (4) The volatile budget (e.g., F, Cl, H₂O) of the Moon has implications for the origin and evolution of the Moon. In fact, lunar meteorites Miller Range 05035 and Dhofar 458 record extremes in the range of Cl isotopic compositions of lunar apatites, which help in our understanding of the origin and distribution of volatiles in the lunar interior [8,9] (5) Samples from the South Pole-Aitken (SPA) Basin (the largest and oldest basin on the Moon) likely hold the key to whether there was a terminal lunar cataclysm and perhaps are a direct sampling of the lunar mantle. Based on the number of source craters, there is a ~95% chance that there is a SPA meteorite in the lunar meteorite sample suite [10]. There is disagreement about whether a lunar meteorite has been identified from that basin [10,11]. (6) Current evolved lithologies from the Moon (e.g., granites, monzogabbros) are found as small fragments within breccias or fragments in the soils. Our understanding of late stage crustal evolution would be revolutionized if a lunar meteorite could be identified from one of the large evolved volcanic features identified from orbit (e.g., Compton Belkovich region). (7) Additional determination of the age of components in lunar meteorites (especially impact melt clasts) [12, 13] will have important implications for the Moon’s impact history. (8) Exposure records and antiquity records of regolith meteorites will help to unlock surface reprocessing of the Moon. (9) By comparing lunar meteorites with recent high-spatial-resolution remote sensing data sets [14] and, thus, narrowing down their provenance, lunar meteorites can be better utilized to expand our understanding of the Moon.

Summary: Lunar meteorites, both the current collection and those still to be discovered, contain insights into many of the big-picture lunar science questions; their lack of geologic context will limit their usefulness in addressing some lunar science questions [15].