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Lunar Science for Landed Missions Workshop Findings Report

Erica R. Jawin[1], Sarah N. Valencia, Ryan N. Watkins[2], James M. Crowell[3], Clive R. Neal[4], Gregory Schmidt[5]

[1]Brown University Department of Earth, Environmental, and Planetary Sciences, Providence, RI 02912, [2]Planetary Science Institute, 1700 E. Fort Lowell, Suite 106, Tucson, AZ 85719, [3]Arizona State University, School of Earth and Space Exploration, 781 E. Terrace Rd, ISTB4, Tempe, AZ 85287, [4]Notre Dame University Department of Civil & Environmental Engineering & Earth Sciences, Notre Dame, Indiana 46556, [5]NASA AMES Research Center Solar System Exploration Research Virtual Institute, Mountain View, CA 94035

Executive Summary

The Lunar Science for Landed Missions workshop was convened at the NASA Ames campus 10-12 January 2018. Interest in the workshop was broad, with 110 people participating in person and 70 people joining on line for all or part of the workshop. In addition, there have been over 1400 views of the website (https://lunar-landing.arc.nasa.gov/), as it includes video recordings of many of the presentations.

This workshop defined a set of targets that near-term landed missions could visit for primarily scientific exploration. The scope of such missions was aimed primarily, but not exclusively, at commercial exploration companies with interests in pursuing ventures on the surface of the Moon. Contributed and invited talks were presented that detailed many high priority landing site options across the surface of the Moon that would meet scientific goals in a wide variety of areas, including cratering processes and dating, volatiles, volcanism, magnetism, geophysics, and astrophysics. The capabilities of commercial companies were presented in panel discussions and interest was high enough that an extra panel was added to the program. This workshop also heard from JAXA and ESA about international plans for lunar exploration and science.

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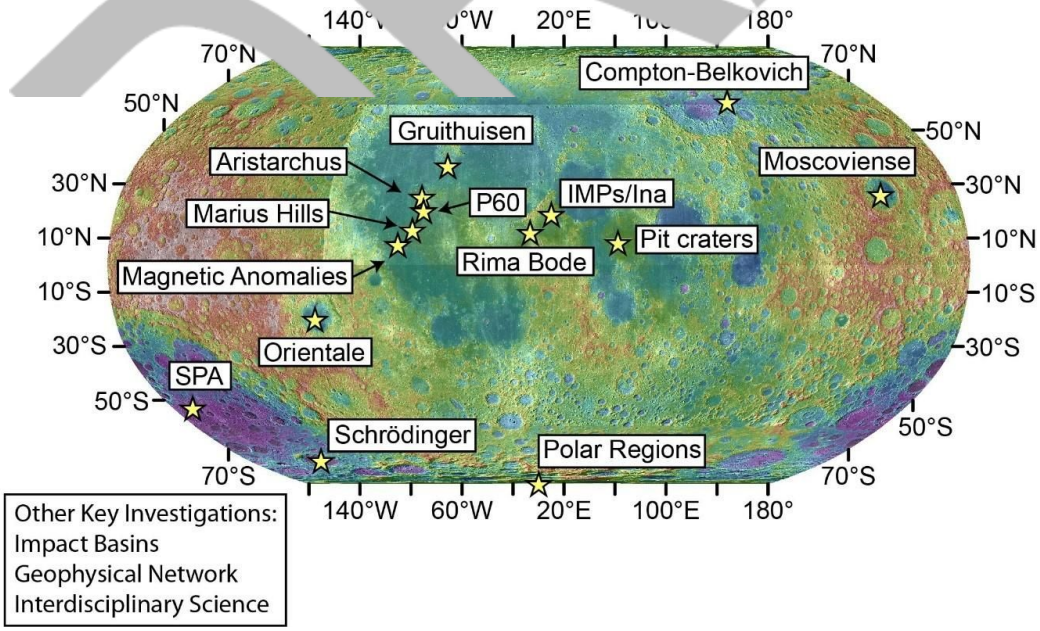

Figure ES-1: Potential landing sites for lunar science outlined in this report, indicated with yellow stars.

As seen in Figure ES-1, there are numerous opportunities for addressing important lunar science questions defined by National Academies documents and Lunar Exploration Analysis Group Reports. Many of these notional sites we discussed in more detail by individual presentations.

The list below represents the set of landing sites and/or investigations that were presented at the workshop that would address high priority science and in many cases exploration questions:

- Aristarchus (50˚W, 25˚N)
- Compton-Belkovich Volcanic Deposit (99.5˚E, 61.1˚N)

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- [illegible] (40.5[illegible].6˚N)
- [illegible]gular Mare Pa[illegible] (5.3˚E, [illegible]66˚N, Ina)
- Magnetic Anomalies and Swirls (e.g., 59˚W, 7.5˚N, Reiner Gamma)
- Marius Hills (53˚W, 13˚N)
- Moscoviense (147˚E, 26˚N)
- Orientale (95˚W, 20˚S)
- P60 Basaltic Unit (49˚W, 20˚N)
- Pit craters (e.g., 33.22˚E, 8.336˚N, Mare Tranquillitatis)
- Polar Regions (e.g., 0.0˚E, 89.9˚S, Shackleton Crater)
- Rima Bode (3.5˚W, 12˚N)
- Schrodinger (135˚W, 75˚S)
- South-Pole Aitken Basin (170˚W, 53˚S)
- Global network of nodes - Geophysical
- Global network of nodes – Exosphere
- Dating Large Impact Basins to Anchor Lunar Chronology
- Interdisciplinary Science – Astrophysics (far side radio telescope; near side deployment of laser retroreflectors); Heliophysics (sampling of paleoregoliths between lava flows)

In addition to landing site discussions, technology developments were also specified and included:

- Communications relay (for far-side operations),
- Lunar night survival,
- Cryogenic sampling, storage, return, and curation,
- Autonomous hazard avoidance
- Mobility
- Dust mitigation.

These technologies were considered as enhancing to the types of investigations presented.

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evident th[illegible] place [illegible] scientific explorat[illegible]gets that will inform us on the origin and evolu[illegible] the Earth-M[illegible]system [illegible] the history of the inner Solar System, but also has enormous potential for enabling human exploration and for the development of a vibrant lunar commercial sector.

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Introduction

The Lunar Science for Landed Missions workshop was held on January 10-12, 2018 at NASA Ames Research Center and was attended by both lunar scientists and representatives from commercial companies. The workshop was co-sponsored by the Solar System Exploration Research Virtual Institute (SSERVI) and the Lunar Exploration Analysis Group (LEAG). The primary goal of the workshop was to produce a set of high-priority landing site targets for near-term lunar missions generated by the lunar science community. These high-priority targets are intended to guide primarily, but not exclusively, commercial companies interested in pursuing scientific missions on the lunar surface. Scientists were invited to submit abstracts detailing high-priority landing sites on the surface of the Moon and discuss the types of science investigations that could be conducted. These contributed talks presented landing site options across the surface of the Moon that would meet scientific goals in a wide variety of areas, including cratering processes and dating, volatiles, volcanism, magnetism, geophysics, and astrophysics. Invited talks and panels from commercial attendees focused on new technologies to enable landed lunar missions and potential payloads of lunar landers. In addition, invited talks from international colleagues spoke about the space programs in Japan and the European Space Agency. This report summarizes the findings of the workshop and provides a brief analysis of priority landing sites and how missions to these sites would meet key science and exploration goals determined by NASA and the scientific community.

Summary of Key Science Goals Identified by Previous Studies

Throughout this report, we will refer to three documents that have outlined key science questions to be addressed through lunar exploration: The 2007 National Research Council's (NRC) Scientific Context for the Exploration of the Moon (SCEM), the 2017 LEAG Specific Action

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Team R[illegible] Advan[illegible] Science [illegible] the Moon (the AS[illegible]AT assessed progress made in achie[illegible] the science go[illegible] laid out [illegible]he 2007 NRC Report), and Vision and Voyages for Planetary Science in the Decade 2013-2022 (henceforth referred to as the Planetary Decadal Survey). Each landing site highlighted in this report addresses at least one, but often many, of the science goals listed in these documents.

The **Scientific Context for the Exploration of the Moon** (SCEM) study identified eight areas of scientific research that should be addressed by future lunar exploration. Within each concept was a list of 35 prioritized science goals, which we do not outline here but instead refer the reader to the SCEM (Table 5.1).

The science concepts were defined and ranked as follows:

S.1 The bombardment history of the inner Solar System is uniquely revealed on the Moon.
S.2 The structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated planetary body.
S.3 Key planetary processes are manifested in the diversity of lunar crustal rocks.
S.4 The lunar poles are special environments that may bear witness to the volatile flux over the latter part of solar system history.
S.5 Lunar volcanism provides a window into the thermal and compositional evolution of the Moon.
S.6 The Moon is an accessible laboratory for studying the impact process on planetary scales.
S.7 The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies.

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S.8 [illegible]ed with [illegible]tmosphere and du[illegible]vironment of the Moon are accessible [illegible] scientific stu[illegible]hile the [illegible]vironment remains in a pristine state.

Research opportunities for science of the universe from the surface of the Moon were discussed separately from these eight science concepts. These science goals included radio astronomy from the surface of the Moon, astrobiology, heliophysics, and remote sensing of Earth from the Moon. While not explicitly outlined as key science concepts by the SCEM, we recognize the value of these types of investigations and include references to them where applicable.

In addition to evaluating the progress made to achieving the 8 scientific concepts of the SCEM report, the **ASM-SAT** also added three new concepts:

A.1 The Lunar Water Cycle: while the SCEM report included polar volatiles, work over the last decade has pointed to a water cycle with three principle components: primordial (interior) water, surficial water (linked to solar wind), and polar (sequestered) water.

A.2 The Origin of the Moon: clues to lunar origin and geologic processes that operated during planetary accretion are recorded in the lunar rock record. Focused sample studies and sample return could be used to unlock these mysteries and test long-standing origin hypotheses.

A.3 Lunar Tectonism and Seismicity: over the last decade, high-resolution imagery has led to a dramatic increase in the number of tectonic landforms present on the lunar surface, including wrinkle ridges, rilles, and lobate scarps. The interior structure, thermal history, and mechanism(s) of heat loss of a planet are all related to the resulting distribution of surface tectonism.

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The [illegible]-SAT report documents that while progress in the original 8 science concepts of the SCEM report has been made, they still remain valid avenues for scientific investigation.

The **Vision and Voyages for Planetary Science**, or the Planetary Decadal Survey, identified key planetary science questions and provided a list of prioritized missions to be undertaken in the decade 2013-2022. The Decadal Survey identified three crosscutting themes for planetary science:

1. Building New Worlds: Understanding Solar System Beginnings
2. Planetary Habitats: Searching for the Requirements for Life
3. Workings of Solar Systems: Revealing Planetary Processes through time

Each of these themes contains key science questions, and we again refer the reader to the Decadal document for these. The report then breaks down key science questions for different categories of Solar System bodies; the Moon was included with the Inner Planets along with Mercury and Venus. The Decadal Survey stated that the overarching science concept that drives the study and exploration of the Inner planets is comparative planetology. Three objectives concerning inner planets were listed:

1. Understand the origin and diversity of terrestrial planets.
2. Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life.
3. Understand the processes that control climate on Earth-like planets.

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Scientific [illegible] that [illegible] be addr[illegible]d through surface e[illegible]ration of the Moon best fit in the first two o[illegible]tives. Several k[illegible] science g[illegible]ls were identified for each of these objectives, as outlined below:

Objective 1: Understand the origin and diversity of terrestrial planets.

- Constrain the bulk composition of the terrestrial planets to understand their formation from the solar nebula and controls on their subsequent evolution
- Characterize planetary interiors to understand how they differentiate and dynamically evolve from their initial state
- Characterize planetary surfaces to understand how they are modified by geologic processes

Objective 2: Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life.

- Understand the composition and distribution of volatile chemical compounds
- Understand the effects of internal planetary processes on life and habitability
- Understand the effects of processes external to a planet on life and habitability.

For the Moon specifically, the Decadal Survey specified two high priority New Frontiers class missions: South Pole-Aitken Basin sample return, and establishing a long-lived global Lunar Geophysical Network. In addition, it also stated there were other important science issues that could be addressed by future missions (see page 133 of the Planetary Decadal Survey). These include the nature of polar volatiles, the significance of recent lunar activity at potential surface vent sites, and the reconstruction of both the thermal-tectonic-magmatic evolution of the Moon

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and the i[illegible] of the in[illegible]olar System throug[illegible]e exploration of better characterized and [illegible] revealed luna[illegible]rains.

After 60 years of scientific exploration beyond Earth, neither humans nor robots have ever landed on the Moon's farside, yet the farside presents a unique opportunity for science and exploration. It contains the oldest impact crater in the inner Solar System – the South Pole Aitken (SPA) Basin, which, as discussed above, has been outlined as a high priority site for exploration by the Planetary Decadal Survey. A sample return mission to the SPA basin would provide a unique test of the lunar cataclysm hypothesis. The farside is also a unique location for low frequency radio astronomy and cosmology because it is free of Earth-based radio-frequency interference (RFI) and ionospheric effects. An array of farside radio telescopes would allow us to probe the first generation of stars and galaxies, to image radio emission from coronal mass ejections for the first time, and to study space weather in extrasolar planetary systems to investigate suitability for life. Missions to the farside would require a dedicated communications satellite, which this report identifies as a key technology development that would enable future exploration.

Summary of SKGs in lunar exploration

In addition to key science questions, Strategic Knowledge Gaps refer to the data that are needed to allow humans to return and thrive on the surface of the Moon. Retiring these SKGs will improve the effectiveness and design of lunar missions, while decreasing the risk associated with the mission. The SKGs were determined by NASA's Human Spaceflight Architecture Team and two LEAG Specific Action Teams.

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The three [illegible] lu[illegible]ience-ex[illegible]ation SKG themes [illegible] as follows:

1. [illegible]erstand the lu[illegible]esourc[illegible]tential (11 open SKGs)
2. Understand the lunar environment and its effects on human life (12 open SKGs)
3. Understand how to work and live on the lunar surface (25 open SKGs)

Each of these SKG themes is subdivided into specific gaps in our understanding of the lunar surface and environment. Theme one focuses on the composition, distribution, and usage of lunar volatiles in the lunar regolith, pyroclastic deposits, and at the lunar poles. Theme two focuses on solar activity and radiation at the lunar surface, the biological impact of dust, and how to maintain human health in the lunar environment. Theme three comprises several sub-themes concentrating on how human can produce resources, move around the lunar surface, and work and live in a safe environment. For these specific SKG subcategories we refer the reader to the LEAG-SAT SKG document available on the LEAG and NASA websites. Missions to each of the landing sites proposed here will aid in closing SKGs for future robotic and human lunar missions. See https://www.nasa.gov/exploration/library/skg.html for full details.

Overview of potential landing sites

Presentations and discussions at the workshop produced a list of the following landing sites where investigations would be relevant to the overarching documents used to guide this workshop. The following sections discuss the SCEM concepts, Planetary Decadal questions, and SKGs each of these sites addresses, as well as some key measurements and exploration scenarios.

- Aristarchus (50°W, 25°N)
- Compton-Belkovich Volcanic Deposit (99.5°E, 61.1°N)

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- C[illegible]ses (40.[illegible] 36.6°N)
- [illegible]egular Mare P[illegible]es (5.3[illegible] 18.66°N, Ina)
- Magnetic Anomalies (e.g., 59°W, 7.5°N, Reiner Gamma)
- Marius Hills (53°W, 13°N)
- Moscoviense (147°E, 26°N)
- Orientale (95°W, 20°S)
- P60 Basaltic Unit (49°W, 20°N)
- Pit craters (e.g., 33.22°E, 8.336°N, Mare Tranquillitatis)
- Polar Regions (e.g., 0.0°E, 89.9°S, Shackleton Crater)
- Rima Bode (3.5°W, 12°N)
- Schrodinger (135°W, 75°S)
- South-Pole Aitken Basin (170°W, 53°S)
- Global network of nodes - Geophysical
- Global network of nodes – Exosphere
- Dating Large Impact Basins to Anchor Lunar Chronology
- Interdisciplinary science

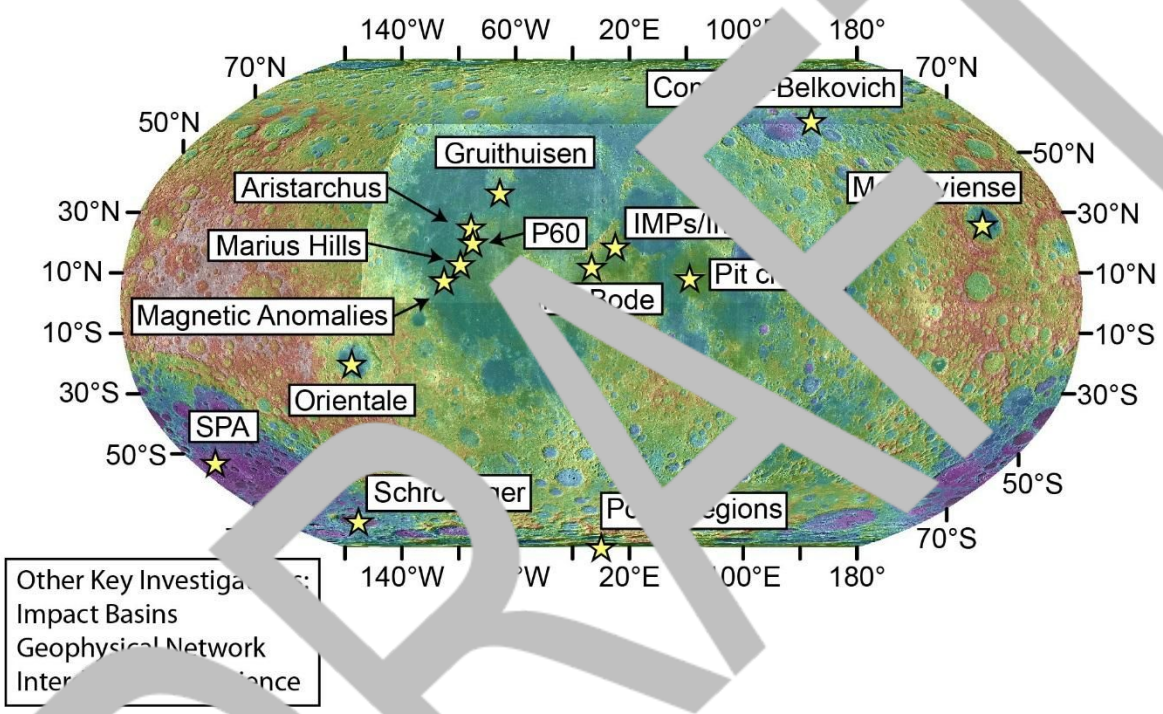

Figure 1: Yellow stars indicate the high-priority landing sites outlined in this report. LROC WAC global basemap (100 m/pix) with LOLA shaded topography.

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<u>Individual site analysis</u>

Aristarchus (50°W, 25°N)

The Aristarchus plateau is an uplifted block of highlands material (Zisk et al., 1977). The plateau contains the largest pyroclastic deposit (Gaddis et al., 2003), the widest and deepest sinuous rille (Hurwitz et al., 2013), and relatively young basalts immediately adjacent to the plateau (Hiesinger et al., 2011, see "P60 Basalt Unit" below). The pyroclastic deposit may contain volatiles in quantities up to several hundred ppm (Milliken & Li, 2017).

Relevance to Science Themes:

- S.1: Aristarchus plateau was uplifted during the formation of Imbrium basin (Zisk et al., 1977), while Aristarchus crater is a well-preserved Copernican-aged impact crater. Precisely dating these two units would help to constrain the crater size-frequency distribution (CSFD).
- S.2: The high concentration of volcanic units on the plateau provides a unique glimpse at the composition of partial melts of the lunar interior.
- S.3: A diverse suite of geologic units is available on the plateau, including mafic volcanic, silicic volcanic, and lunar crustal materials (Mustard et al., 2011).

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- S[illegible] contain[illegible] highest concentra[illegible] of volcanic units on the Moon (Zisk [illegible]al., 1977), incr[illegible]g evide[illegible] of explosive and effusive volcanism.
- S.6: Aristarchus crater is extremely well preserved, with deposits of impact melt accessible in the interior and exterior of the crater.
- A.1: Examination of the volcanic deposits will yield new information on the lunar interior volatile budget.

Decadal Survey relevance – exploration of Aristarchus will address the thermal-tectonic-magmatic evolution of the Moon and the impact history of the inner Solar System.

Decadal Objective 1:

- Constrain the bulk composition of terrestrial planets
- Characterize planetary interiors to determine how they differentiate and evolve
- Characterize planetary surfaces to understand how they are modified by geologic processes

Decadal Objective 2:

- Understand the composition and distribution of volatile chemical compounds

Relevance to Exploration Themes:

- SKG 1: The resource potential can be analyzed through studying the pyroclastic deposit, assessing the H and other volatile species within the deposit, and sampling techniques to best preserve volatiles.

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- S[illegible]: The [illegible]r environ[illegible]ntal effects on hu[illegible]ife can be studied by quantifying [illegible]iation at the lu[illegible] surface [illegible]d by studying the shielding effects of fine-grained pyroclastic materials.
- SKG 3: Living and working on the lunar surface can be studied by excavating, transporting, and roving in thick deposits of fine-grained pyroclastic materials.

Key Measurements: Ages (impact melt, pyroclastics, silicic material, etc.). Bulk chemistry and mineralogy. Volatile contents. Quantify regolith geomechanical properties.
Exploration Scenario 1: A lander to the western portion of the plateau allows access to the pyroclastic deposit or potentially silicic volcanics.
Exploration scenario 2: A rover on Aristarchus crater ejecta would allow access to volcanic and impact-related units from the plateau and surrounding region.

Science Themes	Exploration Themes	Mobility Required?	In Situ or Sample Return
S.1-3, 5-6, A.1	SKGs 1-3	No	Both

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Figure 2 [illegible] Plateau. ([illegible] LROC WAC bas[illegible]p with LOLA shaded topography. (Righ[illegible] LA-derived s[illegible]es.

<u>Compton-Belkovich Volcanic Deposit (99.5°E, 61.1°N)</u>

The Compton-Belkovich Volcanic Complex (CBVC) is a small (~25x35 km), isolated topographic and morphologic feature situated on the second ring of the Humboldtianum basin and ~20 km east of the topographic rim of the crater Belkovich (Jolliff et al., 2011). It lies at the center of a thorium hotspot and has elevated topography and high reflectance compared to the surrounding highlands (Lawrence et al., 1999, 2007; Gillis et al., 2002). The CBVC contains a range of volcanic features, including irregular collapse features, small domes, and several large volcanic constructs (cones or cumulo domes) (Jolliff et al., 2011, Chauhan et al., 2015). LRO Diviner data show evidence for silicic composition corresponding to the CBVC, and rock types such as granite or rhyolite are likely present (Jolliff et al., 2011). Materials such as andesite or dacite, which have never been sampled on the Moon, may be present at some of the larger domes (Clegg-Watkins et al., 2017). Multiple lines of evidence support the existence of unusual pyroclastic compositions (including OH and spinel) at the complex (Pieters et al., 2009; Petro et al, 2013; Bhattacharya et al., 2013; Pieters et al., 2014a; Wilson et al., 2015, Clegg-Watkins et al., 2017).

Relevance to Science Themes:

- S.2: Samples from this site would play a major role in filling in our understanding of crustal petrogenesis. Silicic volcanism has been hypothesized to form as a result of silicate liquid immiscibility, basaltic underplating, or fractional crystallization (Glotch et al., 2010).

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- S[illegible]les that [illegible]oe products of are[illegible] nonmare volcanism, and specifically [illegible]icic volcanism, [illegible] rare an[illegible]nderrepresented in the Apollo, Luna, and lunar meteorite samples, making samples/compositional measurements from a silicic area such as the CBVC especially valuable.
- S.5: Samples from this site would provide constraints on models of formation of non-basaltic volcanic features on the Moon. Additionally, evidence exists for pyroclastic deposits at the CBVC.
- A.1: Analysis of silicic materials for volatiles will add to the emerging lunar volatile story.

Relevance to Exploration Themes:

- SKG1: The resource potential at CBVC can be analyzed by measuring the quantity and distribution of H and other volatile content in-situ or through sample return. The resource potential can also be assessed by measuring the volatile content of local pyroclastic deposits and by evaluating the source of the OH/H_2O signature detected from orbit across the complex (Pieters et al., 2009; Jolliff et al., 2011; Bhattacharya et al., 2013; Petro et al., 2013).
- SKG 2: The lunar environmental effects on human life can be studied by quantifying radiation at the lunar surface and by studying the shielding effects of fine-grained pyroclastic materials.
- SKG3: Living and working on the lunar surface can be studied by excavating, transporting, and processing regolith, especially in areas enriched in H and potentially other volatiles (e.g., pyroclastics).

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Decadal Survey Relevance: A mission to the Compton-Belkovich Volcanic Complex would answer the following Decadal Survey objectives:

Decadal Objective 1:

- Constrain the bulk composition of the terrestrial planets by understanding the compositional diversity of volcanic materials on the lunar surface.
- Characterize planetary surfaces to understand how they are modified by geologic processes (*i.e.,* volcanism)

Decadal Objective 2:

- Understand the composition and distribution of volatile chemical compounds in the volcanic deposits.

Key Measurements: in-situ isotopic age determination (Anderson et al., 2017; Jolliff et al., 2018a), gamma ray and neutron detection for volatile abundances, hyper-spectral imaging, bulk chemistry and mineralogy, quantify regolith geomechanical properties.

Exploration scenario 1: Rover and in-situ analysis: A rover traversing across the complex could take in-situ compositional measurements of silicic features and volcanic constructs (i.e., the alpha- and beta-domes, central portion of the collapsed caldera). The rover would require a long-lived power and thermal source to survive lunar nights (Jolliff et al., 2018a).

Exploration scenario 2: Rover and sample return (including in-situ analyses): A rover traversing across the complex could sample various silicic features and volcanic constructs, store them, and return them to Earth for further analysis.

Science Themes	Exploration Themes	Mobility Required?	In Situ or Sample Return

S.2, S.3 [illegible]	1, 2, 3 [illegible]	Yes	Both

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Figure 3: Compton-Belkovich Volcanic Deposit. (Left) LROC WAC basemap with LOLA shaded topography. (Right) LOLA-derived slopes.

<u>Gruithuisen Domes (36.5°N, 40.2°W)</u>

The Gruithuisen Domes are located on the western edge of Mare Imbrium (Head et al. LPSC-9, 488, 1978), in the NW portion of the Procellarum KREEP Terrane. Their unique surface morphologies suggest that the lava flows that produced the domes were highly viscous (Head and McCord, 1978; Hagerty et al., 2006). Lunar Prospector GRS data and Clementine multispectral data show that these domes are relatively low in FeO (6-8 wt%) and high in Th

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contents [illegible] ppm [illegible] Gruithu[illegible] Gamma and 17±6 ppm for Gruithuisen Delta) (Hagerty et al., 2[illegible], and photometric observations and Diviner spectral data confirm that these domes have silicic compositions (Glotch et al., 2010). Photometric observations suggest that the domes may contain materials of intermediate silicic compositions (Clegg-Watkins et al., 2017).

Relevance to Science Themes:

- S.2: Samples from this site would play a major role in filling in our understanding of crustal petrogenesis. Silicic volcanics have been hypothesized to form as a result of silicate liquid immiscibility, basaltic underplating, or fractional crystallization (Glotch et al., 2010).
- S.3: Lunar samples that may be products of areas of nonmare volcanism, and specifically silicic volcanism, are rare and underrepresented in the Apollo, Luna, and lunar meteorite samples, making samples from the Gruithuisen Domes especially valuable.
- S.5: The Gruithuisen Domes represent a rare and unsampled type of volcanism on the Moon. Samples from this site would provide constraints on models of formation of non-basaltic volcanic features on the Moon.
- A.1: Analysis of the silicic materials for volatiles will add to the emerging lunar volatile story.

Decadal Survey Relevance: A mission to the Gruithuisen Domes would address the following Decadal Survey objective:

Decadal Objective 1:

- Constrain the bulk composition of the terrestrial planets by understanding the compositional diversity of volcanic materials on the lunar surface.

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- Characterize planetary surfaces to understand how they are modified by geologic processes (*i.e.,* volcanism)

Relevance to Exploration Themes:

- SKG1: A surface mission would examine the resource potential of highly silicic deposits by could by assessing the presence (or lack thereof) of volatile-rich deposits.
- SKG3: A landed mission to the Gruithuisen Domes could study how to live and work on the lunar surface by excavating, sorting, and storing materials, understanding dust and blast ejecta, and (for a roving mission) using autonomous surface navigation.

Key Measurements: Bulk chemistry and mineralogy, volatile content, age determination, high-resolution imaging, morphological characterizations (e.g., Head et al., 2018), quantify regolith geomechanical properties.

Exploration scenario 1: Lander: A lander on the flat summit of the Gruithuisen Gamma or Delta dome could document the unique morphological, mineralogical, elemental, and petrological characteristics of the surface in order to resolve the important questions about their petrogenesis and the thermal evolution of the Moon. This mission could serve as a precursor to sample return.

Exploration scenario 2: Rover: Regional roving

Science Themes	Exploration Themes	Mobility Required?	In Situ or Sample Return
S.2, S.3, S.5, A.1	1 and 3	No	Sample Return

Figure 4 [illegible] Domes. ([illegible] LROC WAC base[illegible]p with LOLA shaded topography. (Rig[illegible] LA-derived s[illegible]s.

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<u>Irregular Mare Patches/Ina Caldera (5.3°E, 18.66°N)</u>

Ina caldera is a volcanic landform composed of smooth volcanic mounds surrounded by uneven terrain lower in elevation.

Science theme relevance: A mission to Ina caldera addresses SCEM science concepts 1, 2, 5, and 6 and ASM-SAT concept 1.

- S.1: Ina is proposed to be very young (<100 myr, Braden et al., 2014), and also very old (3.5 byr, Qiao et al., 2017). An age-date of the materials in Ina caldera would resolve this issue and potentially constrain the younger end of the CSFD.
- S.2: If Ina is indeed as young as its CSFD model age, the composition of the volcanic materials will provide information on the late-stage thermal and chemical evolution of the lunar mantle (Wagner et al., 2018)
- S.5: The volcanic processes that led the emplacement of the smooth volcanic mounds at Ina are not well understood. A mission to Ina crater would improve our knowledge of lunar volcanic processes.
- S.6: The materials that compose the Ina landform are proposed to be highly porous, which would yield crater sizes smaller than predicted (Qiao et al., 2017; Wilson and Head, 2017). A mission to Ina would advance our knowledge of target material properties and impact cratering processes.
- A.1: If Ina is indeed young, measuring the volatile content of the exposed materials would allow a temporal evaluation of volatiles in the lunar interior.

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Decadal Survey Relevance: A mission to Ina would address the significance of recent lunar activity and potential surface current sites to be evaluated.

Decadal Objective 1:

- Constrain the bulk composition of terrestrial planets
- Characterize planetary interiors to determine how they differentiate and evolve
- Characterize planetary surfaces to understand how they are modified by geologic processes.

Decadal Objective 2:

- Understand the composition and distribution of volatile chemical compounds

Relevance to Exploration Themes:

- SKG 1: Ina or other irregular mare patches are suspected to be young volcanic features. If they are young, it may be possible to analyze the resource potential of volatiles in young volcanic features.
- SKG 3: A mission to Ina or another irregular mare patch could study how to rove on surfaces with varying surface properties such as roughness and slope.

Key Measurements: High-resolution imaging, high-resolution compositional characterization, high-resolution geomechanical information (e.g. regolith properties), absolute age-determination (Stopar et al., 2018; Wagner et al., 2018).

Exploration scenario 1 - Lander: Landing on a smooth mound (Ina D) would provide a vantage point for high-resolution imaging of both smooth mounds and uneven terrain and contacts between the two (Stopar et al., 2018).

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Explora[illegible] - Rove[illegible]ding on the easte[illegible]e of Ina (18.661°, 5.331° E) with a rove[illegible]d provide acc[illegible]o both [illegible]smooth mounds and uneven terrain. Access to both units will allow study the physical and chemical properties of both units (Wagner et al., 2018).

Science Themes	Exploration Themes	Mobility Required?	In Situ or Sample Return
S.1, S.2, S.5, S.6, A.1	SKG1,SKG3	No	Both

Figure 5: Ina (Irregular Mare Patch). (Left) LROC NAC DTM with shaded topography. (Right) LROC NAC DTM-derived slopes.

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Magnetic Anomalies and Swirls (e.g., 59°W, 7.5°N, Reiner Gamma)

The lunar crust contains regional magnetic areas, a few tens to hundreds of kilometers across, known as magnetic anomalies. The strongest anomalies are ~10-20 nT at 30 km altitude and may be on the order of 1000 nT at the surface (Blewett et al., 2018). Several hypotheses exist for the formation of lunar magnetic anomalies, including basin ejecta magnetized in the impact process (Hood et al., 2001); surface magnetization imprinted by comet-impact plasma interactions (Schultz & Srnka, 1980; Bruck-Syal and Schultz, 2015); igneous intrusion (Srnka et al., 1979; Purucker et al., 2012); or metallic iron impactor remnants (Wieczorek et al., 2012; Oliveira et al., 2017) magnetized in an ancient global field. Several magnetic anomalies are co-located with enigmatic reflectance features called swirls (El-Baz, 1972; Hood et al. 1979a,b; Hood and Williams, 1989; Blewett et al., 2011; Denevi et al., 2016). Lunar swirls are sinuous high-reflectance features with interweaving dark lanes. They appear optically immature, have no topographic relief, and appear depleted in OH relative to their surroundings (Kramer et al., 2011; Pieters and Garrick-Bethell, 2015). There are currently 4 hypotheses for the formation of swirls:

- attenuated space weathering due to solar wind shielding (Hood and Schubert, 1980; Hood and Williams, 1989; Kramer et al., 2011),
- disturbances caused by cometary impacts (Schultz and Srnka, 1980; Pinet et al., 2000; Starukhina and Shkuratov, 2004),
- electrostatic dust accumulation (Garrick-Bethell et al., 2011), and
- collapse of fairy-castle structure (Pieters et al., 2014b).

A surface mission to a lunar swirl such as Reiner Gamma or the Ingenii swirls would answer fundamental questions about the lunar plasma environment, space weathering, and lunar magnetism.

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Science [illegible] relevance:

- [illegible]: Determining [illegible] source [illegible] the magnetic anomalies will provide key information on the interior structure of the Moon. Constraints on the strength and origin of the magnetic anomalies tie into the longevity of a lunar core dynamo and thus the Moon's thermal history.
- S.3: Magnetization is an important aspect of lithologic diversity and crustal structure of the Moon.
- S.4: Lunar swirls allow for the examination of the retention and loss of OH/H_2O in areas of variable solar-wind flux.
- S.6: If the magnetic anomalies are found to have formed by magnetized basin ejecta or by comet impact, then there will be fundamental new insights into planetary impact processes.
- S.7: The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies. The special environment of a magnetic anomaly allows for control on ion flux, one of the presumed agents of space weathering. Swirls present an opportunity to study solar-wind implantation and sputtering and dust motion and accumulation on the lunar surface (Pieters and Noble, 2016; Blewett et al., 2018).
- S.8: Ion bombardment and sputtering are key processes that affect the lunar atmosphere and dust environment. In addition, assessing solar-wind derived OH/H_2O at lunar magnetic anomalies could constrain the sources for polar volatiles.
- A.1: The bright bands of swirls are depleted in OH relative to their surroundings (Kramer et al., 2011). Studying the variation in OH between bright and dark lanes will shed light on volatile abundances across swirls

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Explora[illegible]

- [illegible]G1: A mission [illegible] lunar s[illegible] could investigate ISRU potential by studying the temporal variability and movement dynamics of surface-correlated OH and H_2O, especially in the dark lanes where OH abundances may be higher.
- SGK2: The lunar environmental effects on human life can be studied by quantifying radiation at the lunar surface and if the magnetic anomalies afford any protection from ionizing radiation.
- SKG3: Living and working on the lunar surface can be studied by characterizing geotechnical properties and roving capabilities, and by determining the near-surface plasma environment.

Decadal Survey relevance:

Decadal Objective 1:

- Characterize planetary surfaces to understand how they are modified by geologic processes (page 116).

Decadal Objective 2:

- Understand the composition and distribution of volatile chemical compounds. (page 118)

Key Measurements: near-surface plasma environment, volatile signature (OH/H_2O), magnetic field strength and direction, radiation measurements, solar wind monitoring, high-resolution imaging, regolith properties and dust environment, quantify regolith geomechanical properties.

Exploration scenario 1: Roving mission across a swirl, taking in-situ measurements of the magnetic field and plasma environment across the bright and dark lanes.

Science Themes	Exploration Themes	Mobility Required?	In Situ or Sample Return
S.2, S.3, S.4, S.6, S.7, S.8, A.1	1, 2, 3	Yes	In Situ

Figure 6: Reiner Gamma (Magnetic Anomalies). (Left) LROC WAC basemap with LOLA shaded topography. (Right) LOLA-derived slopes.

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Marius [illegible] (3[illegible]°N)

The [illegible]us Hills are a vo[illegible]ic prov[illegible]e on a broad shield structure that may have experience long-lived volcanism (Spudis et al., 2013; Hiesinger et al., 2016). In addition, the lunar magnetic anomaly Reiner Gamma crosses the site (see "Lunar Magnetic Anomalies" above), and a lava pit occurs at the site (Robinson et al., 2012; see "Pit Crater/Lava Tubes" below).

Science theme relevance: A mission to the Marius Hills addresses SCEM science concepts 1, 2, 5, and 6 and ASM-SAT concept 1.

- S.1: The Marius Hills possibly experienced long-lived volcanism. A precise age-date of the materials in the Marius Hills could provide anchors on the CSFD model.
- S.5: If the Marius Hills did experience long-lived volcanism, the composition of the volcanic materials will provide information on the thermal and chemical evolution of the Moon with time.
- A.1: The Marius Hills provide an opportunity to study the temporal evolution of volcanic volatiles.

Exploration relevance:

- SKG1: A mission to the Marius Hills could provide information about the spatial and temporal distribution of potential volcanic volatile deposits.
- SGK2: The lunar environmental effects on human life can be studied by quantifying radiation at the lunar surface over the time span of a long-lived roving mission

Decadal Survey relevance: A mission to the Marius Hills would provide the opportunity to study the spatial and temporal evolution of lunar volcanism.

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Decadal Objective 1:

- Constrain the bulk composition of terrestrial planets
- Characterize planetary interiors to determine how they differentiate and evolve
- Characterize planetary surfaces to understand how they are modified by geologic processes

Decadal Objective 2:

- Understand the composition and distribution of volatiles on the lunar surface and within the interior.

Key Measurements: Compositional characterization across the shield, in-situ age dating, sample return would allow the study of minor variations in composition and age in samples taken across the shield (Stopar et al., 2018). Quantify regolith geomechanical properties.

Exploration scenario 1: A long-lived rover capable of traversing slopes 10-15° (>20° capabilities desired) could sample several key volcanic landforms including mare, flows, cones, rilles, and shields (Stopar et al., 2016; Stopar et al., 2018).

Science Themes	Exploration Themes	Mobility Required?	In Situ or Sample Return
S.1,S.5,A.1	SKG1,SKG2	Yes	Both

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Figure 7 [illegible] (Left) L[illegible] WAC basemap w[illegible] LOLA shaded topography. (Right) LOL[illegible]ived slopes.

<u>Moscoviense (147°E, 26°N)</u>

Moscoviense basin (Fig 1) on the far side of the Moon is a Nectarian-aged multi-ring impact basin that formed 3.85-2.92 Ga (Wilhelms et al., 1987). The basin contains an elongated floor with non-concentric basin rings. The basin contains some of the thinnest crust on the Moon, although it is located in the relatively thicker crust of the lunar highlands (Wieczorek et al., 2013). The basin contains a deposit of mare, a pyroclastic deposit, and several lunar swirls. The basin contains geologic diversity, including orthopyroxene, olivine, and Mg-Al Spinel (OOS; Pieters et al., 2011; Pieters et al., 2014a) in an anorthosite-rich peak ring which may have originated from differentiated magmatic intrusions into the lower crust, potentially near the crust/mantle boundary. The mare within the basin is also diverse, including low and high FeO, low and high TiO_2, and possibly high alumina (Kramer et al., 2008).

Relevance to Science Themes:

- S.1: Exploring Moscoviense will provide accurate ages for the formation of a large basin on the lunar farside.
- S.2: Moscoviense provides a unique glimpse at some of the thinnest crust on the Moon, as well as access to mare volcanic deposits within the basin interior that provide insights into the structure and composition of the lunar interior on the far side.
- S.3: A diverse suite of minerals and lunar rock types are present within the basin, including OOS, anorthosite, and diverse mare basalts.

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- S[illegible] and py[illegible]stic deposits prov[illegible]ccess to diverse lunar volcanic units, [illegible]pecially on the [illegible]ide of [illegible] Moon.
- S.6: Exploring this ancient basin will inform our understanding of impact processes on large scales. Studying the unique structure of this basin can help to distinguish between formation mechanisms for the non-concentric rings, distinguishing between an oblique impact, double impact, or an impact into a crustal anomaly (Thaisen et al., 2011).
- S.7: Studying the lunar swirls present within the basin will help to constrain regolith processes and the detailed nature of space weathering (see "Magnetic Anomalies" section).
- A.1: Assessing the swirls present in the basin will also inform the lunar water cycle and the role of hydration due to solar wind implantation and assess the volatile content of the far side mantle.
- A.3: The high density of tectonic features such as wrinkle ridges in the mare basalts can help to constrain interior structure and thermal history of the Moon. In addition, measuring heat flow in thin crustal regions is highly desirable because it helps to constrain the mantle component of the heat flow (Kiefer, 2012).

Decadal Survey relevance – exploration of Moscoviense will address

Decadal Objective 1:

- The diversity of crustal materials present in the basin will allow us to constrain the bulk composition of the Moon
- The secondary crust present in the form of mare and pyroclastic deposits provide a glimpse of the far side planetary interior and the process of thermal evolution. In

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a[illegible], the[illegible] crust in[illegible] region may provi[illegible]que access to lower crustal or mantle [illegible]terials at the s[illegible]ce.

- The presence of impact craters, swirls, wrinkle ridges, and various volcanic units can be studied to better understand how planetary surfaces are modified by geologic processes.

Decadal Objective 2:

- The presence of several lunar swirls and a pyroclastic deposit may help constrain the lunar water cycles and the form and concentration of volatiles on the lunar surface.

Relevance to Exploration Themes:

- SKG 1: The Moscoviense pyroclastic deposit, diverse mare units containing high Fe and Ti, and the lunar swirls will allow for analyses of the lunar resource potential and potential useful resources to be extracted.
- SKG 2: Exploring the lunar surface in the Moscoviense basin will help to better understand the lunar environment and the radiation effects and any protection such magnetic anomalies may afford humans exploring the Moon. The presence of lunar swirls will also provide an opportunity to explore a lunar magnetic anomaly (Blewett et al., 2011) which may affect surface conditions.
- SKG 3: Living and working on the lunar surface can be studied by excavating, transporting, and roving in the pyroclastic deposit, on and across the lunar swirls, as well as on the mare and highland surfaces.

Key Measurements: Ages of Moscoviense impact melt, pyroclastic materials and mare. Bulk chemistry and mineralogy of the diverse mare units and the OOS suite. Volatile contents of the pyroclastic deposit and lunar swirls. Quantify regolith geomechanical properties.

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Exploration scenario 1: An example of a mission with traversability could include regional roving experiments that investigate the peak ring/western basin floor for lunar swirls and pyroclastic deposits.
Exploration scenario 2: A sample return mission could include a diverse suite of samples such as basin impact melt, lower crust mafic minerals (including Mg-Al spinel), pure anorthosite, and/or farside mare basalts.

Science Themes	Exploration Themes	Mobility Required?	In Situ or Sample Return
S.1, 2, 3, 5, 6, 7, A.1, A3	SKG 1-3	No	Both

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Figure 8 [illegible] Basin. ([illegible] LROC WAC base[illegible]p with LOLA shaded topography. (Righ[illegible] LA-derived [illegible]s.

<u>Orientale (95°W, 20°S)</u>

The Orientale basin (Fig 1) is the youngest and best preserved multi-ring basin that formed ~3.68 Ga, located on the transition from thin lunar nearside crust and thick lunar farside crust [e.g., Whitten et al., 2011]. The basin contains three concentric rings named the Cordillera ring, Outer Rook Ring, and Inner Rook Ring, over 20 mare ponds, and the Maunder Formation, believed to indicate primary Orientale ejecta [Head 1974; Whitten et al., 2011].

Relevance to Science Themes:

- S.1: Determining the age of the Maunder Formation impact melt can constrain the bombardment history of the inner Solar System.
- S.2 Analyzing the composition and structure of the Orientale basin rings will yield insight into the structure and composition of the lunar interior.
- S.3 Characterizing the diversity of lunar crustal rocks is possible through measurements of mare basalts, impact melt in the Maunder Formation, and primary crustal materials.
- S.5 Investigations of lunar volcanic materials in the mare basalts and pyroclastic deposit can constrain the thermal and compositional evolution of the Moon via measurements of the composition and age of mare basalts.
- S.6 Studying Orientale basin will aid in constraining the formation of large-scale impact basins.
- S.7 Regolith processes and weathering on airless bodies can be informed by measuring the composition of regolith on both mare and primary crust surfaces.

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- A[illegible] assess[illegible] the pyroc[illegible]c deposit will inf[illegible]e lunar water cycle and the role of [illegible]uration due to [illegible]r wind [illegible]lantation.
- A.3: The presence of tectonic features such as wrinkle ridges in the mare basalts can help to constrain interior structure and thermal history of the Moon.

Decadal Survey relevance – exploration of Orientale will address

Decadal Concept 1:

- The diversity of crustal materials present in the basin will allow us to constrain the bulk composition of the Moon
- The secondary crust present in the form of mare and pyroclastic deposits provide a glimpse of the planetary interior and the process of thermal evolution.
- The presence of impact craters, wrinkle ridges, and various volcanic units can be studied to better understand how planetary surfaces are modified by geologic processes.

Decadal Concept 2:

- The presence of a large pyroclastic deposit may help constrain the lunar water cycle and the form and concentration of volatiles on the lunar surface.

Relevance to Exploration Themes:

- SKG 1: The Orientale pyroclastic deposit and several mare units would allow for analyses of the lunar resource potential and potential useful resources to be extracted.
- SKG 2: Exploring the lunar surface in the Orientale basin will help to better understand the lunar environment especially as related to radiation dosage.

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- S[illegible]. Li[illegible] and work[illegible]on the lunar surfac[illegible] be studied by excavating, [illegible]nsporting, and [illegible]ing in t[illegible]vroclastic deposit, as well as on the mare, impact melt, and primary crust surfaces.

Key Measurements:
Determine composition and age of the Maunder Formation impact melt, volcanic units, basin rings, and lunar regolith. Constrain composition and source depth of the basin rings. Determine the structure of lunar regolith and regolith geomechanical properties.

Exploration Scenario 1: A mission with roving capabilities could be sent to Lacus Veris, the largest mare pond, which could access mare units including a sinuous rille, the impact melt sheet in the Maunder Formation, and basin ring materials.
Exploration scenario 2: A potential lander mission could explore the Maunder Facies to investigate the physical and chemical properties of the impact melt unit, which could also return samples of the impact melt unit to Earth.

Science Themes	Exploration Themes	Mobility Required?	In Situ or Sample Return
S.1, 2, 3, 5, 6, 7, A.1, 3	SKG 1-3	No	Both

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Figure 9 [illegible] in. (Left) [illegible] OC WAC basemap [illegible] th LOLA shaded topography. (Right) LOL[illegible] ived slopes.

<u>P60 Basaltic Unit (53.8°W, 22.5°N)</u>

The P60 basalt unit is located just south of the Aristarchus Plateau. The CSFD model age for the P60 basalt is the youngest mare basalt on the Moon (~1 Ga, Hiesinger et al., 2010).

Science theme relevance:

- S.1: The P60 basalt unit has the youngest mare basalt CSFD model age. A precise age-date of the materials in the P60 could provide an anchor on the young end of the CSFD model.
- S.5: If the P60 basalt unit is as young as is indicated by its CSFD model age, compositional analyses of the mare basalts would provide information about the evolution and composition of the lunar mantle at the end of the eruption of mare basalts.
- A.1: If the P60 basalt unit is indeed young, measuring the volatile content of the unit would allow an evaluation of volatiles in the lunar interior in some of the youngest lunar rocks.

Exploration relevance:

- SKG1: A mission to the P60 basalt unit could provide information about the volatile contents of young lunar basalts.
- SGK2: The lunar environmental effects on human life can be studied by quantifying radiation at the lunar surface over the time span of a long-lived roving mission

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Decadal Survey Relevance: A mission to the P60 would provide the opportunity to study the spatial and temporal evolution of lunar volcanism.

Decadal Concept 1:

- Constrain the bulk composition of terrestrial planets; P60 will be able to study the nature of the mantle source that produced these young basalts.
- Characterize planetary interiors to determine how they differentiate and evolve
- Characterize planetary surfaces to understand how they are modified by geologic processes

Decadal Concept 2:

- Understand the composition and distribution of volatile chemical compounds

Key Measurements: Absolute age-determination

Exploration scenario 1: A short lived (less than 1 lunar day) sample return mission that would return

< 2 kg of rocks and regolith (Lawrence et al., 2018).

Exploration scenario 2: Sampling the P60 basalt unit as part of a long-lived rover traverse that also includes the Aristarchus region.

Science Themes	Exploration Themes	Mobility Required?	In Situ or Sample Return
S.1,S.5,A.1	SKG1,SKG2	No	Both

Figure 1 [illegible] Unit. ([illegible] LROC NAC imag[illegible]1206371351L with LROC NAC DTM [illegible]ed topograph[illegible] Right) [illegible]C NAC DTM-derived slopes.

<u>Pit crater/lava tubes (e.g., 33.22°E, 8.336°N, Mare Tranquillitatis)</u>

Lunar pit craters are small, steep-walled collapse features that suggest subsurface voids. Most pit craters (>200) are located in impact melt and are relatively shallow (~10 m). However, 10 pits are located in mare highland units and are much deeper (~40-100 m) (Wagner and Robinson, 2014). Pit craters located in mare units may indicate the presence of lava tubes of unknown lateral extent, while pits in non-mare impact melt may indicate networks of sublunarean tubes (Haruyama et al., 2009; Robinson et al., 2012).

Relevance to Science Themes:

- S.1: Pit craters within impact melt deposits provide access to unique impact-related units that have not been exposed to space weathering, allowing for extremely precise dating of impact events.
- S.5: Exploring pit craters within mare deposits allows unparalleled access to lunar volcanic stratigraphy through time, as well as the physical, chemical, and thermal nature of effusive lava flows.
- S.6: Studying impact melt on the surface and subsurface will provide extreme insight into crater formation processes as well as crater evolution.
- S.7: Study of trapped regolith between lava flows potentially present at lunar pits could give insight to how the Sun has evolved by evaluation of solar wind implanted species.
- A.1: Volatiles may become trapped accumulate within pit craters or in the interior of lava tubes, providing access to the lunar water cycle over time.

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Decadal Survey Relevance: A mission to the lunar pit craters would address the following Decadal Survey objectives:

Decadal Objective 1:

- Characterize planetary surfaces to understand how they are modified by geologic processes, specifically how volcanic flows shaped the surface of the Moon.

Decadal Objective 2:

- Understand the composition and distribution of volatile chemical compounds in the volcanic deposits.

Relevance to Exploration Themes:

- SKG1: Detailed analyses of layered basaltic deposits will help to constrain the volatile budget of lunar volcanism through time; likewise, the exploration of pit crater/lava tube interiors may lead to the discovery of water ice deposits within cold, shadowed subsurface voids.
- SKG2: Quantifying radiation at the surface as well as within the interiors of pit craters/lava tubes will help to determine where a persistent habitat could be placed to protect human health.
- SKG3: Developing technology that can access a pit crater/lava tube will greatly inform future technology design with respect to accessing difficult areas with steep slopes, persistent shadow, cold temperatures, etc.

Key Measurements: Lava stratigraphy, composition, grain size, spatial mapping of the subsurface void space to determine if a subsurface void is present (lava tube).

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Explora[illegible]: Deploy[illegible]uite of instrument[illegible]vestigate the interior structure and com[illegible]on of a pit crat[illegible]d how [illegible]ensive an sublunarean cavern is beneath the surface as a potential site for human habitation.

Science Themes	Exploration Themes	Mobility Required?	In Situ or Sample Return
S.1, 5, 6, 7, A.1	SKG1-3	Yes	In Situ

Figure 11: Mare Tranquillitatis Pit Crater. (Left) LROC NAC image M144395745L with LROC NAC DTM shaded topography. (Right) LROC NAC DTM-derived slopes. Topography data is not available inside the pit.

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Polar R[illegible] (e.g. [illegible]°E, 89.[illegible] Shackleton Crat[illegible]

Prev[illegible] missions, like C[illegible]entine a[illegible] LCROSS, have revealed water exists in lunar polar regions (Nozette et al. 1996; Colaprete et al. 2010). This water predominantly resides in some permanently shaded regions (PSRs) on the floors and walls of craters. Being able to ground truth these data from different PSRs and better understand polar volatiles (e.g., amount, form, composition, etc.) is of critical importance to the scientific, exploration, and commercial communities. There are known hydrogen deposits at the north pole (Peary Crater and NE of Hevesy Crater) and the south pole (Cabeus, Shoemaker, Faustini, Nobile, and Shackleton Craters) (Figure 12).

Relevance to Science Themes:

- S.4: The lunar poles host environments that are seen nowhere else on the Moon, making them unique environments for study.
- S.7: The water ice in these PSRs could affect how regolith accumulates and migrates along the lunar surface.
- A.1: The sequestered water at the poles and its relation to the lunar water cycle is of primary interest in the ASM-SAT.
- A.2: Polar sample return missions would provide benefit to the scientific community's understanding of the origin of the Moon as well as to the commercial community for their planned ISRU operations.

Relevance to Exploration Themes:

- SKG 1: Due to the quantities of volatiles at the poles, these areas are of great interest to the community for their resource potential. Understanding precise locations,

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characteristics and types of volatiles in the polar regions would especially allow the commercial sector to develop business plans and future mission scenarios.

- SKG 2: Given the resource potential at the poles, extraction of these resources is a possibility, and these operations may be overseen by humans in-situ. These activities will most likely stir up a significant amount of dust. Understanding the impact of dust on crews during surface activity is an important endeavor.
- SKG 3: Should mining operations be established at the poles, the proximity to resources would encourage bases to be established in these areas. This would provide the opportunities to greater understand how to work and live on the lunar surface, particularly in regards to resource production, surface trafficability, radiation shielding, and life support systems.

Decadal Survey relevance:
Missions to the lunar polar regions could answer the following Decadal Survey objectives:

Decadal Objective 1:

- Characterize planetary interiors to understand how they differentiate and dynamically evolve from their initial state.
- Characterize planetary surfaces to understand how they are modified by geologic processes.

Decadal Objective 2:

- Understand the composition and distribution of volatile chemical compounds.
- Understand the effects of internal planetary processes on life and habitability.

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Key Measurements: Characterize distribution, quantity, and species of volatiles. Characterize abundance of volatiles with depth, characterize regolith geotechnical properties.
Exploration scenario 1: Deploy assets (including a rover) to explore polar PSRs to characterize volatiles and survivability of mechanical devices in cold traps.
Exploration scenario 2: Collect and return samples to better understand volatile species present at the lunar poles.

Science Themes	Exploration Themes	Mobility Required?	In Situ or Sample Return
S.4, 7, A.1, 2	SKG1-3	Yes	Both

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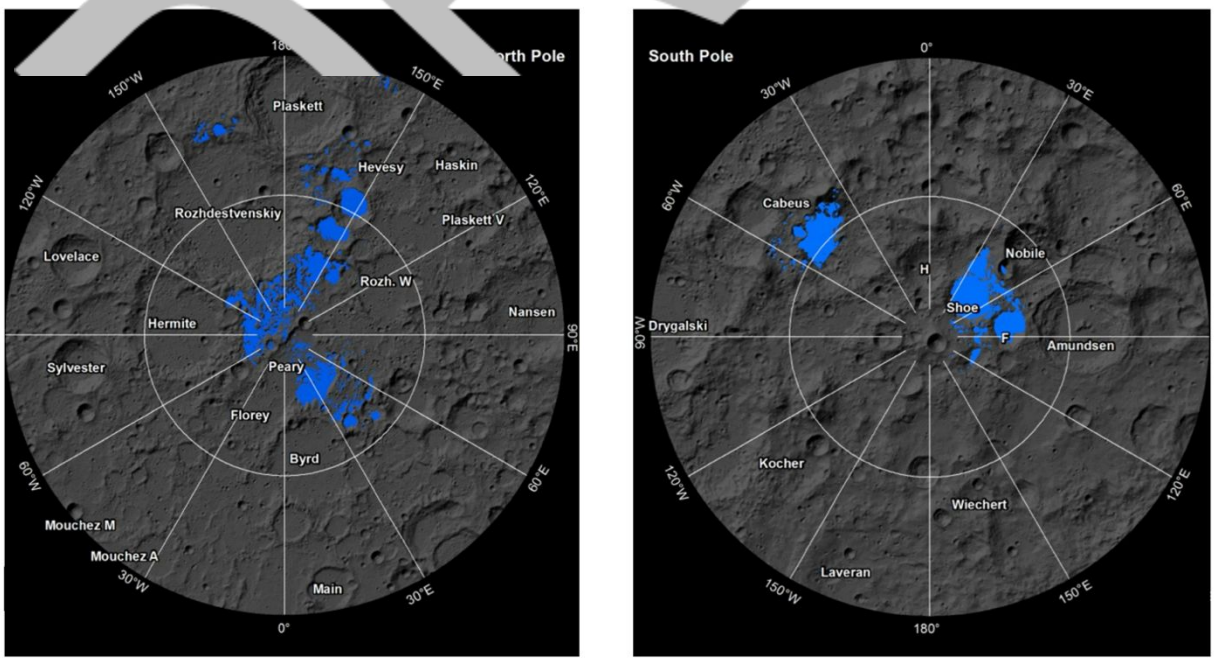

Figure 12: Known Polar Volatile Deposits from LEAG Volatiles Specific Action Team Final Report. (Left) North Pole. (Right) South Pole.

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Figure 1 [illegible] Region. [illegible]) LROC WAC ba[illegible]ap with LOLA shaded topography. (Righ[illegible]LA-derived s[illegible]es.

<u>Rima Bode (3.5°W, 12°N)</u>

Rima Bode is a spatially extensive (~7000 km^2) dark mantling deposit produced by fire fountaining, possibly composed of black glass, as indicated by its very low albedo (Gaddis et al., 1985; Gaddis et al., 2003; Spudis, 2018). The deposit is embayed by ~3.5 Ga maria, indicating that these pyroclastics are potentially ancient.

Science theme relevance:

- S.2: Compositional data from the Rima Bode pyroclastics will provide information about the composition of the lunar mantle.
- S.5: Rima Bode provides a laboratory to study large pyroclastic deposits on the lunar surface.
- A.1: Analyzing the volatiles in a large pyroclastic deposit such as Rima Bode would provide information about the endogenous volatile composition and concentration in the lunar mantle.

Exploration relevance:

- SKG1: Rima Bode is an extensive, high-Ti pyroclastic deposit, which potentially contains volatiles both from the mantle and from solar wind implantation. A mission to Rima Bode could assess the pyroclastic concentrations in mature, high-Ti pyroclastic deposits.

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- S[illegible] The [illegible] environ[illegible]tal effects on hum[illegible]ife, especially the radiation [illegible]vironment, cou[illegible]e mitig[illegible]d by studying the radiation shielding effects of fine-grained pyroclastic materials.
- SKG3: A mission to Rima Bode would provide the opportunity to study dust mitigation of mature, fine-grained pyroclastic deposits, and how to use these deposits to support and potentially enable long-term human presence on the lunar surface.

Decadal Survey relevance: A mission to Rima Bode would provide the opportunity to study the spatial and temporal evolution of lunar volcanism.

Decadal Concept 1:

- Constrain the bulk composition of terrestrial planets
- Characterize planetary interiors to determine how they differentiate and evolve by examining the mantle source composition of these materials.
- Characterize planetary surfaces to understand how they are modified by geologic processes

Decadal Concept 2:

- Understand the composition and distribution of volatile chemical compounds by defining the endogenous volatile budget in these pyroclastic glasses and in the mantle source region.

Key Measurements: Chemical composition of the pyroclastic deposit, Bulk H_2 in upper meter of regolith (Spudis, 2018), quantify the geomechanical properties of the pyroclastic deposit. Potential sample return of the pyroclastic materials once in-situ data have defined the variability in the deposit.

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Explora[illegible]: Short [illegible] (less than 1 luna[illegible] landed mission on the dark mantle depo[illegible] analyze chem[illegible] compos[illegible]n and volatile content of the pyroclastics (Spudis, 2018).

Science Themes	Exploration Themes	Mobility Required?	In Situ or Sample Return
S.2,S.5,A.1	SKG1,SKG2,SKG3	No	Both

Figure 14: Rima Bode. (Left) LROC WAC basemap with LOLA shaded topography. (Right) LOLA-derived slopes.

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Schrödi[illegible] (13[illegible]5°S)

Sch[illegible]ger basin is the s[illegible]nd you[illegible]t impact basin and sits adjacent to the oldest (and largest) impact basin, South Pole-Aitken. Schrödinger contains well-preserved, impact-generated materials and volcanic deposits, including mare basalts in the northeast and a vent surrounded by pyroclastic deposits to the southeast (Shoemaker et al., 1994; Gaddis et al., 2003). Schrödinger has a diameter of 315 km, a depth of 4.5 km, and a prominent inner peak ring that rises 1-2.5 km above the basin floor. Schrodinger may have tapped deep crustal lithologies associated with the SPA-forming impact, making it an ideal location for a future landing site (O'Sullivan et al., 2011; Kramer et al., 2013; Kring et al., 2016). The floor of the basin contains two impact melt lithologies (Shoemaker et al., 1994): a rough plains unit and a smooth plains unit, both of which are predominantly noritic in composition. Recent data from LRO, Kaguya, and the Chandrayaan-1 Moon Mineralogy Mapper suggest that the peak ring contains exposures of anorthositic, noritic, and olivine-bearing lithologies (Ohtake et al., 2009; Yamamoto et al., 2012; Kramer et al., 2013). The southern wall of Schrödinger hosts exposures of pyroxene-bearing anorthosite as well as pure anorthosite (>97% plagioclase) (Kramer et al., 2013).

Relevance to Science Themes:

- S.1: A mission to Schrödinger has the possibility to sample materials from both a young basin (Schrödinger) and the oldest basin on the Moon (SPA), providing constraints to the start and end of the basin-forming epoch and thus anchoring the lunar impact-basin chronology (e.g., Martin et al., 2016).
- S.2: Analyzing the composition and structure of peak ring materials will yield insight into the composition and structure of the lunar interior.

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- S[illegible] diverse suite of geologic units is available within Schrödinger, including mafic volcanic materials, pyroclastics, and peak ring materials that may contain exposures of anorthositic, noritic, and troctolitic rocks (Kramer et al., 2013).
- S.5: The floor of the basin contains two types of lunar volcanism - mare basalts and products of explosive volcanism (pyroclastics). Investigations of these volcanic materials can constrain the thermal and compositional evolution of the Moon via measurements of their composition and age.
- S.6: Exploring Schrödinger would inform the formation and structure of large basins. Studying the unique structure of Schrödinger, especially its peak ring, would allow us to probe basin formation and the movement of materials during the formation of peak- and multi-ring craters (e.g., Kramer et al., 2013).
- A.1: Examining the pyroclastic deposits on the floor of Schrödinger will yield new information on the endogenous lunar volatile budget.
- A.3: Studying lobate scarps present on the floor of Schrodinger will inform the tectonic and seismic nature and history of the Moon.

Relevance to Exploration Themes:

- SKG1: A surface mission could examine resource potential and preservation of volatile components during robotic sampling, handling, and storage by assessing the volatile content of pyroclastics within Schrödinger.
- SKG 3: Living and working on the lunar surface can be studied by excavating, transporting, and roving in the pyroclastic deposit, and on and across the various floor units (including the impact melt deposits).

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Decadal Survey Relevance:
A sub-orbital mission to Schrödinger would answer the following Decadal Survey questions:
Decadal Objective 1:

- Constrain the bulk composition of terrestrial planets by analyzing the diversity of rock units present in the basin, especially in the peak ring.
- Characterize planetary interiors to determine how they differentiate and evolve.
- Characterize planetary surfaces to understand how they are modified by geologic processes such as volcanism, tectonism, and impacts.

Decadal Objective 2:

- Understand the composition and distribution of volatile chemical compounds in the volcanic deposits.

Key Measurements: age of impact melts, bulk chemistry and mineralogy of surface units, volatile content of the pyroclastic glasses, high-resolution imaging, composition and ages of volcanic units, composition and source depth of the peak ring, quantify regolith geotechnical properties.
Exploration scenario 1: Rover that traverses across various geologic terrains (smooth inner-peak ring, mare basalts, inner-peak ring, peak ring, pyroclastics), with specific locations selected for imaging and in-situ analysis.
Exploration scenario 2: Rover or static lander that would return samples from the basin floor for age-dating and compositional analyses back on Earth.

Science Themes	Exploration Themes	Mobility Required?	In Situ or Sample Return

S.1-3, 5	SKG	Yes	Both

Figure 15: Schrödinger Basin. (Left) LROC WAC basemap with LOLA shaded topography. (Right) LOLA-derived slopes.

<u>South Pole-Aitken Basin (170°W, 53°S)</u>

The South Pole-Aitken Basin (SPA) is the oldest, deepest, and largest impact basin on the Moon (Stuart-Alexander, 1978; Wilhelms, 1987) and has long been recognized as a high-priority location for scientific studies and exploration (Wilhelms, 1987; Head et al., 1993; Spudis et al., 1994; Jolliff et al., 2000; Hurwitz and Kring, 2014). SPA is located on the far side between Aitken crater and the South Pole, and has a diameter of ~2600 km. SPA contains a diversity of units, including ancient impact melt, basalts, excavated substrate materials (pre-SPA materials

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such as l[illegible] crust[illegible]ntle ma[illegible]s), and swirls. The [illegible]A impact event is likely to have exca[illegible] deeply enoug[illegible] contain [illegible]osures of lower crustal and/or mantle materials (Pieters et al., 2001; Petro et al., 2011). Samples returned from SPA would answer fundamental questions about lunar and Solar System evolution, and would establish the SPA large impact chronology. Dating the basin formation would test on the "cataclysm" or late-heavy bombardment that is implied by the analysis of the current lunar sample collection.

For the purpose of this report, we do not include the South Pole as part of the SPA exploration site.

Science theme relevance:

- S.1: Dating the SPA impact would place constraints on the timing and duration of early, heavy impact bombardment of the Moon and inner Solar System, thus addressing fundamental questions about inner solar system impact processes and chronology. The age of SPA would anchor the lunar impact-basin chronology. If the SPA Basin formation age proves to be relatively close to 4 Ga, then a cataclysm or spike in the heavy impact bombardment at that time is supported.
- S.2: Understanding the source and distribution of heat-producing elements (e.g. thorium) in the basin will inform lunar differentiation and thermal evolution. Determining the remanent magnetization of SPA impact melt rocks would answer key questions about the existence of a core dynamo early in lunar history (Jolliff et al., 2018b).
- S.3: The SPA-forming impact may have excavated deeply enough to contain exposures of lower crustal and/or mantle materials. Samples from SPA would provide direct

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k[illegible]ge [illegible]ck types, [illegible]stallization ages, a[illegible]epth constraints, therefore unraveling [illegible] nature of the [illegible]n's lov[illegible] crust and mantle.

- S.5: Determining the ages and compositions of SPA basalts will inform how farside mantle source regions differ from regions sampled by Apollo and Luna. Portions of SPA are relatively smooth, indicating that basalts may lie beneath the observed surface materials in the form of cryptomare. Understanding the composition of cryptomare deposits is important for determining what materials are present within the basin interior (Petro et al., 2011; Gibson and Jolliff, 2011).
- S.6: SPA holds the key to understanding the formation and structure of large basins. The basin contains impact melt deposits that likely contain lower crustal or upper mantle components

Decadal Survey Relevance: Exploration of SPA would allow the reconstruction of both the thermal-tectonic-magmatic evolution of the Moon and an evaluation of the early impact history of the inner Solar System.

Decadal Objective 1:

- Constrain the bulk composition of the terrestrial planets by sampling possible lower crustal/upper mantle materials.
- Characterize planetary interiors to understand how they differentiate and dynamically evolve from their initial state
- Characterize planetary surfaces to understand how they are modified by geologic processes, i.e. volcanism and impacts

Exploration relevance:

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- SKG2: A sample mission could examine resource potential and preservation of volatile components during robotic sampling, handling, and storage by assessing the volatile content of volcanic materials within the SPA basin.
- SKG3: Living and working on the lunar surface can be studied by excavating, sorting, refining, and storing materials, and by taking measurements of actual landing conditions to assess the effects of rocket exhaust on the surface directly beneath the lander.

Key Measurements: Absolute age determination, bulk chemistry and mineralogy, scooping and sieving capabilities, high-resolution imaging (particularly to assist with scooping and sampling), quantify regolith geomechanical properties.

Exploration scenario 1: Automated sample return of regolith or sieved rock fragments, using a static lander. Many potential landing sites, with the center of the basin or the transient crater rim as prime candidates.

Figure 1 [illegible] uth Pole [illegible] ken Basin with LO[illegible] derived slopes.

Science Themes	Exploration Themes	Mobility Required?	In Situ or Sample Return
S.1-3, S.5, S.6	SKG1, SKG3	No	Sample Return

<u>Long Lived Global Monitoring Network - Geophysics</u>

Apollo seismic data and GRAIL gravity data revolutionized our understanding of the Moon's interior, its formation, and evolution. However, many questions still remain regarding the amount and distribution of seismicity on the Moon, as well as the detailed structure of the crust, mantle, and core (Weber et al., 2018). A global network of nodes would contain seismometers, heat flow probes, retroreflectors, and magnetometers distributed across the lunar surface (including the far side), with a wider aperture network than that created with the Apollo seismic network. The Apollo heat flow data is anomalous because the probes were placed on the boundaries of the PKT, so new heat flow data at locations outside of (or interior to) the PKT would place constraints on the thermal state of the lunar interior. Heat flow measurements should be made in regions of varying crustal thickness, including regions of very thin crust such as the central portions of the Crisium or Moscoviense basins. It is preferable to avoid locating heat flow measurements near the rim zones of large impact basins (Kiefer, 2012; Nagihara et al., 2017). This global network of nodes would allow us to answer questions regarding the seismic state and internal structure of the Moon.

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Science [illegible] relevance:

- [illegible]. A variety of geophysical measurements across the surface of the Moon will enable researchers to determine the internal structure and composition of a differentiated planetary body. Heat flow probes would allow us to characterize the thermal state of the interior (Nagihara et al., 2018; Siegler et al., 2018). Seismometers would allow us to determine the thickness of the lunar crust, to characterize the mantle, and to determine the size, composition, and state of the Moon's core. Laser ranging would supplement existing GRAIL data and aid in our understanding of the deep interior structure of the Moon (Orlando et al., 2018).
- A.3: A global network of nodes would answer fundamental questions regarding the interior thermal distribution of the Moon (heat flow probes) and the internal structure of the Moon (seismometers) and how they related to surface tectonism.

Decadal Survey relevance:

A global network of nodes would address the following objective presented in the Decadal Survey:

Decadal Objective 1:

- Characterize planetary interiors to understand how they differentiate and dynamically evolve from their initial state:

A Lunar Geophysical Network was also identified by the Decadal Survey as a high priority target for New Frontiers 5.

Exploration relevance:

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- S[illegible] A g[illegible] geophy[illegible] network would pr[illegible]e key information about the lunar [illegible]vironment and [illegible] effects [illegible] seismic activity and heat flow would have on human life.

Key Measurements: seismicity, heat flow, laser ranging, electromagnetic sounding
Exploration scenario 1: Multiple landed missions across the lunar surface to deploy the geophysical package. Favored landing sites are internal or external to the Procellarum KREEP Terrane (not at the boundaries), close to the lunar limbs, and on the far side (Weber et al., 2018).
Exploration scenario 2: Any lander to any of the locations described in this report could have a seismometer that would address geophysical questions about the internal structure and current seismicity of the Moon.

Science Themes	Exploration Themes	Mobility Required?	In Situ or Sample Return
S.2, A.3	SKG2	No	In situ

<u>Long-Lived Global Monitoring Network - Exosphere</u>

Understanding how the exosphere varies over time at the surface as it is affected by impacts, solar and cosmic radiation, the Earth's magnetotail, etc., is critical for understanding space weathering, regolith formation, and regolith maturation processes, as well as volatile deposition, loss, and transport. Advances in our understanding of the lunar environment this century have demonstrated there is a lunar volatile cycle that could explain the hydrogen/water ice deposits at the lunar poles. It is unclear if volatiles delivered to the lunar surface are then transported to the

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polar regions and stored in permanently shadowed regions. Surface monitoring networks could do this by measuring exospheric species, monitoring the plasma environment at the lunar surface, and also monitor dust activity. Such nodes would need to be globally distributed from the equator to the poles, as well as on the near and far sides of the Moon.

Science theme relevance:

- S.4: The lunar poles are special environments that may bear witness to the volatile flux over the latter part of solar system history.
- S.7: The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies.
- S.8: Processes involved with the atmosphere and dust environment of the Moon are accessible for scientific study while the environment remains in a pristine state.
- A.1: The current lunar water and other volatile cycles would be investigated by understanding if there is a long-term migration of volatile species to the poles of the Moon.

Decadal Survey relevance:

A global network of exospheric monitoring nodes would address the following objective presented in the Decadal Survey:

Decadal Objective 1:

- Characterize planetary interiors to understand how they differentiate and dynamically evolve from their initial state:

Exploration relevance:

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- S[illegible]: A g[illegible] exosphe[illegible] monitoring netwo[illegible]uld show any volatile transport [illegible]wards the poles [illegible]d allow [illegible]estimate of how long the polar volatile deposits may have taken to form to assess how renewable they are.
- SKG2: A global exospheric monitoring network would provide key information about the lunar environment and how it changes over time.

Key Measurements: exospheric composition, dust, plasma environment (including electrical properties).
Exploration scenario: Multiple landed missions across the lunar surface to deploy nodes of the monitoring network. Each node must be long-lived so the global network can be built up over a number of years. The nodes need to be globally distributed from the equator to the poles, as well as on the near and far sides of the Moon.

Science Themes	Exploration Themes	Mobility Required?	In Situ or Sample Return
S.4, S.7, S.8, A.1	SKG1, SKG2	No	In situ

<u>Dating Large Impact Basins to Anchor Lunar Impact Chronology</u>

Radiometric and exposure ages from samples returned from the Apollo and Luna missions have been correlated with crater size-frequency distributions (CSFDs) to anchor the lunar cratering chronology (Basaltic Volcanism Study Project (BVSP), 1981; Neukum, 1983; Neukum and Ivanov, 1994; Stöffler and Ryder, 2001, Le Feuvre and Wieczorek, 2011), but many

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uncertai[illegible] for the pr[illegible]ectarian period (>[illegible]) and the Eratosthenian and Cope[illegible]n periods (<3 [illegible]). There [illegible]ill considerable debate about the ages of individual basins on the Moon, which serve as benchmarks that allow the global determination of the relative age of lunar surfaces. Therefore, dating large impact basins on the Moon (e.g., Nectaris, Crisium, etc.) is critical for determining an accurate lunar cratering chronology and for understanding the impact rate in the inner Solar System. The lunar cratering chronology has also been used to date unsampled surfaces throughout the Solar System [e.g., Strom and Neukum, 1988; Hartmann and Neukum, 2001; Ivanov, 2001], thus it is critical to determine the lunar impact rate as accurately as possible.

Note: SPA, Schrodinger, and Moscoviense all fit in this broad category, but are also treated as separate candidate landing sites in this report.

Relevance to Science Themes:

- S.1: Dating impact melts from basins such as Nectaris, Crisium, etc. will allow us to establish a precise absolute chronology and to assess the recent impact flux.
- S.6: Exploring large impact basins will inform our understanding of impact processes on large scales.

Decadal Survey relevance:

Decadal Objective 1:

- Constrain the bulk composition of terrestrial planets by analyzing the diversity of rock units present in each basin, especially in ring materials.
- Characterize planetary surfaces to understand how they are modified by geologic processes such as impacts.

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Decadal Objective
Understand the effects of processes external to a planet on life and habitability.

Relevance to Exploration Themes:

- SKG 1: A mission to any large lunar impact basin could examine the resource potential of the local regolith and any potential volatiles (especially those found in volcanic materials).
- SKG 3: Living and working on the lunar surface can be studied by excavating, transporting, and roving across basin materials.

Key Measurements: Ages of basin impact melts. Bulk chemistry and mineralogy of surface units. Quantify regolith geomechanical properties.
Exploration Scenario 1: Rover or static lander that would return samples from impact melts in the basin for age-dating and compositional analyses back on Earth.

Science Themes	Exploration Themes	Mobility Required?	In Situ or Sample Return
S.1, 6	SKG1, 3	No	Sample Return

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Figure 1 [illegible] of lunar [illegible] act basins. Figure [illegible] the Lunar and Planetary Institute, https[illegible]w.lpi.usra.edu[illegible]oloratio[illegible]ining/illustrations/bombardment/

Interdisciplinary Science

Astrophysics. The lunar far side presents several unique opportunities for science and exploration, but perhaps the most unusual is that it represents a preserve for low frequency radio astronomy (10-50 MHz) and cosmology. Portions of the far side are free of Earth-based radio-frequency interference (RFI) and ionospheric effects (e.g., Alexander et al., 1975; Zarka et al., 2012). An array of radio telescopes (spread over a region of 10-20 km) will allow us to matchlessly probe the first generation of stars and galaxies using the redshifted hyperfine 21-cm line of neutral hydrogen (NRC Astrophysics Decadal Survey, 2010), to image radio emission from coronal mass ejections for the first time, and to study space weather in extrasolar planetary systems to investigate the suitability for life. To accomplish these goals, low radio frequency arrays must be on the far side at locations that reduce RFI from Earth by factors of ~80 dB. Calculations indicate that craters at the lunar poles provide insufficient attenuation, and that crater rims both block significant portions of the sky and produce radio frequency distortions of antenna beams. On the other hand, new electromagnetic simulations suggest that at latitudes of ±80°, the necessary RFI attenuation can be achieved at ~45° from the lunar limb at a frequency of 1 MHz. This includes the northern third of the Schrödinger impact basin within the SPA basin, which could facilitate both Decadal-level lunar geology and cosmology. Other potential sites for a low radio frequency array include mid-latitude regions on the far side such at the Tsiolkovsky crater.

Lunar laser ranging (LLR) affords an opportunity to continue to make tests and refinements of gravitational physics, specifically the equivalence principle, the implications for Parameritized

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Post-Ne[illegible] variabili[illegible] the gravitational c[illegible]ant (e.g., Williams et al., 2006). The curre[illegible]twork includes [illegible]oreflec[illegible] at the Apollo 11, 14, and 15 sites, along with those on the Lunokhod rovers 1 and 2 (**Figure 18**). The equivalence principle is a foundation of Einstein's theory of gravity. Analysis of LLR data tests the equivalence principle by examining if the Moon and Earth have similar accelerations in the Sun's gravity field. Current data indicate similar accelerations of the Earth and Moon yielding a $\Delta_{acceleration}$ of $(-1 \pm 1.4) \times 10^{-13}$ (Williams et al., 2006).

While Einstein's theory of relativity does not predict a variable gravitational constant, G, other theories do. If there is a changing G, this would alter the scale and periods or the orbits of the Moon and planets and the LLR data are sensitive to G/G at the 1 AU scale of the annual orbit (Williams et al., 1996). At the resolution of current data, no variation of G is discernible.
A wider geographic spread of retroreflectors on the Moon, particularly in the southern hemisphere and limbs of the Moon, would improve sensitivity by several times. In addition, such a LLR network expansion would also result in better refinement of the Moon's internal structure. Any expansion of the current network would be an improvement (Williams et al., 2006).

Heliophysics. The lunar regolith contains a treasure-trove of materials both lunar and extra-lunar. One extra-lunar component that is gaining in significance is the solar wind. The Apollo missions collected solar wind samples on Al and Pt foils and the compositions of He, Ne, and Ar have been compared with data from the Genesis mission and subtle differences noted (Vogel et al., 2015). The Apollo samples have experienced diffusional loss and overall, there is little differences in the composition of the solar wind in the ~30 years between sample collections. But has this always been the case? The Moon potentially records snap-shots of solar wind over geologic time through preservation of paleoregoliths between lava flows that could

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contain i[illegible]ted [illegible] wind sp[illegible] that can be comp[illegible] with the present day activity of the Sun ([illegible] Fagents et al., [illegible]0; Craw[illegible]d et al., 2010). By getting samples of lava flows above and below the paleoregolith horizon, the age of the regolith is constrained and, therefore, a snap-shot of the Sun's activity at that time is obtained. While this type of research is important for both lunar and heliophysics science, it also has implications for the study of exoplanets. For example, the Kepler mission results on Sun-like-stars show 'superflares' with orders of magnitude greater energy output than what we observe in current epoch are common, but occur once per ~500-1000 years or so (e.g., Clery, 2016). Has our Sun emitted such "superflares" in the past? The Moon is the ideal place to address this question.

Surface Gravimetry. Few exploration techniques provide information about the composition and structure of the lunar subsurface, the most difficult and expensive being drilling/excavation. However, the well-known terrestrial geophysics technique of surface gravimetry surveying can provide some subsurface information much more easily. This has been used once on the Moon, with Apollo 17's Traverse Gravimeter experiment (TGE), whose measurements provided the basis for determining the thickness of the basalt underlying the Taurus Littrow Valley. The availability of new technology in the form of a space gravimeter that is smaller and more accurate than the TGE instrument would open the prospect of conducting lunar surface gravimetric surveys using small lunar rovers. Unlike other geophysical techniques, such as ground-penetrating radar, gravimetry is passive, requiring little power. Gravimetry can be used to determine the size and extent of interesting subsurface features such as lava tubes, ice deposits, buried craters and boulders, and volcanic intrusive features such as those that may cause the magnetic anomalies associated with lunar swirls. Conducting gravimetric surveys around the sites of Lunar Geophysical network stations can also yield knowledge of the density

of

geologic[illegible]ers i[illegible]ose stat[illegible] which may help w[illegible]he processing and interpretation of local [illegible] global seismo[illegible]al signa[illegible]ollected by those stations, which are sensitive to density variations.

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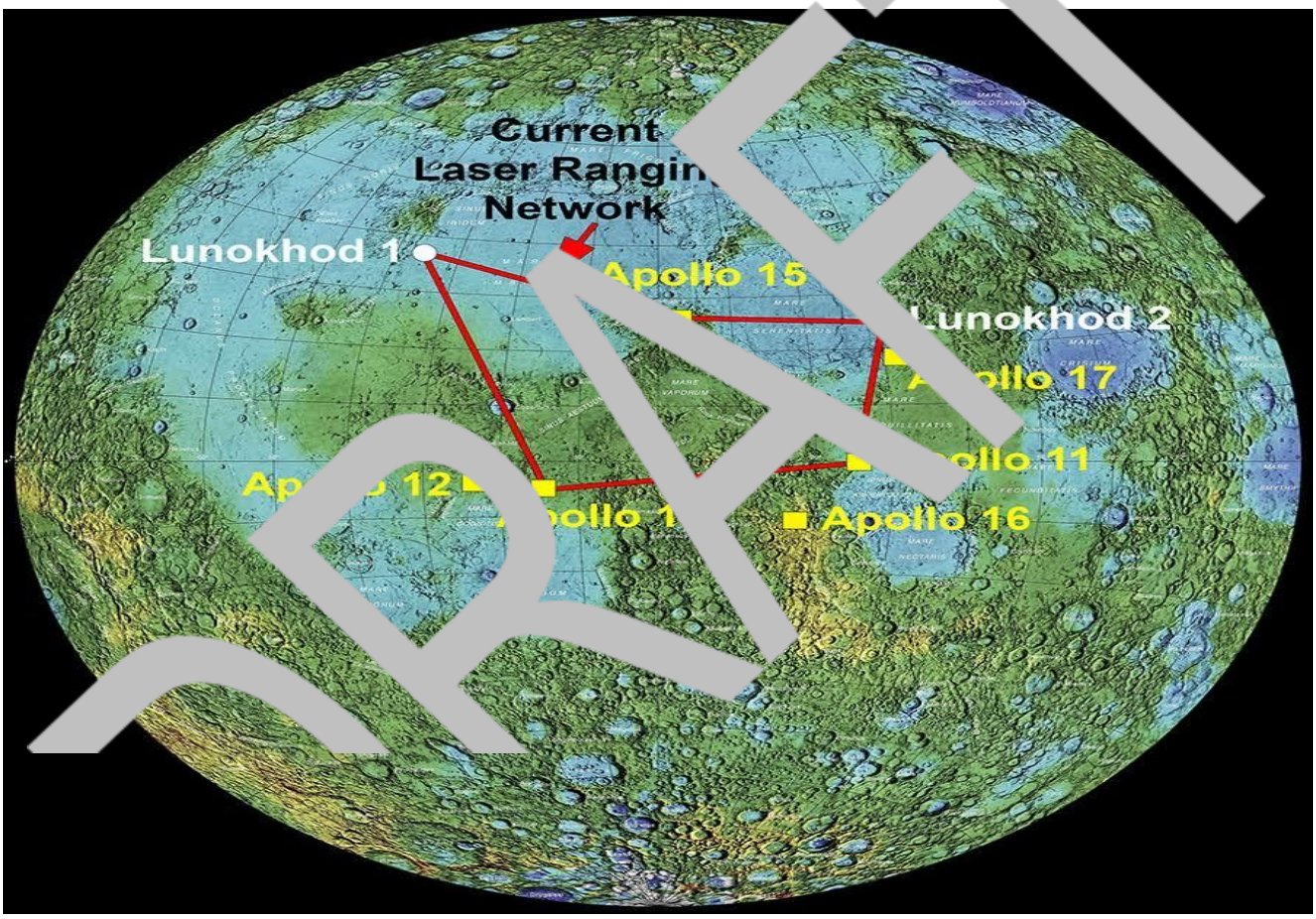

Figure 18: The locations of the retroreflectors that comprise the current LLR network.

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Table 1: Summary of Science Themes Addressed at Each Landing Site

	SCE Overarching Themes								ASM Overarching Themes			Enhancing		
	S1: Bombardment	S2: Interior	S3: Crust	S4: Volatile Flux	S5: Volcanism	S6: Impacts	S7: Regolith	S8: Exosphere	A1: Water Cycle	A2: Origins	A3: Tectonics	Communications Relay	Night Survival	Cryo c Samp
Aristarchus	×	×	×		×	×			×				X	
Compton Belkovich		×	×		×				×			X	X	
Gruithuisen Domes		×	×		×				×				X	
Ina/IMPs	×	×			×	×			×				X	
Magnetic Anomalies		×	×	×		×	×	X	×			X	X	
Marius Hills	×				×				×				X	
Moscoviense	×	×	×		×	×	×		×		×	X	X	
Orientale	×	×	×		×	×	×		×		×	X	X	
P60 Basalt	×				×				×				X	
Pit Craters	×				×		×		×			X	X	
Polar Regions				×					×			X	X	X
Rima Bode		×			×				×				X	
Schrödinger	×	×	×		×	×			×		×	X	X	
SPA	×	×	×		×	×						X	X	
Network of Nodes - Geophysics		×									×	X	X	
Network of Nodes - Exosphere				X			X	X	X			X	X	

Basin Chronology	X					X						X	X	

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Enhanc[illegible]

A se[illegible]of technology pr[illegible]ies hav[illegible]en identified that would enhance operations at all places on the lunar surface. They are outlined below in no order of preference.

Communications relay

Currently, there is no infrastructure in place to communicate with assets on the lunar far side, essentially leaving half of the Moon inaccessible to surface exploration. By installing a communications relay system, consisting of one or more spacecraft, high priority targets on the lunar far side would be open to exploration. The technology needed for these relay assets exists today, so the technological barrier of achieving this relay system is relatively low for a high level of valuable scientific return. Table 1 highlights those surface targets that would be enabled by the ability to communicate with surface assets on the lunar far side.

Surviving lunar night & PSRs

At the present time, the majority of mission architectures for exploring and conducting science on the lunar surface are limited to less than 14-Earth-days, due to limitations imposed by the harsh lunar night or the low temperatures in permanently shaded regions (PSRs) at the poles. Developing systems that can survive these low temperatures and large temperature swings would greatly expand the portfolio of mission concepts possible on the lunar surface. Systems that could hibernate during the lunar night and reactivate when the Sun reappears would be an improvement. However, systems that could operate during the lunar night would enhance operations on the lunar surface and have the added benefit of progressing the exploration of PSRs at the lunar poles.

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Cryogenic sampling, transportation, storage, analysis

When conducting analysis of samples, maintaining sample integrity such that the original state from collection through transportation and storage to analysis is critical. Without this protection, sample properties and compositions will change, ultimately influencing the interpretation and understanding of a given sample. This is especially critical for the sampling, transportation, storage, and analysis of volatile rich samples, especially those sourced from PSRs. Systems capable of maintaining samples under lunar cryogenic conditions will be of value not only to the Moon, but also Mars, comets, and potentially the ocean world satellites of the outer planets.

Automated hazard avoidance

Since many hazards are smaller than the highest resolution imagery available, having automated hazard avoidance software as part of landers' guidance, navigation, and control software is critical to ensure safe landings on the Moon. The 2013 Chinese Chang'e-3 lunar lander mission successfully demonstrated that automated hazard avoidance software can be utilized to successfully achieve a safe powered descent and landing on the lunar surface (e.g., Zhang et al., 2014). At an altitude of 100 m above the lunar surface, the CE-3 spacecraft adjusted its thrust to enable it to enter a hovering stage. An optical imaging sensor was then utilized to detect craters or rocks on the surface that had diameters larger than 1 m. Landing camera images clearly show that the spacecraft adjusted its position during this hovering stage, approximately 6m in the north-south direction and 6m in the east-west direction, to avoid obstacles (Liu et al., 2014)

Mobility

There are many examples of the benefits of mobile assets on a planetary surface. The series of rovers on the martian surface have provided the scientific community with an unprecedented

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amount of data and understanding of Mars. On the lunar surface, the operations of Apollos 15-17 were greatly enhanced by the access the crews were afforded by the Lunar Roving Vehicle (LRV). LRV allowed them to travel further distances, collect a more diverse suite of samples, and gain a better understanding of the surrounding areas than the missions that came before them. For future missions, while not all mission concepts require mobility, having mobility technology available would be enhancing for a more detailed investigation. Additionally, multiple mission concepts to the same, similar, or adjacent areas could be grouped together into one mission if the rover was durable and able to survive the lunar night.

Dust mitigation/plume effects

A hazard of operating on the lunar surface that was made apparent during the Apollo missions was the interaction of lunar regolith with machines, suits, and human biology. Methods for mitigating the amount of regolith interactions with people and equipment in addition to a reliable system for removing regolith from suits and lunar habitats is of great interest to the lunar community to both increase longevity of systems and enhance safety for human crews.

Additionally, the descent engine exhaust plumes of the Surveyor, Luna, Apollo, and Chang'e-3 spacecraft significantly affected the regolith surrounding their landing sites. These areas, which are referred to as "blast zones" (BZs), are interpreted as disturbances of the regolith by rocket exhaust during descent of the spacecraft and activity of the astronauts in the area right around the landers (**Figure 19**; Clegg et al., 2014; Clegg-Watkins et al., 2016). These blast zones consist of an area of lower reflectance compared to the surroundings that extends up to a few meters out from the landers, as well as a broader halo of higher reflectance (HR-BZ) that extends tens to hundreds of meters away from the landers (Clegg et al., 2014). The BZs likely formed as a result

of

the remo[illegible] fine p[illegible]icles, the [illegible]ruction of the fairy [illegible]stle structure, and/or surface smoo[illegible]g (Kaydash et a[illegible]2011; C[illegible] et al., 2014; Clegg-Watkins et al., 2016).

Metzger et al. (2011) described 4 stages of plume/soil interaction, based on detailed analyses of Apollo descent videos:

1. *Smooth flow stage* – the beginning stages of plume impingement (about 30-40 m above the surface). A homogenous sheet of dust begins moving radially away from the impingement point, at an angle of ~1-3 degrees above the terrain (Immer et al., 2011a; Lane et al., 2008; 2010).
2. *Streaking stage* - the haze of dust separates into distinct streaks correlated to specific terrain features such as rocks and crater edges. Towards the end of the streaking stage, rocks can move across the surface.
3. *Terrain modification stage* – soil is removed by the plume in large amounts, often appearing as "bursts" in Apollo descent camera videos. These large removals of soil may have been caused by the soil failing wherever the gas flow was most perturbed (i.e., where the lander's legs, footpads, and contact probes gouged the surface) and/or wherever the shape of the terrain rendered it the weakest (e.g., the rims of nearby craters).
4. *Clearing stage* – the last of the blown soil travels away, leaving a clear view of the surface around the spacecraft. This stage generally occurs when the engine is shut off.

For more on the detailed physics of plume effects during descent, we refer the reader to Lane et al., (2008), Metzger et al., (2010, 2011), Immer et al., (2011a; 2011b), and Lane and Metzger, (2012).

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Although the exhaust plumes only excavated a few cm of regolith beneath each lander (Shkuratov et al., 2012; Chang et al., 2014), it is important to consider these surface alterations when planning missions that will take samples or study surface features in the immediate vicinity of the lander. More pristine samples may be obtained by being able to move away from the immediate area of the landed spacecraft. The plume also injects volatiles into the local environment, some of which could migrate into cold traps and be measured by instruments that are directed at understanding the volatile distribution in PSRs. Shipley et al. (2014) developed deposition maps that estimate direct exhaust deposition to cold traps. They also recommend most braking be performed while the engine is pointed over the horizon, to ensure that most exhaust leaves the lunar environment.

The impingement of rocket exhaust on the surface can cause rocks to move, which is a serious concern for launching and landing on the Moon in the presence of scientific instruments, historic spacecraft, and a lunar outpost. Analysis of Apollo descent videos by Metzger et al. (2011) measured rocks 4-10 cm in size moving across the surface during landing, but a large quantity of rocks smaller than this were likely blown away and could significantly damage hardware and instruments at a future lunar outpost. The impingement of rocket exhaust can also cause morphological changes on the surface. For example, the soil erodes in clods and discrete layers, as noted by Metzger et al. (2011), and the effects of this layered erosion is visible in Apollo surface images of the areas beneath the LMs (**Figure 20**). Rocket exhaust also has electrostatic effects on soil during descent. Since rocket exhaust is a positively charged plasma, it was observed to cause dust levitation up to a half minute after lunar landings and Apollo ascents (see Lane et al., 2012). Other effects of this large injection of charge into the lunar environment are described in Lane et al. (2012).

Figure [illegible] image showing erosion by discrete layers under the Apollo 11 rocket nozzle (top). Arrows show the contact between the upper soil layer and the sublayer. Area A has numerous radial erosional remnants, each headed by gravel. Area B has a set of short longitudinal features in the form of downward steps from the impingement point. Trench C was caused by the soil contact probe during landing. (Figure from Metzger et al., (2011); detail from NASA photograph AS11-40-5921HR.)

Using LROC NAC images to measure the extent of each blast zone, Clegg-Watkins et al. (2016) found a consistent correlation between blast zone area and lander dry mass (**Figure 21**), despite variations in descent trajectories, maneuvering, engine configuration, and spacecraft design. This relationship will serve as an important tool in predicting the scale of rocket exhaust effects for future landed missions. However, while BZs are the visible effects of rocket exhaust interacting with the lunar surface, plume effects go much farther than what we observe from orbit. The smallest particles that were lifted into the exhaust plume are blown at velocities reaching up to 3 km/s, in some cases exceeding the 2.4 km/s escape velocity of the Moon (Lane et al., 2008; Metzger et al., 2011), and often travel distances on the order of kilometers to thousands of kilometers (Lane et al., 2008; Lane and Metzger, 2012). Modeling of plume effects give different estimates of how much material was ejected with each Apollo landing, but most models are consistent that one ton to several tons of soil were ejected (Metzger et al., 2011; Immer et al., 2011). It is unknown how the BZs are related to the flux of ejecta during descent, but materials outside of the observable BZ are not necessarily safe from the sandblasting effects.

Because of these plume effects during landing, NASA has established guidelines for approach paths of future landed missions. These approach paths protect the historic sites in the event of an

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engine o[illegible] failure d[illegible] landing. The exc[illegible] zone is a 2 km radius centered on the si[illegible] interest; landi[illegible] ehicles [illegible]t approach this zone tangentially and may not fly directly towards it for the purpose of landing on its perimeter. This ensures that if a spacecraft goes too far or not far enough, it will crash outside of this exclusion zone and protect the historic US spacecraft from blowing dust. **Figure 22** shows a schematic of this keep out zone. For more details on the exclusion zones, see https://www.nasa.gov/pdf/617743main_NASA-USG_LUNAR_HISTORIC_SITES_RevA-508.pdf

However, much is still not understood about the lunar environment and plume effects, so these guidelines may not be adequately constrained and we recommend using an overabundance of caution when planning missions that would land near U.S. legacy landing sites. It is imperative that all landers collect as much plume information and descent data as possible, and then share this data with the community, so we can gain a better understanding of the effects of rocket exhaust with lunar soil. This data will allow us to improve upon the guidelines for safe landing zones near historic U.S. spacecraft.

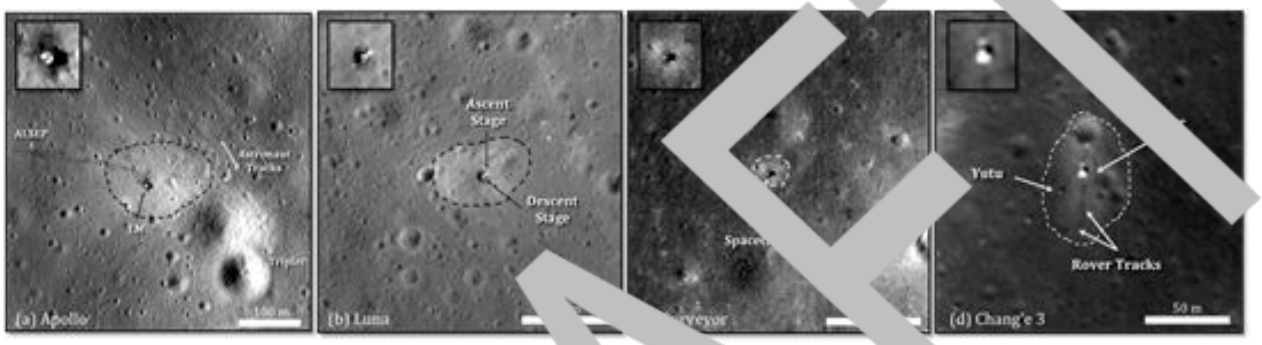

Figure 2[illegible] of the [illegible]o, Luna, Surveyor, [illegible] Chang'e 3 landing sites, with dash[illegible]es indicating t[illegible]uter ext[illegible] of each blast zone. Insets are zoomed in on the lander. a) Apollo 14, image M114064206L. b) Luna 23, image M174868307R. c) Surveyor 1, image M122495769L. d) Chang'e 3, image M1147290066R. Figure from Clegg and Jolliff, (2014).

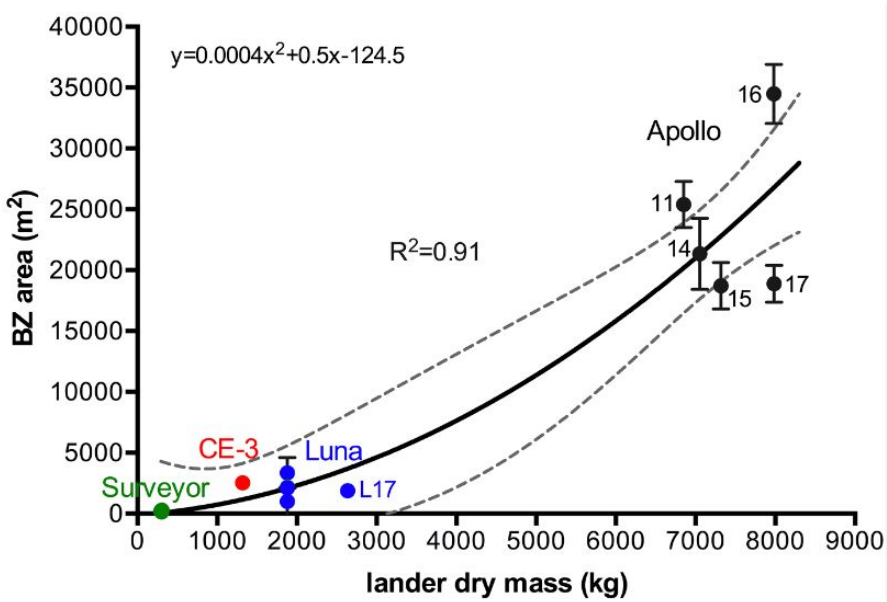

Figure 21: Lander dry mass versus blast zone area. Dashed lines are 95% confidence envelope based on Apollo, Luna, and Surveyor correlation (solid line; quadratic fit). Variations in BZ area at constant lander dry mass are largely a function of descent parameters and spacecraft specifications. Figure from Clegg-Watkins et al., (2016).

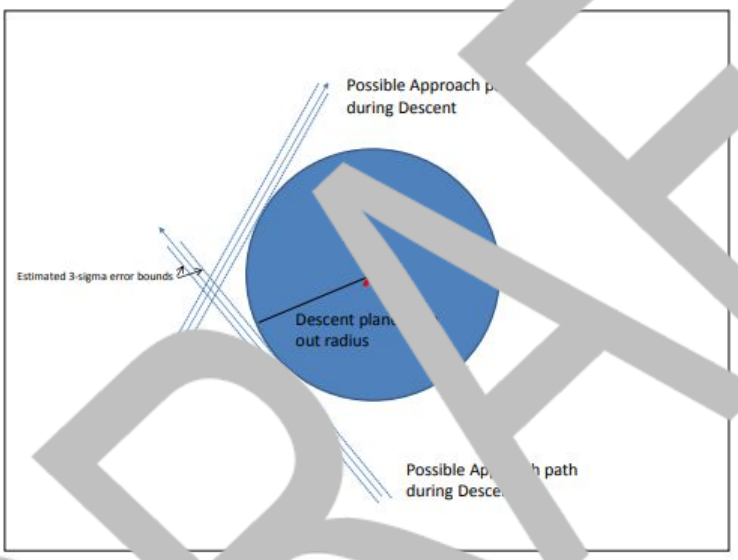

Figure 2 [illegible] showing [illegible] exclusion zone (bla[illegible]cle) centered on a site of interest (e.g [illegible]ric US spacec[illegible] Future [illegible]ded missions should approach this exclusion zone tangentially, as indicated by possible approach paths (blue lines).

References

Alexander J.K., Kaiser M.L., Novaco J.C., Grena F.R., and Weber R.R. (1975) Scientific instrumentation of the Radio-Astronomy-Explorer-2 satellite. *Science, 40,* 365-371.

Anderson, F. S., Whitaker, T. J., & Levine, J. (2017). How to Acquire a Successful In-Situ Date: CODEX Mission Design. 48th Lunar Planet. Sci. Conf., Abstract #2957.

Basaltic Volcanism Study Project (1981), Basaltic Volcanism on the Terrestrial Planets, Pergamon, New York.

Bhattacharya, S., Saran, S., Dagar, A., Chauhan, P., Chauhan, M., Ajai, A., & Kiran Kumar, S. (2013). Endogenic water on the Moon associated with non-mare silicic volcanism: implications for hydrated lunar interior. *Current Science*, *105*, 685–691.Blewett, D. T., Coman, E. I., Hawke, B. R., Gillis-Davis, J. J., Purucker, M. E., & Hughes, C. G. (2011). Lunar swirls: Examining crustal magnetic anomalies and space weathering trends. *Journal of Geophysical Research: Planets*, *116*(E2), E02002. https://doi.org/10.1029/2010JE003656

Blewett, D., Hurley, D. M., Denevi, B. W., Cahill, J. T. S., Klima, R. L., Jozwiak, L. M., Plescia, J. B., Paranicas, C. P., Greenhagen, B. T., Hibbits, C. A., Anderson, B. A., Korth, H., Ho, G. C., Nunez, J. I., Zimmerman, M. I., Brandt, P. C., Johnson, J. R., Stanley, S., Westlake, J. H., & Diaz-Calderon, A. (2018). Landed Science at a Lunar Crustal

DRAFT

M[illegible]ly. Pres[illegible]d at the Lunar Sc[illegible]for Landed Missions Workshop, [illegible]ASA Ames.

Braden, S. E., Stopar, J. D., Robinson, M. S., Lawrence S. J., van der Bogert C. H., and Hiesinger H. (2014) Evidence for basaltic volcanism on the Moon within the past 100 million years. *Nature Geoscience, 7*, 787-791.

Chauhan, M., Bhattacharya, S., Saran, S., Chauhan, P., & Dagar, A. (2015). Compton–Belkovich Volcanic Complex (CBVC): An ash flow caldera on the Moon. *Icarus*, *253*, 115–129. https://doi.org/10.1016/j.icarus.2015.02.024

Clegg, R. N., Jolliff, B. L., Robinson, M. S., Hapke, B. W., & Plescia, J. B. (2014). Effects of rocket exhaust on lunar soil reflectance properties. *Icarus*, *227*, 176–194. https://doi.org/10.1016/j.icarus.2013.09.013

Clegg, R. N. & Jolliff, B. L., (2014). Comparing rocket exhaust effects across lunar landing sites using LRO Narrow Angle Camera images. Paper 115 presented at Earth and Space 2014, 14th ASCE Aerospace Division Conf. on Engineering, Construction, and Operations in Challenging Environments, Am. Soc. Of Civ. Eng., Saint Louis, MO.

Clegg-Watkins, R. N., Jolliff, B. L., Boyd, A., Robinson, M. S., Wagner, R., Stopar, J. D., … Speyerer, E. J. (2016). Photometric characterization of the Chang'e-3 landing site using LROC NAC images. *Icarus*, *273*, 84–95. https://doi.org/10.1016/j.icarus.2015.12.010

Clegg-Watkins, R. N., Jolliff, B. L., Watkins, M. J., Coman, E., Giguere, T. A., Stopar, J. D., & Lawrence, S. J. (2017). Nonmare volcanism on the Moon: Photometric evidence for the presence of evolved silicic materials. *Icarus*, *285*, 169–184. https://doi.org/10.1016/j.icarus.2016.12.004

Clery D. (2016) Could Earth be fried by a "superflare" from the Sun? Science doi:10.1126/science.aaf9831 (http://www.sciencemag.org/news/2016/03/could-earth-be-fried-superflare-sun).

DRAFT

DRAFT

Crawfor[illegible], Fag[illegible] S. A., Jo[illegible] H., & Rumpf, M. [illegible] (2010) Lunar paleoreglith deposits as [illegible]orders of gala[illegible] environ[illegible]nt of the solar system and implications for astrobiology. *Earth Moon Planets, 107*, 75-85.

Denevi, B. W., Robinson, M. S., Boyd, A. K., Blewett, D. T., & Klima, R. L. (2016). The distribution and extent of lunar swirls. *Icarus*, *273*, 53–67. https://doi.org/10.1016/j.icarus.2016.01.017

El-Baz, F., (1972). The Alhazen to Abul Wafa swirl belt: An extensive field of light-colored, sinuous markings. Apollo 16 Prelim. Sci. Rep., NASASP-315,29-93–29-97.

Fagents S.A., Rumpf M.E., Crawford I.A., and Joy K.H. (2010) Preservation potential of implanted solar wind volatiles in lunar paleoregolith deposits buried by lava flows. *Icarus, 207,* 595-604.

Gaddis, L. R., Staid, M. I., Tyburczy, J. A., Hawke, B. R., & Petro, N. E. (2003). Compositional analyses of lunar pyroclastic deposits. *Icarus*, *161*(2), 262–280. https://doi.org/10.1016/S0019-1035(02)00036-2

Gaddis, L. R., Pieters, C. M., and Hawke, B. R. (1985). Remote sensing of lunar pyroclastic mantling deposits. *Icarus, 61*, 461-489.

Garrick-Bethell, I., Head, J. W., & Pieters, C. M. (2011). Spectral properties, magnetic fields, and dust transport at lunar swirls. *Icarus*, *212*(2), 480–492. https://doi.org/10.1016/j.icarus.2010.11.036

Gibson, K. E., & Jolliff, B. L. (2011). Correlation of surface units and FeO concentrations in the South Pole-Aitken Basin interior. *42nd Lunar Planet. Sci. Conf.,* Abstract #2326.

Gillis, J. J., Jolliff, B. L., Lawrence, D. J., Lawson, S. L., & Prettyman, T. H. (2002). The Compton-Belkovich Region of the Moon: Remotely Sensed Observations and Lunar Sample Association. 33rd Lunar Planet. Sci. Conf., Abstract #1967.

DRAFT

Glotch, T[illegible] Lucey[illegible] G., Ba[illegible]d, J. L., Greenhag[illegible]. T., Thomas, I. R., Elphic, R. C., … [illegible]ge, D. A. (20[illegible] Highly [illegible]cic Compositions on the Moon. *Science*, *329*(5998), 1510–1513. https://doi.org/10.1126/science.1192148

Hagerty, J. J., Lawrence, D. J., Hawke, B. R., Vaniman, D. T., Elphic, R. C., & Feldman, W. C. (2006). Refined thorium abundances for lunar red spots: Implications for evolved, nonmare volcanism on the Moon. *Journal of Geophysical Research*, *111*(E6). https://doi.org/10.1029/2005JE002592Hagerty, J. J., Lawrence, D. J., Hawke, B. R., Vaniman, D. T., Elphic, R. C., & Feldman, W. C. (2006). Refined thorium abundances for lunar red spots: Implications for evolved, nonmare volcanism on the Moon. *Journal of Geophysical Research*, *111*(E6). https://doi.org/10.1029/2005JE002592

Hartmann, W. K., and G. Neukum (2001). Cratering chronology and the evolution of Mars, *Space Sci. Rev., 96*, 165–194, doi:10.1023/A:1011945222010.

Haruyama, J., Hioki, K., Shirao, K.M., Morota, T., Hiesinger, H., van der Bogert, C.H., Miyamoto, H., Iwasaki, A., Yokota, Y., Ohtake, M., Matsunaga, T., Hara, S., Nakanotani, S., & Pieters, C.M. (2009). Possible lunar lava tube skylight observed by SELENE cameras. Geophysical Research Letters 36, L21206, http://dx.doi.org/10.1029/2009GL040635

Head, J. W. (1974). Lunar dark-mantle deposits - Possible clues to the distribution of early mare deposits (Vol. 5, pp. 207–222). Presented at the Lunar and Planetary Science Conference Proceedings. Retrieved from http://adsabs.harvard.edu/abs/1974LPSC....5..207H

Head, J. W., & McCord, T. B. (1978). Imbrian-Age Highland Volcanism on the Moon: The Gruithuisen and Mairan Domes. *Science*, *199*(4336), 1433–1436. https://doi.org/10.1126/science.199.4336.1433Head, J. W., Hess, P. C., & McCord, T. B. (1978). Geologic Characteristics of Lunar Highland Volcanic Domes (Gruithuisen and

DRAFT

M[illegible] Reg[illegible] and Pos[illegible] Eruption Condit[illegible] pp. 488–490). Presented at the Lunar [illegible] Planetary Sc[illegible]e IX.

Head, J.W., Murchie, S., Mustard, J. F., Pieters, C. M., Neukum, G., McEwen, A., Greeley, R., Nagel, E., & Belton, M. J. S. (1993). Lunar impact basins: New data for the western limb and far side (Orientale and South Pole-Aitken basins) from the first Galileo flyby. *J. Geophys. Res., 98,* 17149—17181.

Head, J. W., Ivanov, M. A., & Wilson, L. (2018). Lunar Non-Mare Volcanism: The Role of Commercial Missions in the Exploration of the Gruithuisen Domes. Presented at the Lunar Science for Landed Missions Workshop, NASA Ames.

Hiesinger, H., Head, J. W., Wolf, U., Jaumann, R., & Neukum, G. (2010). Ages and stratigraphy of lunar mare basalts in Mare Frigoris and other nearside maria based on crater size-frequency distribution measurements. *Journal of Geophysical Research: Planets*, *115*, E03003, doi:10.1029/2009JE003380

Hiesinger, H., Head, J. W., Wolf, U., Jaumann, R., & Neukum, G. (2011). Ages and stratigraphy of lunar mare basalts: A synthesis. *Geological Society of America Special Papers*, *477*, 1–51. https://doi.org/10.1130/2011.2477(01)

Hiesinger H., Gebhart, J., van der Bogert, C. H., Pasckert, J. H., Weinauer, J., Lawrence, S. J., Stopar, J. D., and Robinson, M. S. (2016). Stratigraphy of low shields and mare basalts of the Marius Hills region, Moon. *47th Lunar Planet. Sci. Conf.,* Abstract #1877.

Hood, L. L., Coleman Jr., P.J., & Wilhelms, D. E. (1979a). Lunar nearside magnetic anomalies. Proc. Lunar Planet. Sci. Conf. 10th, 2235–2257.

Hood, L. L., Coleman Jr., P. J., & Wilhelms, D. E. (1979b). The Moon:Sources of the crustal magnetic anomalies. *Science, 204,* 53–57.

Hood, I[illegible] C. (19[illegible] The lunar swirls. [illegible]ibution and possible origins, *Proc. [illegible]nar Planet. Sc[illegible]nf. 19[illegible]*[illegible]9–113.

Hood, L. L., & Schubert, G. (1980). Lunar magnetic anomalies and surface optical properties. *Science, 208,* 49–51.

Hurwitz, D. M., Head, J. W., & Hiesinger, H. (2013). Lunar sinuous rilles: Distribution, characteristics, and implications for their origin. *Planetary and Space Science*, *79–80*, 1–38. https://doi.org/10.1016/j.pss.2012.10.019

Hurwitz, D. M., & Kring, D. A. (2014). Differentiation of the South Pole-Aitken basin impact melt sheet: Implications for lunar exploration: SPA Impact Melt Sheet Differentiation. *Journal of Geophysical Research: Planets*, *119*(6), 1110–1133. https://doi.org/10.1002/2013JE004530

Immer, C., Lane, J., Metzger, P., & Clements, S. (2011a). Apollo video photogrammetry estimation of plume impingement effects. *Icarus, 214(1),* 46–52. https://doi.org/10.1016/j.icarus.2011.04.018

Immer, C., Metzger, P., Hintze, P. E., Nick, A., & Horan, R. (2011b). Apollo 12 Lunar Module exhaust plume impingement on Lunar Surveyor III. *Icarus, 211(2),* 1089–1102. https://doi.org/10.1016/j.icarus.2010.11.013

Ivanov, B. A. (2001). Mars/Moon cratering rate ratio estimates. *Space Sci. Rev., 96,* 87–104, doi:10.1023/A:1011941121102.

Jolliff, B.L., Gillis, J. J., Haskin, L. A., Korotev, R. L., & Wieczorek, M. A. (2000). Major lunar crustal terranes: Surface expressions and crust-mantle origins. *J. Geophys. Res., 105,* 4197-4216.

Jolliff, B. L., Watkins, R. N., Shirley, K. A., Glotch, T. D., Petro, N. E., Greenhagen, B. T., Lawrence, D. J., Lawrence, S. J.., & Simon, J. I. (2018a). Compton-Belkovich Volcanic Complex as an Exploration Destination. Presented at the Lunar Science for Landed Missions Workshop, NASA Ames.

DRAFT

Jolliff, B., Shearer, C., Petro, N., Cohen, B., Liu, Y., Watkins, R., Moriarty, D., Lawrence, S., Neal, C. (2018b). Landing Sites for South Pole-Aitken Basin Sample Return. Presented at the Lunar Science for Landed Missions Workshop, NASA Ames.

Jolliff, B. L., Wiseman, S. A., Lawrence, S. J., Tran, T. N., Robinson, M. S., Sato, H., … Paige, D. A. (2011). Non-mare silicic volcanism on the lunar farside at Compton–Belkovich. *Nature Geoscien*, *4*(8), 566–571. https://doi.org/10.1038/ngeo1212

Kaydash, V., Shkuratov, Y., Korokhin, V., & Videen, G. (2011). Photometric anomalies in the Apollo landing sites as seen from the Lunar Reconnaissance Orbiter. *Icarus*, *211*(1), 89–96. https://doi.org/10.1016/j.icarus.2010.08.024

Kiefer, W. S. (2012). Lunar heat flow experiments: Science objectives and a strategy for minimizing the effects of lander-induced perturbations. *Planetary and Space Science*, *60*(1), 155–165. https://doi.org/10.1016/j.pss.2011.07.016

Kramer, G. Y., Jolliff, B. L., & Neal, C. R. (2008). Distinguishing high-alumina mare basalts using Clementine UVVIS and Lunar Prospector GRS data: Mare Moscoviense and Mare Nectaris. *Journal of Geophysical Research: Planets*, *113*(E1), E01002. https://doi.org/10.1029/2006JE002860

Kramer, G. Y., Besse, S., Dhingra, D., Nettles, J., Klima, R., Garrick-Bethell, I., … McCord, T. B. (2011). M^3 spectral analysis of lunar swirls and the link between optical maturation and surface hydroxyl formation at magnetic anomalies. *Journal of Geophysical Research*, *116*. https://doi.org/10.1029/2010JE003729

Kramer, G. Y., Kring, D. A., Nahm, A. L., Pieters, C. M., (2013). Spectral and photogeologic mapping of Schrodinger Basin and implications for post-South Pole-Aitken impact deep subsurface stratigraphy. *Icarus, 223,* 131-148.

Kring, D. A., Kramer, G. Y., Collins, G. S., Potter, R. W. K., & Chandnani, M. (2016). Peak-ring structure and kinematics from a multi-disciplinary study of the Schrödinger impact basin. *Nature Communications*, *7*, 13161. https://doi.org/10.1038/ncomms13161

DRAFT

Lane, J. [illegible] T., Imm[illegible] D., & Li, X. (20[illegible] Lagrangian trajectory modeling of [illegible]ar dust partic[illegible] In Earth [illegible] Space 2008: Engineering, Science, Construction, and Operations in Challenging Environments, pp. 1-9.

Lane, J. E. & Metzger, P. T. (2012). Ballistics model for particles on a horizontal plane in a vacuum propelled by a vertically impinging gas jet. *Particulate Science and Technology*, *30*(2), 196-208.

Lane, J., Trigwell, S., Hintze, P., & Metzger, P. (2012). Further Analysis on the Mystery of the Surveyor III Dust Deposits. In *Earth and Space 2012: Engineering, Science, Construction, and Operations in Challenging Environments*,135-144.

Lawrence, D. J. (2003). Small-area thorium features on the lunar surface. *Journal of Geophysical Research*, *108*(E9). https://doi.org/10.1029/2003JE002050

Lawrence, S., Draper, D., Stopar, J. D., Jolliff, B. L., Neal, C. R., and Gruener, J. E. (2018). Sampling the youngest lunar basalts. Presented at the Lunar Science for Landed Missions Workshop, NASA Ames.

Le Feuvre, M., and M. A. Wieczorek (2008). Nonuniform cratering of the terrestrial planets. *Icarus, 197,* 291–306, doi:10.1016/j.icarus.2008.04.011.

Liu, J.-J., et al., 2014. Reconstructing the landing trajectory of the CE-3 lunar probe by using images from the landing camera. Res. Astron. Astrophys. 14, 1530–1542. doi: 10.1088/1674-4527/14/12/003

Martin, D. J. P., McDonald, F. E., Steenstra, E. S., Paisarnsombat, S., Venturino, C. S., O'Hara, S., Calzada-Dia, A., Leader, M. K., Bottoms, S., Klaus, K. K., Hurwitz-Needham, D., Kring, D. A. (2016). A long duration human-assisted robotic sample return mission to the Schrodinger Basin Part 2: Traversing towards the basin wall. *47th Lunar Planet. Sci. Conf.,* Abstract #1468.

DRAFT

Metzger, [illegible], Lane, [illegible] F., Immer, [illegible] D., & Clements, [illegible] (2010). Cratering and Blowing Soil by Rocket Engines During Lunar Landings. in Lunar Settlements, ed. by Haym Benaroya (CRC Press, 2010), 551-576.

Metzger, P. T., Smith, J., & Lane, J. E. (2011). Phenomenology of soil erosion due to rocket exhaust on the Moon and the Mauna Kea lunar test site. Journal of Geophysical Research, 116(E6). https://doi.org/10.1029/2010JE003745

Milliken, R. E., & Li, S. (2017). Remote detection of widespread indigenous water in lunar pyroclastic deposits. *Nature Geoscience*, *10*(8), 561. https://doi.org/10.1038/ngeo2993

Mustard, J. F., Pieters, C. M., Isaacson, P. J., Head, J. W., Besse, S., Clark, R. N., … Tompkins, S. (2011). Compositional diversity and geologic insights of the Aristarchus crater from Moon Mineralogy Mapper data. *Journal of Geophysical Research: Planets*, *116*(E6), E00G12. https://doi.org/10.1029/2010JE003726

Nagihara, S., Kiefer, W. S., Zacny, K. (2018). In-Situ Heat Flow Measurements In The Maria Outside The Procellarum Kreep Terrane. Presented at the Lunar Science for Landed Missions Workshop, NASA Ames.

National Research Council (NRC, 2010) Committee for a Decadal Survey of Astronomy and Astrophysics, New Worlds, New Horizons in Astronomy and Astrophysics. National Academy Press, Washington, pp. 46–47.

Neukum, G. (1983), Meteoritenbombardement und Datierung planetarer Oberflächen, Habilitation Thesis, Univ. München, Munich, Germany.

Neukum, G., and B. A. Ivanov (1994). Crater size distributions and impact probabilities on Earth from lunar, terrestrial-planet, and asteroid cratering data, in Hazard Due to Comets and Asteroids, edited by T. Gehrels, pp. 359–416, Univ. of Ariz. Press, Tucson, Ariz.

DRAFT

Ohtake, M., Matsuoka, T., Haruyama, J., Yokota, Y., Morota, T., Honda, C., … Josset, J.-L. (2009). The global distribution of pure anorthosite on the Moon. *Nature*, *461*(7261), 236–240. https://doi.org/10.1038/nature08317

O'Sullivan, K., Kohout, T., Thaisen, K., & Kring, D. (2011). Calibrating several key lunar stratigraphic units representing 4 b.y. of lunar history within Schrödinger basin. In: Ambrose, W., Williams, D. (Eds.), Recent Advances and Current Research Issues in Lunar Stratigraphy. Special Paper 477. Geological Society of America, 117–127.

Petro, N. E., Isaacson, P. J., Pieters, C. M., Jolliff, B. L., Carter, L. M., & Klima, R. L. (2013). Presence of OH/H2O Associated with the Lunar Compton-Belkovich Volcanic Complex Identified by the Moon Mineralogy Mapper (M^3). Presented at the 44th Lunar Planet. Sci. Conf., Abstract #2688.

Petro, N. E., Mest, S. C., Teich, Y. (2011). Geomorphic terrains and evidence for ancient volcanism within northeastern South Pole-Aitken basin. in Ambrose, W.A., and Williams, D.A., eds., Recent Advances and Current Research Issues in Lunar Stratigraphy: Geological Society of America Special Paper 477, 129-140.

Pieters, C. M., Goswami, J. N., Clark, R. N., Annadurai, M., Boardman, J., Buratti, B., … Varanasi, P. (2009). Character and Spatial Distribution of OH/H2O on the Surface of the Moon Seen by M^3 on Chandrayaan-1. *Science*, *326*(5952), 568–572. https://doi.org/10.1126/science.1178658

Pieters, C. M., Besse, S., Boardman, J., Buratti, B., Cheek, L., Clark, R. N., … Whitten, J. (2011). Mg-spinel lithology: A new rock type on the lunar farside. *Journal of Geophysical Research: Planets*, *116*(E6), E00G08. https://doi.org/10.1029/2010JE003727

Pieters, C. M., K. L. Donaldson Hanna, L. C. Cheek, D. Dhingra, T. C. Prissel, C. R. M. Jackson, D. P. Moriarty III, S. W. Parman, and L. A. Taylor (2014a), The distribution of

DRAFT

DRAFT

M[illegible] the Mo[illegible]nd constraints on [illegible]al origin, American Mineralogist, 99, [illegible]93-1910, doi: [illegible]138/am[illegible]14-4776.

Pieters, C. M., Moriarty III, D. M., Garrick-Bethell, I. (2014b). Atypical regolith processes hold the key to enigmatic lunar swirls. *45th Lunar Planet. Sci. Conf.*, Abstract #1408.

Pieters, C. M., and S. K. Noble (2016), Space weathering on airless bodies, J. Geophys. Res., 121, 1865-1884, doi: 10.1002/2016JE005128. SSERVI-2016-157.

Pinet, P., Shevchenko, V., Chevrel, S., Daydou, Y., &. Rosemberg, C. (2000). Local and regional lunar regolith characteristics at Reiner Gamma Formation: Optical and spectroscopic properties from Clementine and Earth-based data. *J. Geophys. Res., 105,* 9457–9475, doi:10.1029/1999JE001086.

Qiao, L., Head J., Wilson L., Xiao L., Kreslavsky M., and Dufek J. (2017) Ina pit crater on the Moon: Extrusion of waning-state lava lake magmatic foam results in extremely young crater retention ages. *Geology, 45*, 455-458. https://doi.org/10.1130/G38594.1

Robinson, M. S., Ashley, J. W., Boyd, A. K., Wagner, R. V., Speyerer, E. J., Ray Hawke, B., Hiesinger, H., van der Bogert, C. H. (2012). Confirmation of sublunarean voids and thin layering in mare deposits. *Planetary and Space Science*, *69*(1), 18–27. https://doi.org/10.1016/j.pss.2012.05.008

Shipley, S. T., Metzger, P. T., & Lane, J. E. (2014). Lunar Cold Trap Contamination by Landing Vehicles. In *Earth and Space 2014*, 152-164.

Schultz, P. H., & Srnka, L. J. (1980). Cometary collisions with the Moon and Mercury, *Nature, 284,* 22–26, doi:10.1038/284022a0

Shkuratov, Y., Kaydash, V., Sysolyatina, X., Razim, A., & Videen, G. (2013). Lunar surface traces of engine jets of Soviet sample return probes: The enigma of the Luna-23 and

L[illegible] sites. *P[illegible]ary and Space Sc[illegible]*, *75*, 28–36. [illegible]ps://doi.org/1[illegible]16/j.pss[illegible]12.10.016

Shoemaker, E.M., Robinson, M.S., & Eliason, E.M. (1994). The south pole region of the Moon as seen by Clementine. *Science, 266*, 1851–1854.

Starukhina, L. V., & Shkuratov, Y. G. (2004). Swirls on the Moon and Mercury: meteoroid swarm encounters as a formation mechanism. *Icarus*, *167*(1), 136–147. https://doi.org/10.1016/j.icarus.2003.08.022

Stöffler, D., and G. Ryder (2001), Stratigraphy and isotope ages of lunar geologic units: Chronological standard for the inner solar system, Space Sci. Rev., 96, 9–54, doi:10.1023/A:1011937020193.

Stopar, J. D., Lawrence, S. J., Jolliff, B. L., Speyerer, E. J., and Robinson M. S. (2016). Defining long-duration traverses of lunar volcanic complexes with LROC NAC images. *Annual Meeting of the Lunar Exploration Analysis Group.* Abstract # 5074.Stopar, J., Lawrence, S. J., Speyerer, E. J., Draper, D., and Denevi B. W. (2018). Exploring lunar volcanism at two unique mar basalt sites: Ina Caldera and the Marius Hills volcanic complex. Presented at the Lunar Science for Landed Missions Workshop, NASA Ames.

Strom, R. G., and G. Neukum (1988). The cratering record on Mercury and the origin of impacting objects, in Mercury, edited by F. Vilas, C. R. Chapman, and M. S. Matthews, pp. 336–373, Univ. of Ariz. Press, Tucson, Ariz.

Stuart-Alexander, D.E. (1978). U.S. Geol. Surv. Map I-1047.

Spudis P.D., Reisse, R. A., & Gillis, J. J. (1994). Ancient multiring basins on the Moon revealed by Clementine laser altimetry. *Science, 266,* 1848-1851

Spudis, P. D., Richards, R. D. (2018). Mission to the Rima Bode regional deposit. Presented at the Lunar Science for Landed Missions Workshop, NASA Ames.

DRAFT

Spudis, P. D., McEwen, M. P. J., & Kiefer W. S. (2015). Large shield volcanoes on the Moon. *Journal of Geophysical Research: Planets, 118*, 1063-1081. doi:10.1002/jgre.20059.

Thaisen, K. G., Head, J. W., Taylor, L. A., Kramer, G. Y., Isaacson, P., Nettles, J., … Pieters, C. M. (2011). Geology of the Moscoviense Basin. *Journal of Geophysical Research: Planets*, *116*(E6), E00G07. https://doi.org/10.1029/2010JE003732

Wagner, R. V., & Robinson, M. S. (2014). Distribution, formation mechanisms, and significance of lunar pits. *Icarus*, *237*, 52–60. https://doi.org/10.1016/j.icarus.2014.04.002

Wagner, R. V., Denevi, B. W., Stopar, J. D., van der Bogert, C. H., Robinson M. S. (2018). The age of Ina and the thermal history of the Moon. Presented at the Lunar Science for Landed Missions Workshop, NASA Ames.

Whitten, J., Head, J. W., Staid, M., Pieters, C. M., Mustard, J., Clark, R., … Taylor, L. (2011). Lunar mare deposits associated with the Orientale impact basin: New insights into mineralogy, history, mode of emplacement, and relation to Orientale Basin evolution from Moon Mineralogy Mapper (M3) data from Chandrayaan-1. *Journal of Geophysical Research: Planets*, *116*(E6), E00G09. https://doi.org/10.1029/2010JE003736

Wieczorek, M. A., Neumann, G. A., Nimmo, F., Kiefer, W. S., Taylor, G. J., Melosh, H. J., … Zuber, M. T. (2013). The Crust of the Moon as Seen by GRAIL. *Science*, *339*(6120), 671–675. https://doi.org/10.1126/science.1231530

Wilhelms, D.E. (1987). The Geologic History of the Moon. *U.S. Geol. Surv. Prof. Pap. 1348.*

Williams J.G., Turyshev S.G., Boggs D.H., and Radcliff J.T. (2006). Lunar laser ranging science: Gravitational physics and lunar interior and geodesy. *Adv. Space Res., 37*, 67-71.

Williams J.G., Newhall X.X., and Dickey J.O. (1996). Relativity parameters determined from lunar laser ranging. *Phys. Rev. D, 53*, 6730–6739.

DRAFT

DRAFT

Wilson, [illegible] Like, [illegible] Massey, [illegible] J., Elphic, R. C., [illegible], B. L., Lawrence, D. J., … Teodoro, [illegible] F. A. (2015). Evidence for explosive silicic volcanism on the Moon from the extended distribution of thorium near the Compton-Belkovich Volcanic Complex. *Journal of Geophysical Research: Planets*, *120*(1), 92–108. https://doi.org/10.1002/2014JE004719

Wilson, L., and Head, J. W. (2017). Generation, ascent and eruption of magma on the Moon: New insights into source depths, magma supply, intrusions and effusive/explosive eruptions (Part 1: Theory). *Icarus, 283*, 146-175.

Yamamoto, S., Nakamura, R., Matsunaga, T., Ogawa, Y., Ishihara, Y., Morota, T., … Haruyama, J. (2012). Olivine-rich exposures in the South Pole-Aitken Basin. *Icarus*, *218*(1), 331–344. https://doi.org/10.1016/j.icarus.2011.12.012

Zarka P., Bougeret J.-L., Briand C., Cecconi B., Falcke H., Girard J., Grießneier J.-M., Hess S., Klein-Wolt M., Konovalenko A., Lamy L., Mimoun D., and Aminaei A. (2012) Planetary and exoplanetary low frequency radio observations from the Moon. *Planet. Space Sci., 74*, 156-166.

Zhang et al., (2014) - http://engine.scichina.com/publisher/scp/journal/SST/44/6/10.1360/092014-51?slug=full%20text

Zisk, S. H., Hodges, C. A., Moore, H. J., Shorthill, R. W., Thompson, T. W., Whitaker, E. A., & Wilhelms, D. E. (1977). The Aristarchus-Harbinger region of the moon: Surface geology and history from recent remote-sensing observations. *The Moon*, *17*(1), 59–99. https://doi.org/10.1007/BF00566853