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Key Points:
- This report outlines lunar sites that landed missions could visit for scientific exploration
- High-priority lunar mission targets will aid future public-private partnerships on the Moon
- A series of mission enhancing technology priorities are identified

Supporting Information:
- Supporting Information S1

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Lunar Science for Landed Missions Workshop Findings Report

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Abstract The Lunar Science for Landed Missions workshop was convened at the National Aeronautics and Space Administration Ames Research Center on 10–12 January, 2018. Interest in the workshop was broad, with 110 people participating in person and 70 people joining online. In addition, the workshop website (https://lunar-landing.arc.nasa.gov) includes video recordings of many of the presentations. This workshop defined a set of targets that near-term landed missions could visit for 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 impact cratering processes and dating, volatiles, volcanism, magnetism, geophysics, and astrophysics. Representatives from the Japan Aerospace Exploration Agency and the European Space Agency also presented about international plans for lunar exploration and science. This report summarizes the set of landing sites and/or investigations that were presented at the workshop that would address high priority science and exploration questions. In addition to landing site discussions, technology developments were also specified that were considered as enhancing to the types of investigations presented. It is evident that the Moon is rich in scientific exploration targets that will inform us on the origin and evolution of the Earth-Moon system and the history of the inner Solar System, and also has enormous potential for enabling human exploration and for the development of a vibrant lunar commercial sector.

Plain Language Summary Where should we explore next on the Moon? This report summarizes potential future landing sites on the surface of the Moon, as presented at the Lunar Science for Landed Missions Workshop in January 2018 at NASA Ames.

1. Introduction

The Lunar Science for Landed Missions workshop was held on 10–12 January, 2018 at NASA Ames Research Center and was attended by both lunar scientists and representatives from commercial companies. The workshop was cosponsored 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, generated by the lunar science community, for near-term lunar missions. 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 impact cratering processes and crater 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

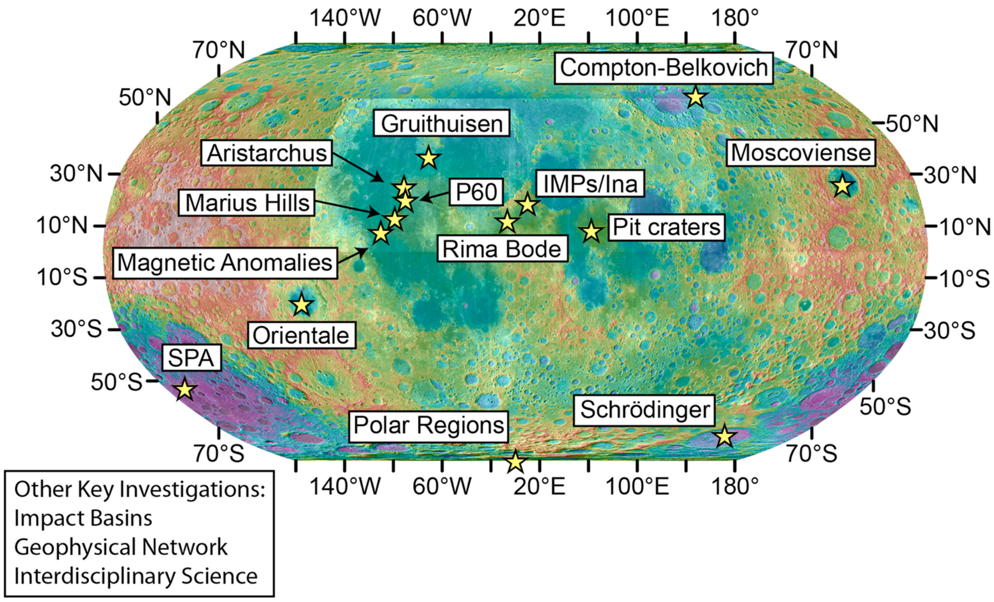

Figure 1. Yellow stars indicate the high-priority landing sites outlined in this report. LROC WAC global basemap (100 m/pix) with LOLA-shaded topography.

programs in Japan and Europe. 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. The landing sites in this report represent those advocated at the 2-day workshop (Figure 1). They are reasonable targets for commercial landers, although it should not be inferred that the list in this document represents a global assessment of potential landing sites, as there are undoubtedly other sites that will yield a high scientific return that were not discussed in the workshop.

1.1. Summary of Key Science Goals Identified by Previous Studies

Throughout this report, we refer to three documents that have outlined key science questions to be addressed with lunar exploration: the 2007 National Research Council (NRC) Scientific Context for the Exploration of the Moon (henceforth referred to as the SCEM), the 2017 LEAG Specific Action Team Report Advancing Science of the Moon (ASM-SAT, which assessed progress made in achieving the science goals laid out in the SCEM), 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 the SCEM, ASM-SAT, and the Decadal Survey. The goals and major findings of each of these documents are briefly summarized below.

The SCEM (National Research Council, 2007) 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.

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.

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 eight scientific concepts of the SCEM report, the ASM-SAT (Lunar Exploration Analysis Group LEAG, 2017) 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 recognized 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.

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

The Planetary Decadal Survey (NRC, 2011) 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 cross-cutting 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 original Decadal Survey for these details. 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

Scientific goals that can be addressed through surface exploration of the Moon best fit in the first two objectives. Several key science goals were identified for each of these objectives, as outlined below:

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

1. Constrain the bulk composition of the terrestrial planets to understand their formation from the solar nebula and controls on their subsequent evolution
2. Characterize planetary interiors to understand how they differentiate and dynamically evolve from their initial state
3. 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.*

1. Understand the composition and distribution of volatile chemical compounds
2. Understand the effects of internal planetary processes on life and habitability
3. 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 (SPA) basin sample return and establishing a long-lived global Lunar Geophysical

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Network. In addition, it also stated there were other important science issues that could be addressed by future missions (see page 133, NRC, 2011). These issues 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 and the impact history of the inner Solar System through the exploration of better characterized and newly revealed lunar terrains.

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 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 SPA 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 enhance future exploration.

We also refer the readers to a 6-year global landing site study, *Global Lunar Landing Site Study to Provide the Scientific Context for Exploration of the Moon*, which identified landing sites where SCEM goals could be addressed (Kring and Durda, 2012), and also to the Lunar Exploration Roadmap, a living document that was developed by LEAG over a period of 6 years (https://www.lpi.usra.edu/leag/roadmap/index.shtml).

1.2. Summary of Strategic Knowledge Gaps in Lunar Exploration

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

The three broad lunar science-exploration SKG themes are as follows:

1. understand the lunar resource potential (11 open SKGs),
2. understand the lunar environment and its effects on human life (12 open SKGs), and
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 1 focuses on the composition, distribution, and usage of lunar volatiles in the lunar regolith, pyroclastic deposits, and at the lunar poles. Theme 2 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 3 comprises several subthemes concentrating on how humans 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.

2. Overview of Individual Landing Sites

Presentations and discussions at the workshop produced a list of several potential landing sites where investigations would be relevant to the overarching documents discussed above (Figure 1). The following section presents each landing site and discusses the relevance to SCEM concepts, planetary decadal questions, and SKGs, as well as key measurements and potential exploration scenarios. Requirements pertaining to mobility and sample return (versus in situ science) for these potential exploration scenarios are specified. Each landing site is accompanied by a figure showing the region including shaded relief topography and slope data. Alternate versions of these figures are available as supporting information for those suffering from colorblindness. Note that the discussions of specific exploration scenarios are summarized in this work as they were presented at the workshop and do not include an exhaustive list of potential mission architectures.

Table 1
Summary of Science Themes Addressed at Each Landing Site

	SCEM overarching themes								ASM overarching themes			Enhancing technologies					
	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	Cryogenic sampling	Automated hazard avoidance	Mobility	Dust mitigation
Aristarchus	×	×	×		×	×			×				×		×	×	×
Compton Belkovich		×	×		×				×			×	×		×	×	×
Gruithuisen domes		×	×		×				×				×		×	×	×
Ina/IMPs	×	×			×	×			×				×		×	×	×
Magnetic anomalies		×	×	×		×	×	×	×			×	×		×	×	×
Marius Hills	×				×				×				×		×	×	×
Moscoviense	×	×	×		×	×	×		×		×	×	×		×	×	×
Orientale	×	×	×		×	×	×		×		×	×	×		×	×	×
P60 basalt	×				×				×				×		×	×	×
Pit craters	×				×		×		×			×	×		×	×	
Polar regions				×					×			×	×	×	×	×	×
Rima bode		×			×				×				×		×	×	×
Schrödinger	×	×	×		×	×			×		×	×	×		×	×	×
SPA	×	×	×		×	×						×	×		×	×	×
Network of nodes - geophysics		×									×	×	×		×		×
Network of nodes - exosphere				×			×	×	×			×	×		×		×
Basin chronology	×					×						×	×		×	×	

Note. IMPs = irregular mare patches; SPA = South Pole-Aitken.

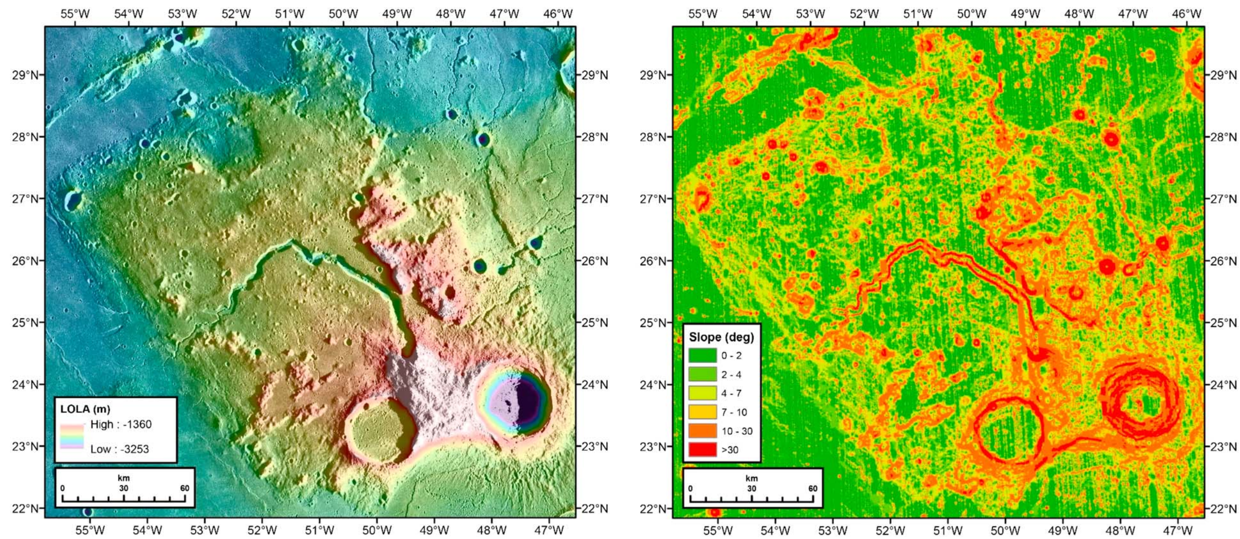

Figure 2. Aristarchus plateau. (left) LROC WAC basemap with LOLA-shaded topography. (right) LOLA-derived slopes.

The analyses for all regions are then summarized in Table 1. The landing sites are listed below in alphabetical order (note that central coordinates are given for each site; for landing sites that have multiple locations, such as magnetic anomalies, coordinates are given for a single location): (1) Aristarchus (50°W, 25°N), (2) Compton-Belkovich volcanic deposit (99.5°E, 61.1°N), (3) Gruithuisen domes (40.5°W, 36.6°N); (4) irregular mare patches (IMPs, 5.3°E, 18.66°N, Ina), (5) magnetic anomalies (e.g., 59°W, 7.5°N, Reiner Gamma), (6) Marius Hills (53°W, 13°N), (7) Moscoviense (147°E, 26°N), (8) Orientale (95°W, 20°S), (9) P60 basaltic unit (49°W, 20°N), (10) pit craters (e.g., 33.22°E, 8.336°N, Mare Tranquillitatis), (11) polar regions (e.g., 0.0°E, 89.9°S, Shackleton crater), (12) Rima Bode (3.5°W, 12°N), (13) Schrödinger (135°W, 75°S), (14) SPA basin (170°W, 53°S), (15) global network of nodes - geophysical, (16) global network of nodes - exosphere, (17) dating large impact basins to anchor lunar chronology, and (18) interdisciplinary science.

2.1. Aristarchus (50°W, 25°N)

The Aristarchus plateau (Figure 2) is a topographic high rising ~2 km above the surrounding terrain (Zisk et al., 1977). The plateau contains the largest pyroclastic deposit on the Moon (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 parts per million (Milliken & Li, 2017).

Relevance to Science Themes

1. S.1: Aristarchus plateau was shaped 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).
2. 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.
3. 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).
4. S.5: The plateau contains the highest concentration of volcanic units on the Moon (Zisk et al., 1977), including evidence of explosive and effusive volcanism.
5. S.6: Aristarchus crater is extremely well preserved, with deposits of impact melt accessible in the interior and exterior of the crater.
6. A.1: Examination of the volcanic deposits will yield new information on the lunar interior volatile budget.

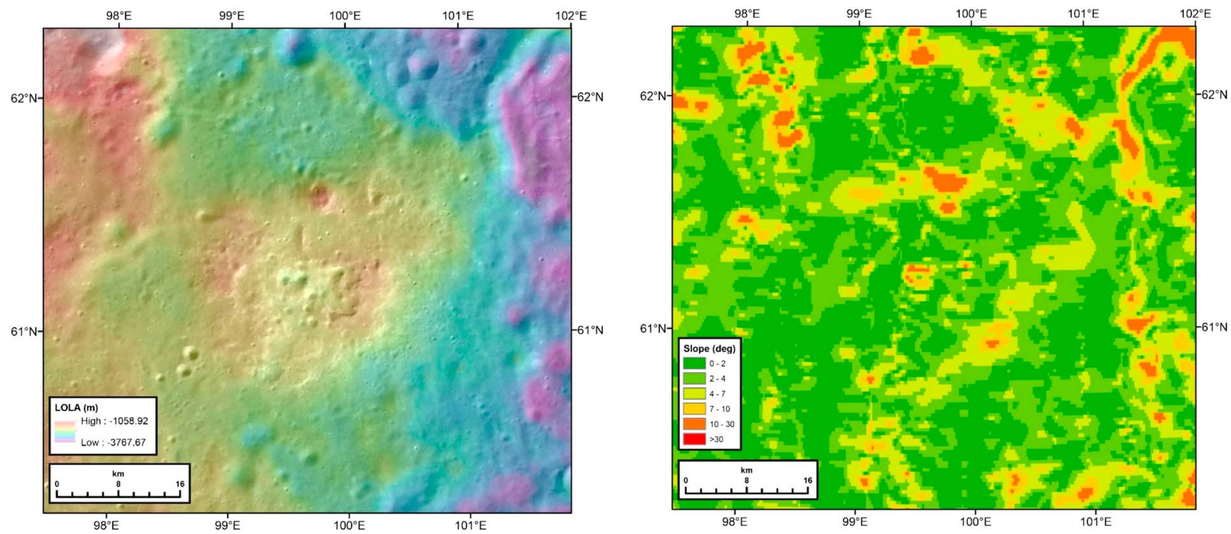

Figure 3. Compton-Belkovich Volcanic Deposit. (left) LROC WAC basemap with LOLA-shaded topography. (right) LOLA-derived slopes.

Relevance to decadal survey
Decadal objective 1

1. Constrain the bulk composition of terrestrial planets by studying the products of volcanism and impact processes.
2. Characterize planetary interiors to determine how they differentiate and evolve based on the volcanic products of partial melts from the lunar interior.
3. Characterize planetary surfaces to understand how they are modified by geologic processes (i.e., volcanism and impact cratering).

Decadal objective 2

1. Understand the composition and distribution of volatile chemical compounds by studying the pyroclastic deposit.

Relevance to exploration themes

1. SKG 1: The resource potential can be analyzed through studying the pyroclastic deposit, assessing H and other volatile species within the deposit, and developing sampling techniques to best preserve volatiles.
2. 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.
3. 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; and quantified 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	SKG 1-3	No	Both

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2.2. Compton-Belkovich Volcanic Deposit (99.5°E, 61.1°N)

The Compton-Belkovich Volcanic Complex (CBVC) (Figure 3) is a small (~25 × 35 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 hot spot and has elevated topography and high reflectance compared to the surrounding highlands (Gillis et al., 2002; Lawrence et al., 2000, 2007). The CBVC contains a range of volcanic features, including irregular collapse features, small domes, and several large volcanic constructs (cones or cumulo domes, Chauhan et al., 2015; Jolliff et al., 2011). Lunar Reconnaissance Orbiter 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 (Bhattacharya et al., 2013; Clegg-Watkins et al., 2017; Petro et al., 2013; Pieters et al., 2009, 2014; Wilson et al., 2015).

Relevance to Science Themes

1. 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).
2. 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/compositional measurements from a silicic area such as the CBVC especially valuable.
3. S.5: Samples from this site would provide constraints on models of formation of nonbasaltic volcanic features on the Moon. Additionally, evidence exists for pyroclastic deposits at the CBVC.
4. A.1: Analysis of silicic materials for volatiles will add to the emerging lunar volatile story.

Relevance to Decadal Survey
Decadal objective 1

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

Decadal objective 2

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

Relevance to exploration themes

1. SKG 1: 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 (Bhattacharya et al., 2013; Jolliff et al., 2011; Petro et al., 2013; Pieters et al., 2009).
2. 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.
3. SKG 3: 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).

Key measurements: In situ isotopic age determination (Anderson et al., 2017; Jolliff et al., 2018); gamma ray and neutron detection for volatile abundances; hyperspectral imaging; bulk chemistry and mineralogy; and quantified regolith geomechanical properties.

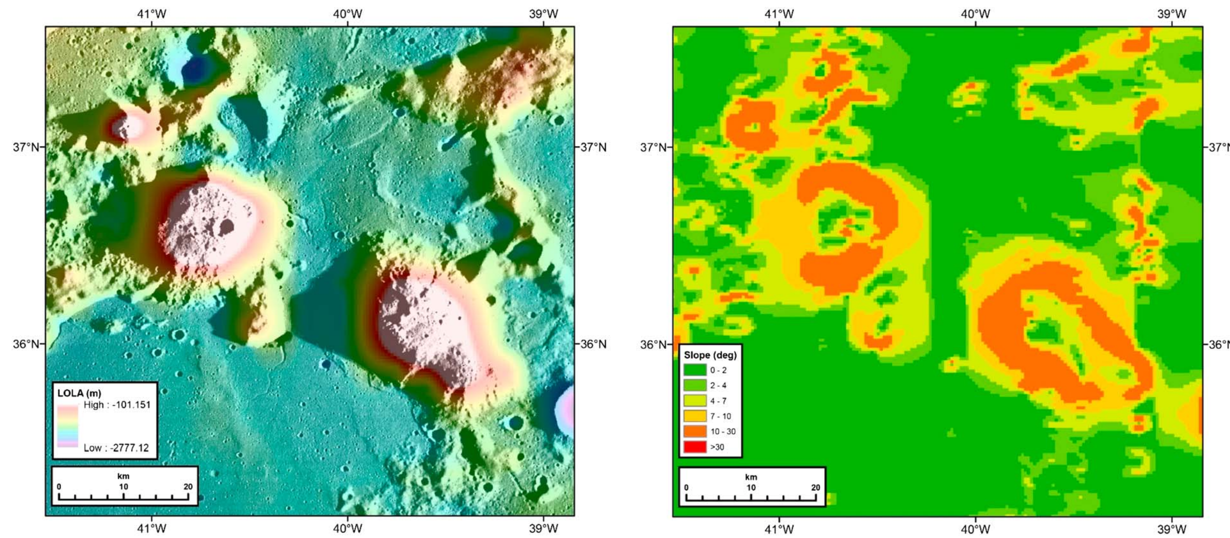

Figure 4. Gruithuisen domes. (left) LROC WAC basemap with LOLA-shaded topography. Gruithuisen gamma is the large western dome containing a crater on the summit. Gruithuisen delta is to the east. (right) LOLA-derived slopes.

Exploration scenario 1: A rover traversing across the complex could take in situ compositional measurements of silicic features and volcanic constructs.

Exploration scenario 2: 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, S.5; A.1	SKG 1-3	Yes	Both

2.3. Gruithuisen Domes (40.2°W, 36.5°N)

The Gruithuisen domes (Figure 4) are located on the western edge of Mare Imbrium (Head et al., 1978), in the NW portion of the Procellarum KREEP Terrane (potassium, rare-earth element, and phosphorous-rich unit). Their unique surface morphologies suggest the lava flows that produced the domes were highly viscous (Hagerty et al., 2006; Head & McCord, 1978). Lunar Prospector Gamma ray spectrometer (GRS) data and Clementine multispectral data show that these domes are relatively low in FeO (6–8 wt %) and high in Th contents (43 ± 3 ppm for Gruithuisen Gamma and 17 ± 6 ppm for Gruithuisen Delta, Hagerty et al., 2006), and photometric observations and Diviner spectral data confirm that these domes have intermediate silicic compositions (Clegg-Watkins et al., 2017; Glotch et al., 2010).

Relevance to Science Themes

1. 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).
2. 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.
3. 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 nonbasaltic volcanic features on the Moon.
4. A.1: Analysis of the silicic materials for volatiles will add to the emerging lunar volatile story.

Relevance to Decadal Survey
Decadal objective 1

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

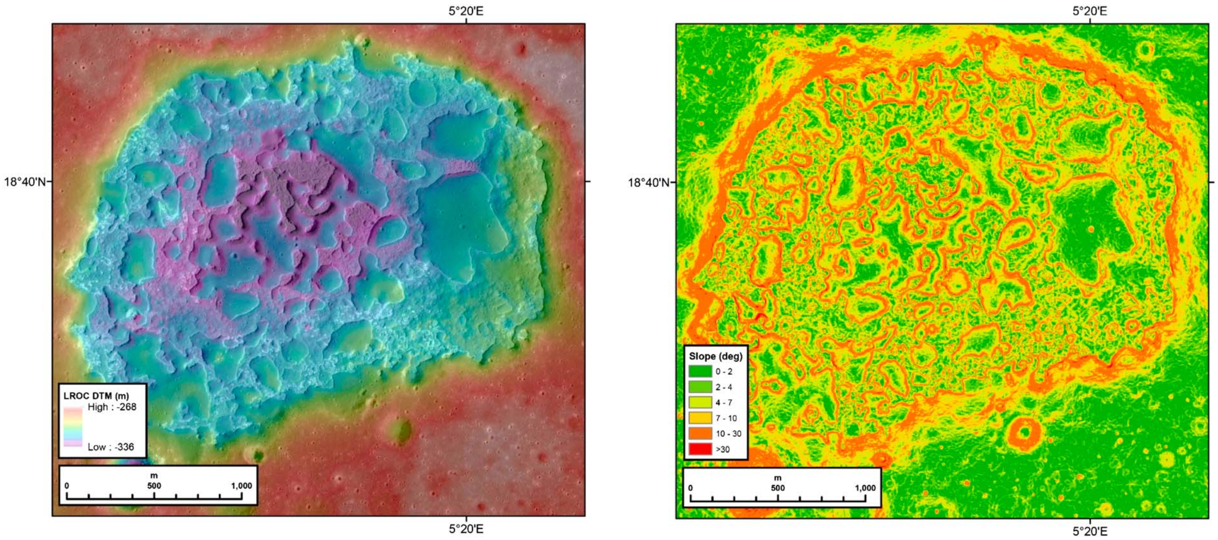

Figure 5. Ina (irregular mare patch). (left) LROC NAC digital terrain model (DTM) with shaded topography. (right) LROC NAC DTM-derived slopes.

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

Relevance to exploration themes

1. SKG 1: A surface mission would examine the resource potential of highly silicic deposits by assessing the presence (or lack thereof) of volatile-rich deposits.
2. SKG 3: 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); and quantify regolith geomechanical properties.

Exploration scenario 1: A lander on the flat summit of either of the Gruithuisen domes 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: A rover would allow analyses of different locations on the domes for more rigorous analyses that would provide regional context.

Science themes	Exploration themes	Mobility required?	In situ or sample return
S.2, S.3, S.5; A.1	SKG 1, 3	No	Sample return

2.4. IMPs/Ina Caldera (5.3°E, 18.66°N)

IMPs are volcanic constructs that are relatively small (100–5,000 m) and are characteristically irregular in morphology and texture (e.g., Braden et al., 2014). The example used here, Ina Caldera (Figure 5), is an IMP in Lacus Felicitatis first recognized in the Apollo 15 panoramic camera images (Strain & El-Baz, 1980; Whitaker, 1972). Ina is composed of smooth volcanic mounds surrounded by uneven terrain lower in elevation, with the whole unit atop a broad shield (e.g., Braden et al., 2014; El-Baz, 1973; Strain & El-Baz, 1980; Whitaker, 1972). The composition of Ina is similar to that of the surrounding mare basalts (Bennett et al., 2015). The smooth mounds of Ina are notably low in crater density, indicating that they may represent some of the youngest volcanism on the Moon; perhaps younger than 100 million years (Braden et al., 2014; El-Baz, 1973; Strain & El-Baz, 1980). In addition, Braden et al., 2014 argued that the morphology of IMPs is consistent with volcanic eruptions considerably later than mare basaltic volcanism. However, recent research by Qiao et al. (2017) argues that if the magmas that formed the IMPs were significantly porous, the crater-derived model age may actually be considerably older (to ~3.5 Ga).

Relevance to Science Themes

1. S.1: IMPs such as Ina have been proposed to be very young (<100 Ma, Braden et al., 2014) and also very old (3.5 Ga, 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.
2. S.2: If IMPs such as Ina are indeed as young as the CSFD model ages, 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).
3. S.5: The volcanic processes that led to the emplacement of the smooth volcanic mounds at IMPs are not well understood. A mission to Ina Caldera would improve our knowledge of lunar volcanic processes.
4. S.6: The materials that compose the IMPs are proposed to be highly porous, which would yield crater sizes smaller than predicted (Qiao et al., 2017; Wilson & Head, 2017). A mission to Ina would advance our knowledge of target material properties and impact cratering processes.
5. A.1: If IMPs are indeed young, measuring the volatile content of the exposed materials would allow a temporal evaluation of volatiles in the lunar interior.

Relevance to Decadal Survey
Decadal objective 1

1. Constrain the bulk composition of terrestrial planets by understanding the composition of volcanic products.
2. Characterize planetary interiors to determine how they differentiate and evolve by analyzing volcanic products generated by partial melts of the lunar interior.
3. Characterize planetary surfaces to understand how they are modified by geologic processes (i.e., volcanism).

Decadal objective 2

1. Understand the composition and distribution of volatile chemical compounds by studying a volatile-rich volcanic deposit.

Relevance to Exploration Themes

1. SKG 1: Ina or other IMPs may be young volcanic features. If they are young, it may be possible to analyze the resource potential of volatiles in young volcanic features.
2. SKG 3: A mission to Ina or another IMP 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: Landing on a smooth mound 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).

Exploration scenario 2: Landing on the eastern side of Ina with a rover would provide access to both the smooth mounds and uneven terrain. Access to both units will allow to 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	SKG 1, 3	No	Both

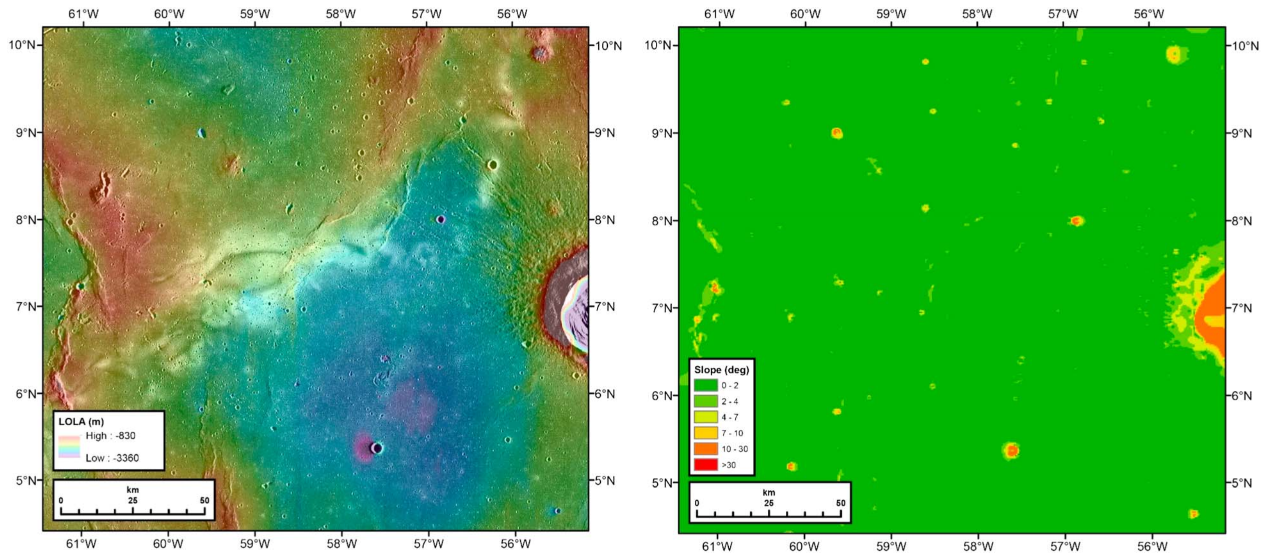

Figure 6. Reiner gamma (magnetic anomalies). (left) LROC WAC basemap with LOLA-shaded topography. (right) LOLA-derived slopes.

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

The lunar crust contains local 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 1,000 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 (Bruck Syal & Schultz, 2015; Schultz & Srnka, 1980); igneous intrusion (Purucker et al., 2012; Srnka et al., 1979); or metallic iron impactor remnants (Oliveira et al., 2017; Wieczorek et al., 2012) magnetized in an ancient global field. Several magnetic anomalies are colocated with enigmatic reflectance features called swirls (Blewett et al., 2011; Denevi et al., 2016; El-Baz, 1972; Hood et al., 1979a, 1979b; Hood & Williams, 1989). Lunar swirls (e.g., Figure 6) 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, Moriarty, et al., 2014). There are currently four hypotheses for the formation of swirls: (1) attenuated space weathering due to solar wind shielding (Hood & Schubert, 1980; Hood & Williams, 1989; Kramer et al., 2011), (2) disturbances caused by cometary impacts (Pinet et al., 2000; Schultz & Srnka, 1980; Starukhina & Shkuratov, 2004), (3) electrostatic dust accumulation (Garrick-Bethell et al., 2011), and (4) collapse of fairy-castle structure (Pieters, Moriarty, et al., 2014)

Relevance to Science Themes

1. S.2: Determining the source of 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.
2. S.3: Magnetization is an important aspect of lithologic diversity and crustal structure of the Moon.
3. S.4: Lunar swirls allow for the examination of the retention and loss of OH/H_2O in areas of variable solar wind flux.
4. 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.
5. 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 (Blewett et al., 2018; Pieters & Noble, 2016).
6. 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.

7. 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.

Relevance to Decadal Survey
Decadal objective 1

1. Characterize planetary surfaces to understand how they are modified by geologic processes (i.e., magnetism).

Decadal objective 2

1. Understand the composition and distribution of volatile chemical compounds by studying solar wind interactions.

Relevance to exploration themes

1. SKG 1: A mission to lunar swirls 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.
2. SGK 2: 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.
3. SKG 3: 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.

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; and quantified regolith geomechanical properties.

Exploration scenario 1: A roving mission across a swirl could take 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.2-4, S.6-8; A.1	SKG 1-3	Yes	In situ

2.6. Marius Hills (53°W, 13°N)

The Marius Hills (Figure 7) are a volcanic province on a broad shield structure that may have experienced long-lived volcanism (Hiesinger et al., 2016; Spudis et al., 2013). The region includes numerous domes (over 150), cones (93), pyroclastic deposits, and sinuous rilles, representing a variety of volcanic eruption styles across the province (Greeley, 1971; Heather et al., 2003; Lawrence et al., 2013). The dome structures that compose the Marius Hills are similar in composition to the surrounding mare (Lawrence et al., 2013; Weitz & Head, 1999). Basalt flow compositions over the Marius Hills vary in Ti contents, indicating multiple eruptions (Heather et al., 2003; Weitz & Head, 1999). Besse et al. (2011) indicate that there are two dominant basalt units—one olivine rich, and one high-calcium pyroxene rich. Results from Diviner indicate that the domes are not silicic (Lawrence et al., 2013). Ages of most of the mare basalts in the region are Imbrian to Eratosthenian in age at 3.0 to 3.5 Ga, but some low shield structures are as young as 1.03 Ga (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).

Relevance to science themes

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.
2. 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.
3. A.1: The Marius Hills provide an opportunity to study the temporal evolution of volcanic volatiles.

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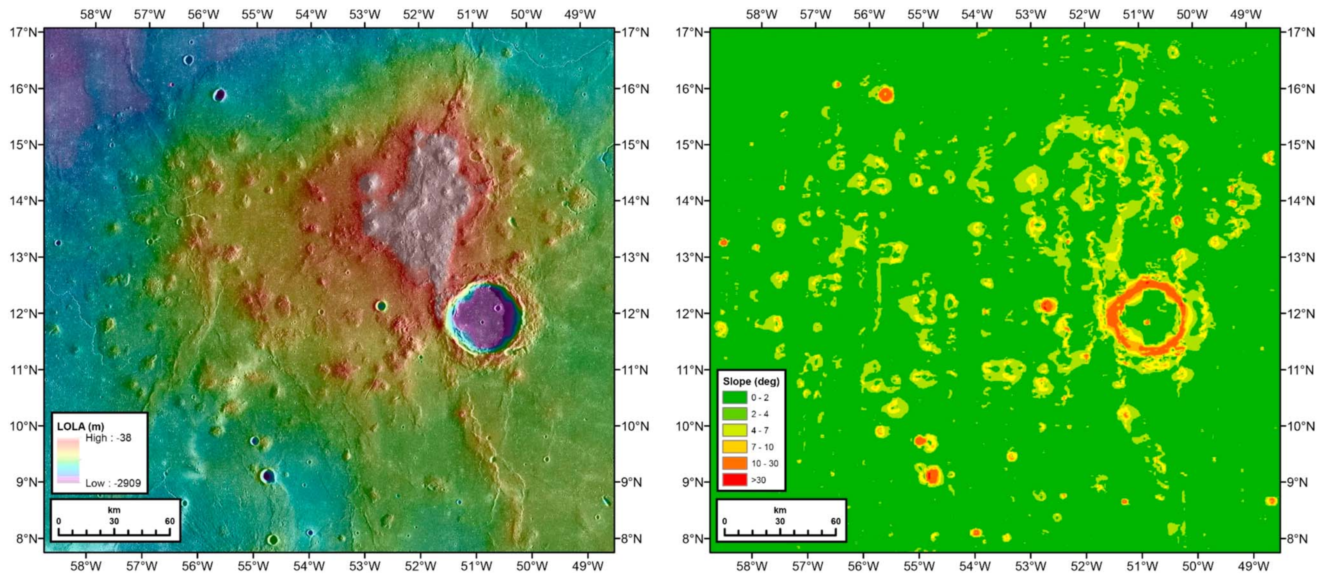

Figure 7. Marius Hills. (left) LROC WAC basemap with LOLA-shaded topography. (right) LOLA-derived slopes.

Relevance to decadal survey
Decadal objective 1

1. Constrain the bulk composition of terrestrial planets by studying the composition of volcanic products.
2. Characterize planetary interiors to determine how they differentiate and evolve by assessing volcanic products created through partial melts of the lunar interior.
3. Characterize planetary surfaces to understand how they are modified by geologic processes (i.e., volcanism).

Decadal objective 2

1. Understand the composition and distribution of volatiles on the lunar surface and within the interior by studying volatile-rich volcanic deposits.

Exploration relevance

1. SKG1: A mission to the Marius Hills could provide information about the spatial and temporal distribution of potential volcanic volatile deposits.
2. 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.

Key measurements: Compositional characterization across the shield; in situ age dating; and quantified 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, 2018).

Science themes	Exploration themes	Mobility required?	In situ or sample return
S.1, S.5; A.1	SKG 1 and 2	Yes	Both

2.7. Moscoviense (147°E, 26°N)

Moscoviense basin (Figure 8) on the farside of the Moon is a Nectarian-aged multiring impact basin that formed 3.85–2.92 Ga (Wilhelms, 1987). The basin contains an elongated floor with nonconcentric

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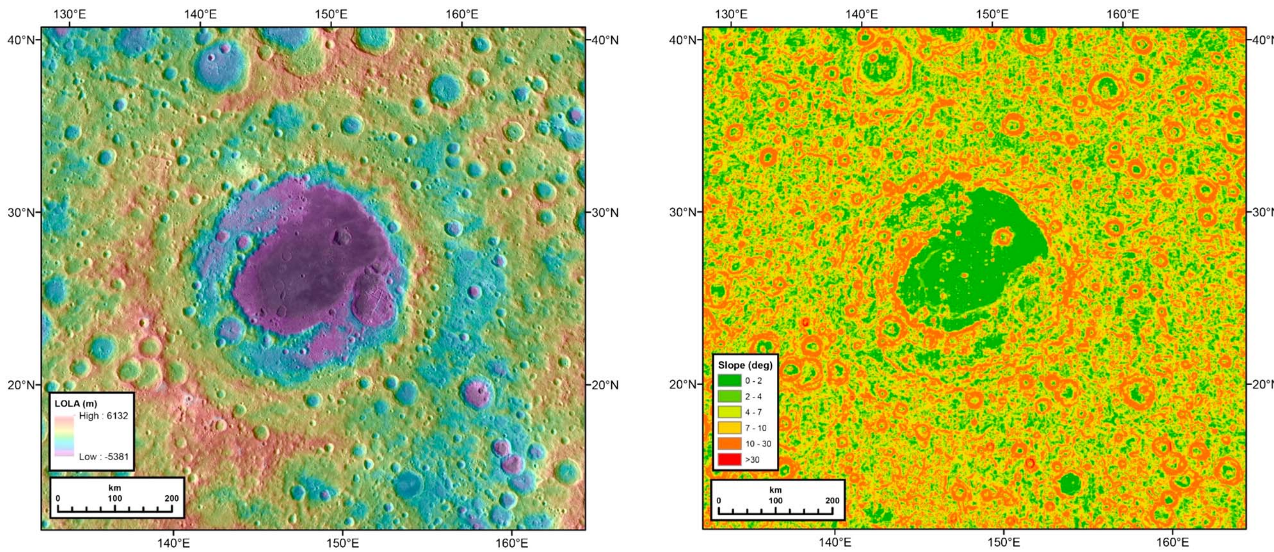

Figure 8. Moscoviense basin. (left) LROC WAC basemap with LOLA-shaded topography. (right) LOLA-derived slopes.

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, Donaldson Hanna, et al., 2014) in an anorthosite-rich peak ring that 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

1. S.1: Exploring Moscoviense will provide accurate ages for the formation of a large basin on the lunar farside.
2. 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 farside.
3. S.3: A diverse suite of minerals and lunar rock types is present within the basin, including OOS, anorthosite, and diverse mare basalts.
4. S.5: Mare basalts and pyroclastic deposits provide access to diverse lunar volcanic units, especially on the farside of the Moon.
5. 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 nonconcentric rings, distinguishing between an oblique impact, double impact, or an impact into a crustal anomaly (Thaisen et al., 2011).
6. S.7: Studying the lunar swirls present within the basin will help to constrain regolith processes and the detailed nature of space weathering (see section 2.5).
7. 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 farside mantle.
8. 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).

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Relevance to decadal survey
Decadal objective 1

1. Constrain the bulk composition of terrestrial planets by studying the different compositional units within the basin.
2. Characterize planetary interiors to determine how they differentiate and evolve by assessing volcanic products created through partial melts of the lunar interior.
3. Characterize planetary surfaces to understand how they are modified by geologic processes (i.e., impacts, tectonism, and volcanism).

Decadal objective 2

1. Understand the composition and distribution of volatiles on the lunar surface and within the interior by studying pyroclastic deposits and solar wind interactions at lunar swirls.

Relevance to Exploration Themes

1. 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.
2. 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) that may affect surface conditions.
3. 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; and quantified regolith geomechanical properties.

Exploration scenario 1: Regional roving experiments could investigate the peak ring/western basin floor for lunar swirls and pyroclastic deposits.

Exploration scenario 2: Sample return 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.1-3, 5-7; A.1, A3	SKG 1-3	No	Both

2.8. Orientale (95°W, 20°S)

The Orientale basin (Figure 9) is the youngest and best-preserved multiring basin on the Moon, which formed ~3.68 Ga and is located on the transition from thin lunar nearside crust to thick lunar farside crust (e.g., Whitten et al., 2011). The basin contains three concentric rings named the Cordillera Ring, the Outer Rook Ring, and the 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

1. S.1: Determining the age of the Maunder Formation impact melt can constrain the bombardment history of the inner Solar System.
2. S.2 Analyzing the composition and structure of the Orientale basin rings will yield insight into the structure and composition of the lunar interior.
3. 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.

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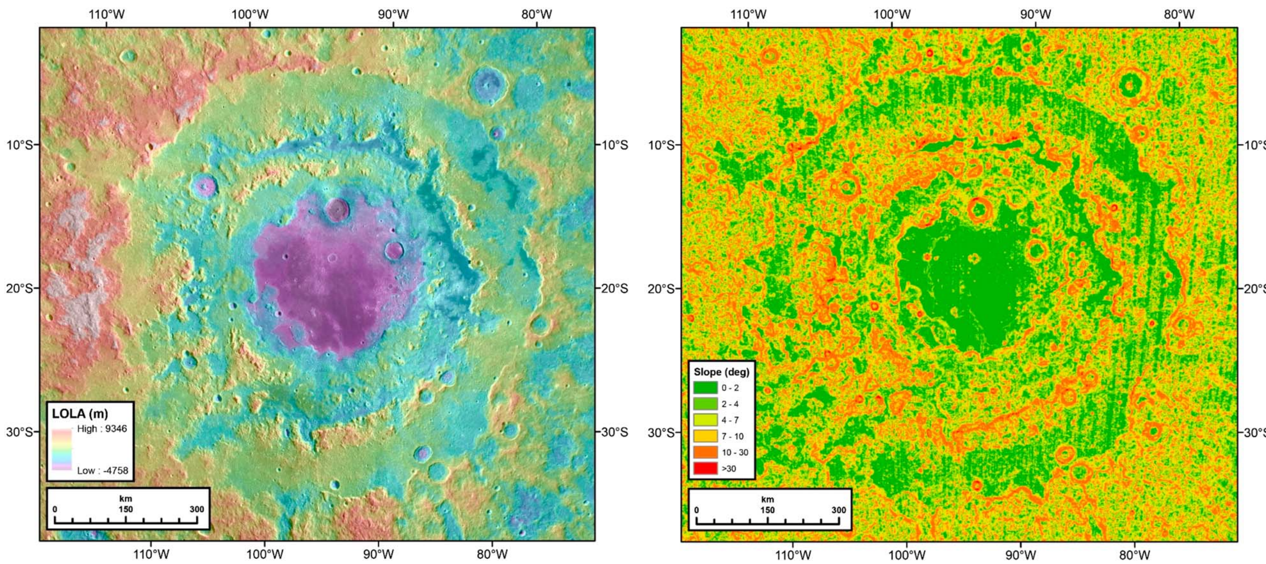

Figure 9. Orientale basin. (left) LROC WAC basemap with LOLA-shaded topography. (right) LOLA-derived slopes.

4. 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.
5. S.6 Studying Orientale basin will aid in constraining the formation of large-scale impact basins.
6. 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.
7. A.1: Assessing the pyroclastic deposit will inform the lunar water cycle and the role of hydration due to solar wind implantation.
8. 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.

Relevance to decadal survey
Decadal concept 1

1. Constrain the bulk composition of terrestrial planets by studying the different compositional units within the basin.
2. Characterize planetary interiors to determine how they differentiate and evolve by assessing volcanic products created through partial melts of the lunar interior.
3. Characterize planetary surfaces to understand how they are modified by geologic processes (i.e., impacts, tectonism, and volcanism).

Decadal objective 2

1. Understand the composition and distribution of volatiles on the lunar surface and within the interior by studying the pyroclastic deposit.

Relevance to exploration themes

1. 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.
2. SKG 2: Exploring the lunar surface in the Orientale basin will help to better understand the lunar environment especially as related to radiation dosage.
3. SKG 3: Living and working on the lunar surface can be studied by excavating, transporting, and roving in the pyroclastic deposit, as well as on the mare, impact melt, and primary crust surfaces.

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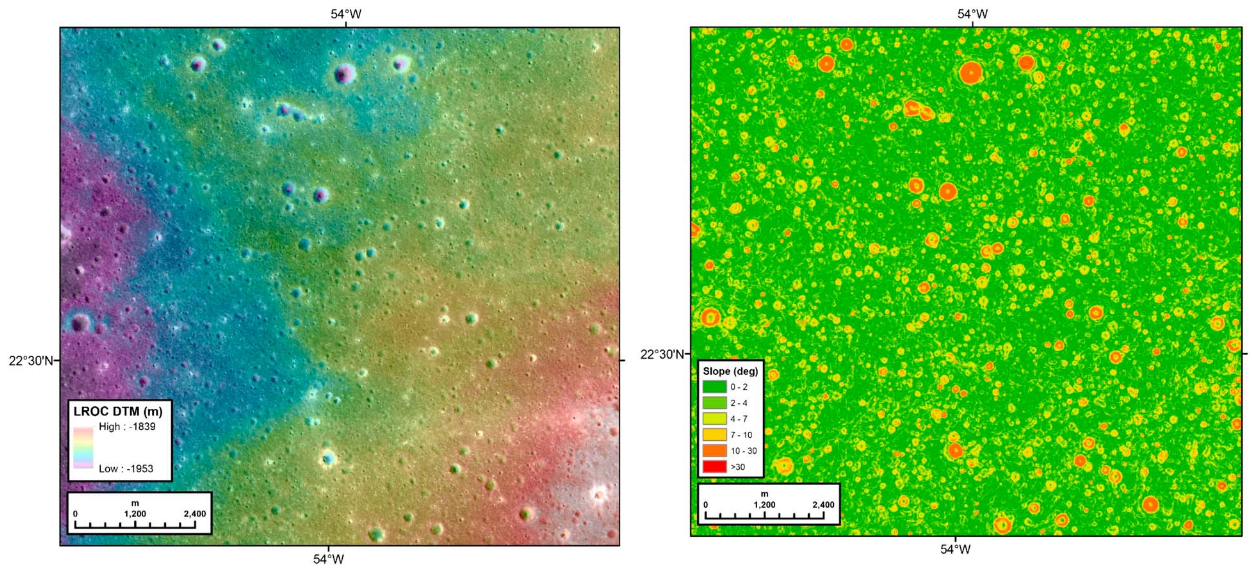

Figure 10. P60 basaltic unit. (left) LROC NAC image M1206371351L with LROC NAC DTM-shaded topography. (right) LROC NAC DTM-derived slopes.

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; and determine the structure of lunar regolith and regolith geomechanical properties.

Exploration scenario 1: A rover 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 lander 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.1-3, 5-7; A.1, 3	SKG 1-3	No	Both

2.9. P60 Basaltic Unit (53.8°W, 22.5°N)

The P60 basalt unit (Figure 10) is located just south of the Aristarchus plateau. The CSFD model age for the P60 basalt suggests it is the youngest mare basalt on the Moon (~1 Ga, Hiesinger et al., 2003, 2010; Stadermann et al., 2018). The P60 unit is a low-Ti basalt, with an estimated TiO_2 content of 4.9 wt % TiO_2 and 18.7 wt % FeO (H. H. Zhang, et al., 2014; F. Zhang, et al., 2014).

Relevance to science themes

1. 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.
2. 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.
3. 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.

Relevance to decadal survey
Decadal concept 1

1. Constrain the bulk composition of terrestrial planets by studying the nature of the mantle source that produced these young basalts.

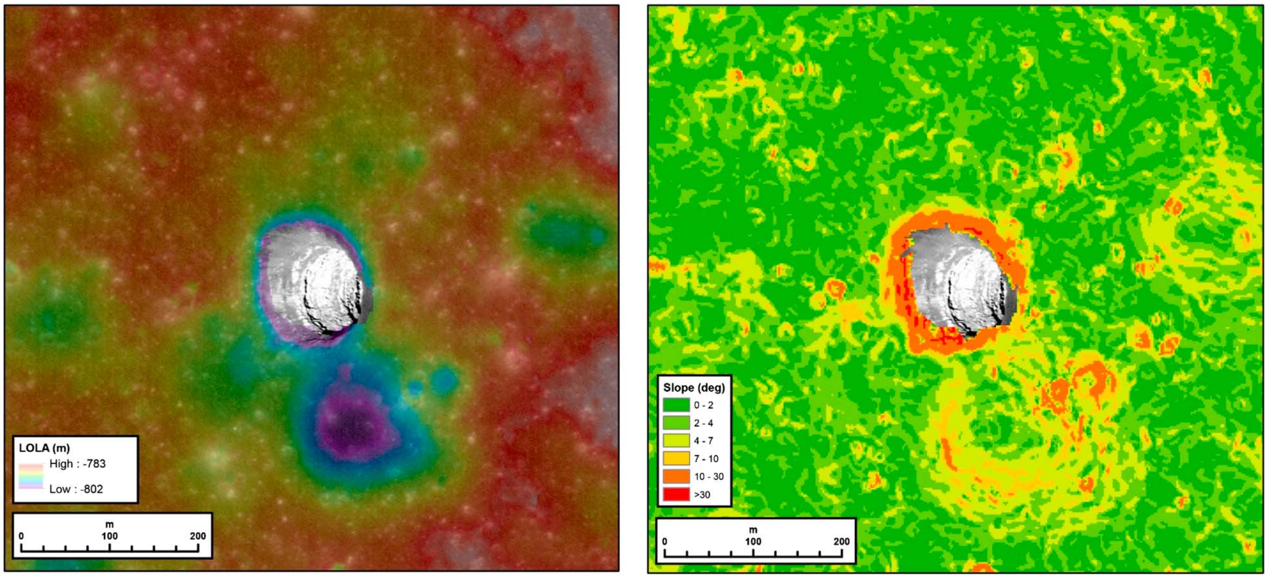

Figure 11. Mare Tranquillitatis pit crater. (left) LROC NAC image M144395745L with LROC NAC DTM-shaded topography. (right) LROC NAC DTM-derived slopes. Topography data are not available inside the pit.

2. Characterize planetary interiors to determine how they differentiate and evolve by assessing the volcanic products produced by partial melts of the lunar interior.
3. Characterize planetary surfaces to understand how they are modified by geologic processes (i.e., volcanism).

Decadal concept 2

1. Understand the composition and distribution of volatile chemical compounds by studying volatile-rich volcanic deposits.

Relevance to exploration themes

1. SKG 1: A mission to the P60 basalt unit could provide information about the volatile contents of young lunar basalts.
2. SGK 2: 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.

Key measurements: Absolute age determination.

Exploration scenario 1: A short-lived (less than 1 lunar day) sample return mission could return <2 kg of rocks and regolith (Lawrence et al., 2018).

Exploration scenario 2: Exploring the region with a long-lived rover would enable more rigorous analyses of the region and could also include the Aristarchus region.

Science themes	Exploration themes	Mobility required?	In situ or sample return
S.1, S.5; A.1	SKG 1, 2	No	Both

2.10. Pit Crater/Lava Tubes (e.g., 33.22°E, 8.336°N, Mare Tranquillitatis)

Lunar pit craters (e.g., Figure 11) 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 & Robinson, 2014). Pit craters located in mare units may indicate the presence of lava tubes of unknown lateral extent, while pits in nonmare impact melt may indicate networks of sublunarean tubes (Haruyama et al., 2009; Robinson et al., 2012).

Relevance to science themes

1. 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.
2. 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.
3. S.6: Studying impact melt on the surface and subsurface will provide extreme insight into crater formation processes as well as crater evolution.
4. 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.
5. 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.

Relevance to decadal survey
Decadal objective 1

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

Decadal concept 2:

1. Understand the composition and distribution of volatile chemical compounds by studying volatile-rich volcanic deposits.

Relevance to exploration themes

1. SKG 1: 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.
2. SKG 2: 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.
3. SKG 3: 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; and spatial mapping of the subsurface void space to determine if a subsurface void is present in a lava tube.

*Exploration scenario 1***:** Deploy a suite of instruments to investigate the interior structure and composition of a pit crater and how extensive a 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, 5-7; A.1	SKG 1-3	Yes	In situ

2.11. Polar Regions (e.g., 0.0°E, 89.9°S, Shackleton Crater)

Previous missions, like Clementine and Lunar Crater Observation and Sensing Satellite, have revealed water exists in lunar polar regions (Colaprete et al., 2010; Nozette et al., 1996) (Figure 12). This water predominantly resides in some permanently shaded regions (PSRs) on the floors and walls of impact craters. Being able to ground truth these data from different PSRs and better understand polar volatiles

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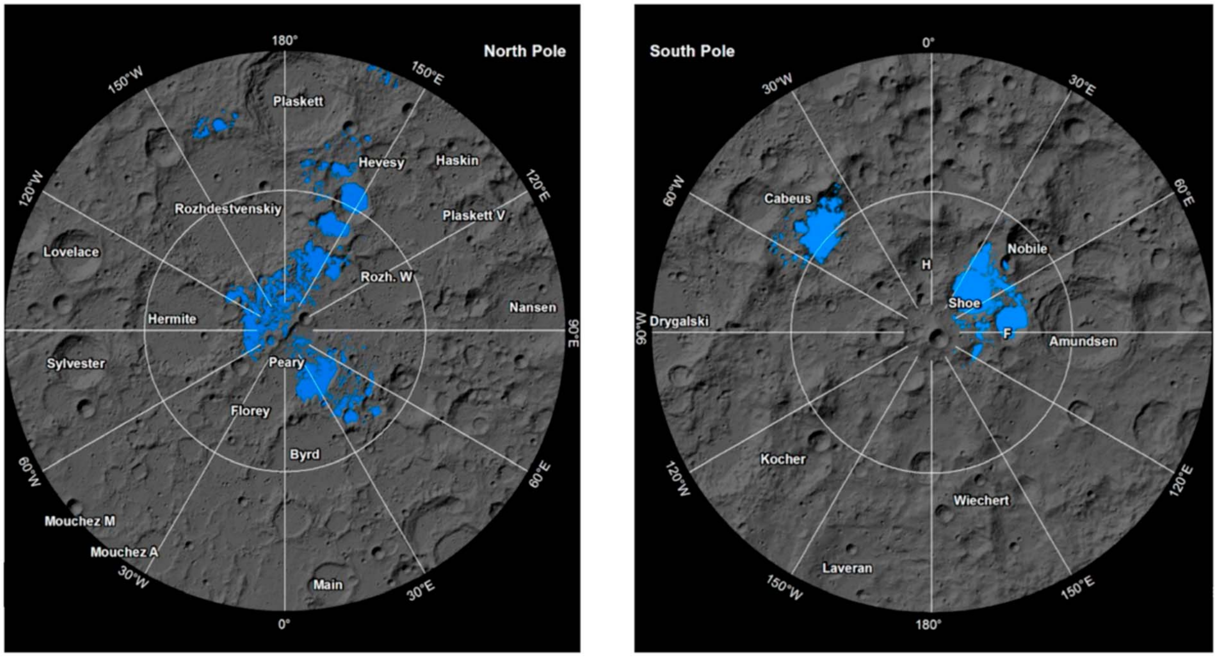

Figure 12. Known polar volatile deposits from the LEAG volatiles specific action team final report (https://www.lpi.usra.edu/leag/reports/vsat_report_123114x.pdf). (Left) North pole. (Right) South pole.

(e.g., amount, form, composition) 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 13).

Relevance to science themes

1. S.4: The lunar poles host environments that are not seen elsewhere on the Moon, making them unique environments for study.
2. S.7: The water ice in these PSRs could affect how regolith accumulates and migrates along the lunar surface.

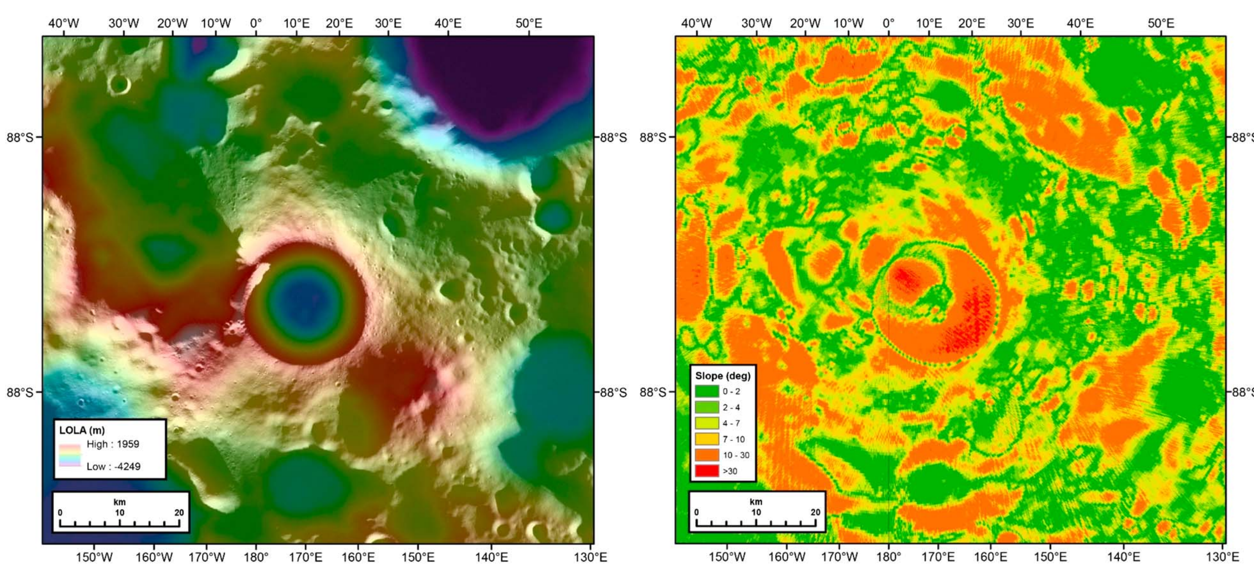

Figure 13. South polar region. (left) LROC WAC basemap with LOLA-shaded topography. (right) LOLA-derived slopes.

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3. A.1: The sequestered water at the poles and its relation to the lunar water cycle is of primary interest in the ASM-SAT.
4. 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 decadal survey
Decadal objective 1

1. Characterize planetary interiors to understand how they differentiate and dynamically evolve from their initial state by constraining the volatile budget of the lunar interior.
2. Characterize planetary surfaces to understand how they are modified by geologic processes (i.e., impacts and volatile transport).

Decadal objective 2:

1. Understand the composition and distribution of volatile chemical compounds by studying deposits of ice.
2. Understand the effects of internal planetary processes on life and habitability by assessing the water ice deposits for purity and abundance.

Relevance to exploration themes

1. SKG 1: Due to the presence of volatiles at the poles, these areas are of great interest to the community for their resource potential. Understanding precise locations, characteristics, and types of volatiles in the polar regions would especially allow the commercial sector to develop business plans and future mission scenarios.
2. SKG 2: Quantifying the magnitude and effects of radiation in polar regions at the surface and in regions of persistent shadow will help to outline habitability for humans.
3. 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 regard to resource production, surface trafficability, radiation shielding, and life support systems.

Key measurements: Characterize distribution, quantity, and species of volatiles; characterize abundance of volatiles with depth; and characterize regolith geotechnical properties.

Exploration scenario 1: Rove 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	SKG 1–3	Yes	Both

2.12. Rima Bode (3.5°W, 12°N)

Located on the central nearside region of the Moon, Rima Bode (Figure 14) is a spatially extensive (~7,000 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, 2003; Spudis & Richards, 2018).

The pyroclastic deposits are spectrally similar to the dark mantling deposits found in the Taurus-Littrow Valley and are believed to be high in titanium and iron. The region contains two concentric units of mantling material that overlay highlands materials: a smaller, continuous, very thick central deposit and an outer, patchy, shallower deposit (Gaddis et al., 2003). A source vent may have been located to the west in Sinus Aestuum, but subsequent episodes of mare volcanism erased any direct evidence of the vent. The deposit is embayed by ~3.5-Ga maria, indicating that these pyroclastics are potentially ancient.

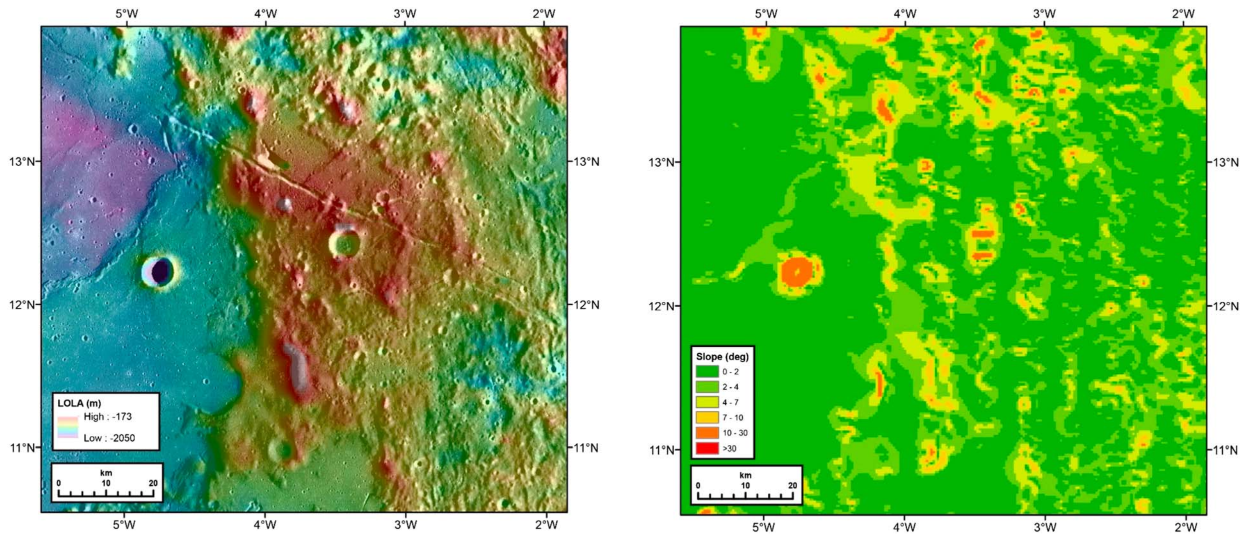

Figure 14. Rima bode. (left) LROC WAC basemap with LOLA-shaded topography. (right) LOLA-derived slopes.

Relevance to Science Themes

1. S.2: Compositional data from the Rima Bode pyroclastics will provide information about the composition of the lunar mantle.
2. S.5: Rima Bode provides a laboratory to study large pyroclastic deposits on the lunar surface.
3. 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.

Relevance to decadal survey
Decadal concept 1

1. Constrain the bulk composition of terrestrial planets by analyzing volcanic products.
2. Characterize planetary interiors to determine how they differentiate and evolve by examining the composition of pyroclastic materials sourced deep from the lunar interior.
3. Characterize planetary surfaces to understand how they are modified by geologic processes (i.e., volcanism).

Decadal concept 2:

1. 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.

Relevance to exploration themes

1. SKG 1: 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.
2. SGK 2: The lunar environmental effects on human life, especially the radiation environment, could be mitigated by studying the radiation shielding effects of fine-grained pyroclastic materials.
3. SKG 3: 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.

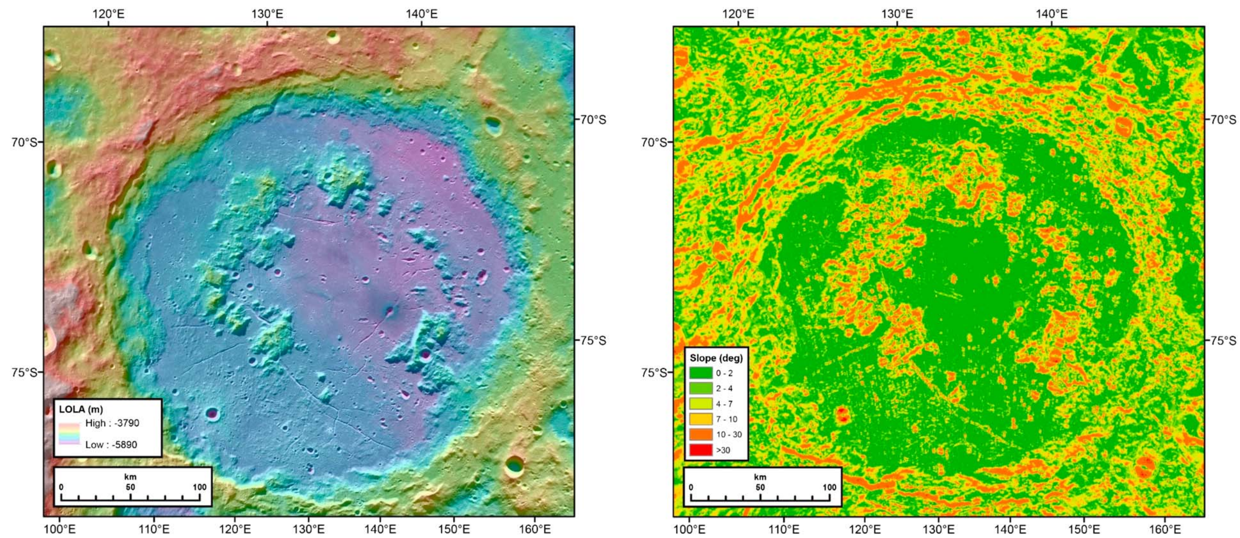

Figure 15. Schrödinger basin. (left) LROC WAC basemap with LOLA-shaded topography. (right) LOLA-derived slopes.

Key measurements: Chemical composition of the pyroclastic deposit; bulk H_2 in upper meter of regolith (Spudis & Richards, 2018); and quantified geomechanical properties of the pyroclastic deposit.

Exploration scenario 1: A lander on the dark mantle deposit could analyze the chemical composition and volatile content of the pyroclastics (Spudis & Richards, 2018).

Science themes	Exploration themes	Mobility required?	In situ or sample return
S.2, 5; A.1	SKG 1-3	No	Both

2.13. Schrödinger (135°E, 75°S)

Schrödinger basin (Figure 15) is the second youngest impact basin and sits adjacent to the oldest (and largest) impact basin, SPA. Schrödinger contains well-preserved impact-generated materials and volcanic deposits, including mare basalts in the northeast and pyroclastic deposits to the southeast (Gaddis et al., 2003; Shoemaker et al., 1994). 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. Schrödinger may have tapped deep crustal lithologies associated with the SPA-forming impact (Kramer et al., 2013; Kring et al., 2016; O'Sullivan et al., 2011). 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 (Kramer et al., 2013; Ohtake et al., 2009; Yamamoto et al., 2012). 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

1. 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).
2. S.2: Analyzing the composition and structure of peak ring materials will yield insight into the composition and structure of the lunar interior (Kring, 2018).
3. S.3: A diverse suite of geologic units is available within Schrödinger, including mafic volcanic materials, pyroclastics, and peak ring materials that may contain diverse lithologies (Kramer et al., 2013).

4. S.5: The floor of the basin contains two types of lunar volcanism-mare basalts and a pyroclastic deposit. Investigations of these volcanic materials can constrain the thermal and compositional evolution of the Moon.
5. S.6: Exploring Schrödinger would provide context into the formation and structure of large basins. Studying the structure of Schrödinger, especially its peak ring, would allow us to probe basin formation and the movement of materials during the formation of peak-ring and multiring basins (e.g., Kramer et al., 2013; Kring, 2018).
6. A.1: Examining the pyroclastic deposits on the floor of Schrödinger would yield new information on the endogenous lunar volatile budget and the volatile cycle of the farside (Kring & Robinson, 2018).
7. A.3: Studying lobate scarps present on the floor of Schrödinger would inform the tectonic and seismic nature and history of the Moon.

Relevance to decadal survey
Decadal objective 1

1. Constrain the bulk composition of terrestrial planets by analyzing the diversity of rock units present in the basin, especially in the peak ring.
2. Characterize planetary interiors to determine how they differentiate and evolve by studying the volcanic units within the basin that formed from partial melts of the lunar interior.
3. Characterize planetary surfaces to understand how they are modified by geologic processes (i.e., volcanism, tectonism, and impacts).

Decadal objective 2:

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

Relevance to exploration themes

1. SKG 1: A surface mission could examine resource potential and preservation of volatile components during robotic sampling, handling, and storage by assessing the volatile content of pyroclastic deposit within Schrödinger.
2. SKG 3: Living and working on the lunar surface could be studied by excavating, transporting, and roving in the pyroclastic deposit, and on and across the various floor units (including the impact melt deposits; e.g., Bunte et al., 2011; Steenstra et al., 2016).

Key measurements: Age of impact melts; bulk chemistry and mineralogy of surface units; volatile content of the pyroclastic deposit; high-resolution imaging; composition and ages of volcanic units; composition and source depth of the peak ring; and quantified regolith geotechnical properties.

Exploration scenario 1: A rover could traverse across various geologic terrains (smooth inner-peak ring, mare basalts, inner-peak ring, peak ring, and pyroclastics), with specific locations selected for imaging and in situ analysis (e.g., Bunte et al., 2011; Burns et al., 2013; Kring, 2018).

Exploration scenario 2: A rover or static lander could return samples to Earth from the basin floor for age dating and compositional analyses (e.g., Kring & Robinson, 2018; Potts et al., 2015).

Science themes	Exploration themes	Mobility required?	In situ or sample return
S.1-3, 5-6; A.1, A.3	SKG 1, 3	Yes	Both

2.14. SPA Basin (170°W, 53°S)

The SPA basin (SPA, Figure 16) 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 (Head et al., 1993; Hurwitz & Kring, 2014; Jolliff et al., 2000; Spudis et al., 1994; Wilhelms, 1987). SPA is located on the lunar farside between Aitken crater and the South Pole and has a diameter of ~2,600 km. SPA contains a diversity of units, including ancient impact melt, basalts,

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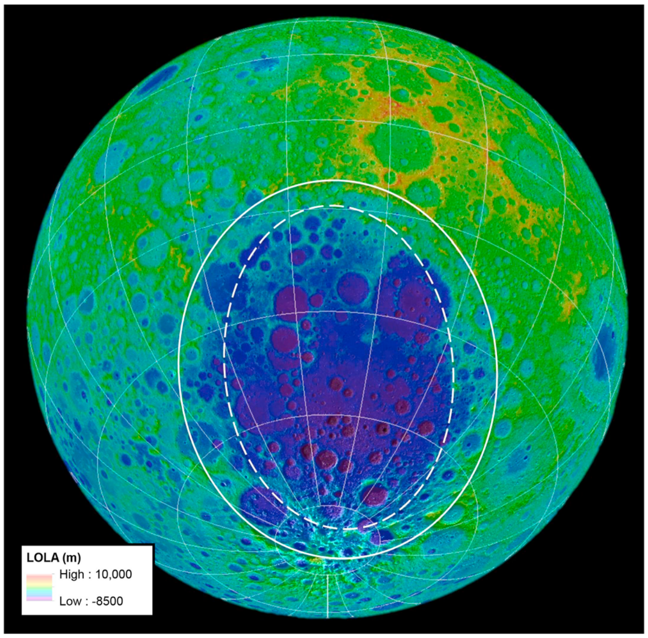

Figure 16. Extent of South Pole-Aitken Basin with LOLA-shaded relief topography.

excavated substrate materials (pre-SPA materials such as lower crustal/mantle materials), and swirls. The SPA impact event is likely to have excavated deeply enough to contain exposures of lower crustal and/or mantle materials (Petro et al., 2011; Pieters et al., 2001). 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 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 as it is included in the polar regions site.

Relevance to science themes

1. 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.
2. S.2: Understanding the source and distribution of heat-producing elements (e.g., thorium) in the basin would 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., 2018).
3. 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 knowledge of rock types, crystallization ages, and depth constraints, therefore unraveling the nature of the Moon's lower crust and mantle.
4. S.5: Determining the ages and compositions of SPA basalts will inform how farside mantle source regions differ from regions sampled by the Apollo and Luna missions. 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 (Gibson & Jolliff, 2011; Petro et al., 2011).
5. 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.

Relevance to decadal survey
Decadal objective 1

1. Constrain the bulk composition of the terrestrial planets by sampling possible lower crustal/upper mantle materials within SPA.
2. Characterize planetary interiors to understand how they differentiate and dynamically evolve from their initial state by sampling excavated basin material as well as volcanic products produced from partial melts of the lunar interior.
3. Characterize planetary surfaces to understand how they are modified by geologic processes (i.e., volcanism and impacts).

Relevance to exploration themes

1. SKG 1: A surface mission could examine the 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.

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2. SKG 3: Living and working on the lunar surface could 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); and quantified 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 expected location of the transient crater rim as prime candidates.

Science themes	Exploration themes	Mobility required?	In situ or sample return
S.1-3, S.5, S.6	SKG1, SKG3	No	Sample return

2.15. Long-Lived Global Monitoring Network - Geophysics

Apollo seismic data and Gravity Recovery and Interior Laboratory 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 farside), with a wider aperture network than that created with the Apollo seismic network. The Apollo heat flow data are anomalous because the probes were placed on the boundaries of the Procellarum KREEP Terrane (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 taking heat flow measurements near the rim zones of large impact basins (Kiefer, 2012). A global network of nodes would allow us to answer questions regarding the seismic state and internal structure of the Moon.

Relevance to science themes

1. S2: 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 Gravity Recovery and Interior Laboratory (GRAIL) data and aid in our understanding of the deep interior structure of the Moon.
2. 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.

Relevance to decadal survey
Decadal objective 1:

1. Characterize planetary interiors to understand how they differentiate and dynamically evolve from their initial state by taking geophysical measurements at a variety of locations on the Moon.
2. A Lunar Geophysical Network was also identified by the Decadal Survey as a high priority target for New Frontiers 5.

Relevance to exploration themes

1. SKG 2: A global geophysical network would provide key information about the lunar environment and the effects that seismic activity and heat flow would have on human life.

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Key measurements: Seismicity, heat flow, laser ranging, and electromagnetic sounding.

Exploration scenario 1: 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.

Exploration scenario 2: 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 farside (Weber et al., 2018).

Science themes	Exploration themes	Mobility required?	In situ or sample return
S.2; A.3	SKG 2	No	In situ

2.16. Long-Lived Global Monitoring Network - Exosphere

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 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 nearside and farside of the Moon.

Relevance to science themes

1. S.4: The lunar poles are special environments that may bear witness to the volatile flux over the latter part of solar system history.
2. S.7: The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies.
3. 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.
4. 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.

Relevance to decadal survey
Decadal objective 1

1. Characterize planetary interiors to understand how they differentiate and dynamically evolve from their initial state by constraining the volatile flux and volatile origins.

Relevance to exploration themes

1. SKG 1: A global exospheric monitoring network would show any volatile transport toward the poles and allow an estimate of how long the polar volatile deposits may have taken to form to assess how renewable they are.
2. SKG 2: A global exospheric monitoring network would provide key information about the lunar environment and how it changes over time.

Key measurements: Exospheric composition, dust, and plasma environment (including electrical properties).

Exploration scenario: Multiple landed missions across the lunar surface could deploy nodes of a monitoring network. Each node must be long lived so the global network can be built up over a number of years.

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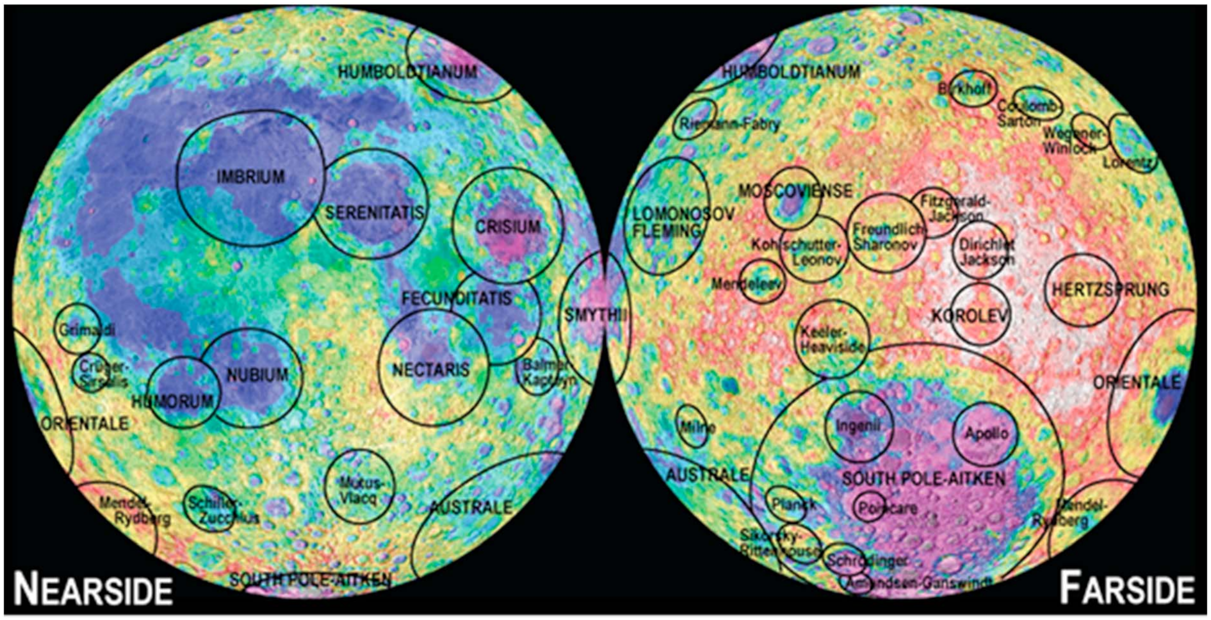

Figure 17. Distribution of lunar impact basins. Figure is from the Lunar and Planetary Institute, https://www.lpi.usra.edu/exploration/training/illustrations/bombardment/.

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	SKG 1, 2	No	In situ

2.17. Dating Large Impact Basins to Anchor Lunar Impact Chronology

Radiometric and exposure ages from samples returned from the Apollo and Luna missions have been correlated with CSFDs to anchor the lunar impact cratering chronology (e.g., Basaltic Volcanism Study Project, 1981; Le Feuvre & Wieczorek, 2008; Neukum, 1983; Neukum & Ivanov, 1994; Stöffler & Ryder, 2001), but many uncertainties still exist for the pre-Nectarian period (>4 Ga) and the Eratosthenian and Copernican periods (<3 Ga). There is still considerable debate about the ages of individual basins on the Moon (Figure 17), which serve as benchmarks that allow the global determination of the relative age of lunar surfaces (e.g., Fassett & Minton, 2013; Orgel et al., 2018). Therefore, dating large impact basins (e.g., Nectaris and Crisium) 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., Hartmann & Neukum, 2001; Ivanov, 2001; Strom & Neukum, 1988); thus, it is critical to determine the lunar impact rate as accurately as possible. Note that SPA, Schrödinger, and Moscoviense all fit in this broad category but are also treated as separate candidate landing sites in this report.

Relevance to science themes:

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

Relevance to decadal survey
Decadal objective 1:

1. Constrain the bulk composition of terrestrial planets by analyzing the diversity of rock units present in each basin, especially in ring materials.

2. Characterize planetary surfaces to understand how they are modified by geologic processes (i.e., impacts).

Decadal objective 2:

1. Understand the effects of impact processes on life and habitability.

Relevance to exploration themes

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

Key measurements: Ages of basin impact melts; bulk chemistry and mineralogy of surface units; and quantified regolith geomechanical properties.

Exploration scenario: A rover or static lander could return samples of basin impact melt for age dating and compositional analyses on Earth.

Science themes	Exploration themes	Mobility required?	In situ or sample return
S.1, 6	SKG 1 and 3	No	Sample return

2.18. Interdisciplinary Science

2.18.1. Astrophysics

The lunar farside 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 farside are free of Earth-based 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, 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 farside at locations that reduce RFI from Earth by factors of ~80 dB. Calculations indicate that impact 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 (Burns, 2018). However, certain locations such as midlatitude regions on the farside (e.g., Tsiolkovsky crater) or portions of Schrödinger basin could provide the necessary RFI attenuation for low radio frequency arrays.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 post-Newtonian *ß*, and variability in the gravitational constant (e.g., Williams et al., 2006). The current network includes retroreflectors 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 $\Delta_{\text{acceleration}}$ 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 an 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).

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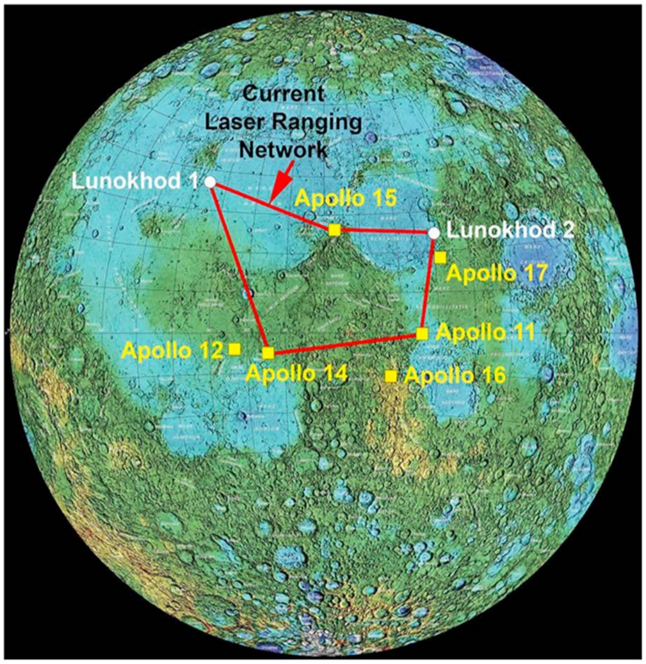

Figure 18. The locations of the retroreflectors that comprise the current LLR network.

2.18.2. Heliophysics

The lunar regolith contains materials that are both lunar and extralunar in origin, including samples that have interacted with 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 the variation over longer timescales remains unconstrained. The Moon potentially records snapshots of solar wind over geologic time through preservation of paleoregoliths between lava flows that could contain implanted solar wind species that can be compared with the present-day activity of the Sun (e.g., Crawford et al., 2010; Fagents et al., 2010). By sampling lava flows above and below the paleoregolith horizon, the age of the regolith is obtained, as is a measure of the Sun's activity at that time. 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 is currently observed are common but occur once per ~500–1,000 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.

2.18.3. 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, 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 Traverse Gravimeter Experiment 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 impact 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 geological layers near those stations, which may help with the processing and interpretation of local and global seismological signals collected by those stations, which are sensitive to density variations.

3. Enhancing Technologies

A series of technology priorities have been identified that would enhance operations at all places on the lunar surface. They are outlined below in no order of importance.

3.1. Communications Relay

Currently, there is no infrastructure in place to communicate with assets on the lunar farside, 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 farside would be open to exploration. The technology needed for these relay assets exists currently, 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 farside.

3.2. Surviving the Lunar Night and 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. Likewise, low temperatures in PSRs inhibit certain exploration architectures at the poles. Developing systems that can survive these low temperatures and large temperature fluctuations would greatly expand the portfolio of mission concepts possible on the lunar surface. Systems that could hibernate during lunar night and reactivate at local sunrise would be an improvement. Additionally, systems that could operate during the lunar night would enhance operations on the lunar surface and facilitate the exploration of PSRs at the lunar poles.

3.3. Cryogenic Sampling, Transportation, Storage, and Analysis

When analyzing samples, maintaining sample integrity of the original state from collection through transportation and storage to analysis is critical. Without this protection, sample properties and compositions can 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 to Mars, comets, and potentially the ocean world satellites of the outer planets.

3.4. Automated Hazard Avoidance

Since many hazards are smaller than the highest resolution imagery available, developing and integrating automated hazard avoidance software as part of a spacecraft's 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., H. H. Zhang, et al., 2014; F. 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 impact 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 6 m in the north-south direction and 6 m in the east-west direction, to avoid obstacles (Liu et al., 2014).

3.5. Mobility

There are many examples of the benefits of mobile assets on a planetary surface. The successful track record of NASA rovers on Mars, for example, has provided the scientific community with unprecedented data and unparalleled insight into the geologic history of Mars, particularly within the local exploration zones. On the Moon, the operations of Apollo 15–17 were greatly enhanced by the Lunar Roving Vehicle. The Lunar Roving Vehicle allowed the crews to travel farther distances, collect a more diverse sample suite, and gain a better understanding of the local geology than was possible in the preceding missions. While not all mission concepts require mobility, the option of mobility would be an enhancing technology in future mission planning. Mobility could also allow for a larger diversity of scientific objectives to be addressed within a single mission that otherwise may not have been available due to lack of access, particularly if other enhancing technologies were also viable, such as the ability to operate for multiple lunar days.

3.6. 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 regolith interactions with humans and equipment are of great interest to the lunar community, as is creating a reliable system for removing regolith from suits and lunar habitats. Developing these capabilities would both increase longevity of systems and enhance safety for human crews to the Moon and other planetary bodies.

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*, 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 (Clegg et al., 2014; Clegg-Watkins et al., 2016). These blast zones have higher reflectance compared to the surroundings and extend tens to hundreds of meters away from the landers (Clegg et al., 2014).

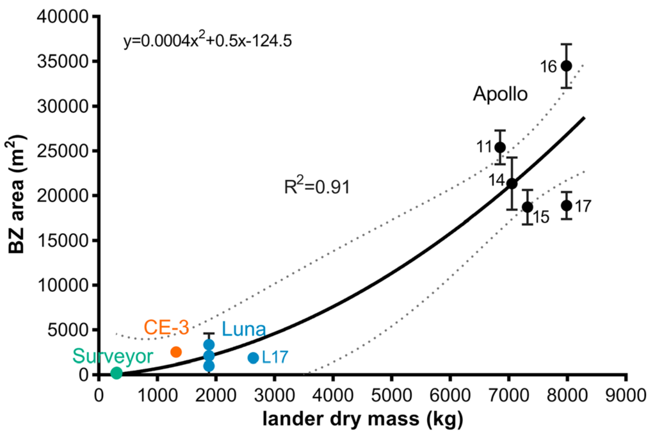

Figure 19. Lander dry mass versus blast zone area. Dotted lines are 95% confidence envelope based on Apollo, Luna, and Surveyor correlation (solid line; quadratic fit). Variations in BZ area at constant lander dry mass are largely a function of descent parameters and spacecraft specifications. Figure is modified from Clegg-Watkins et al. (2016).

For more on the detailed physics and effects of plume effects during descent, we refer the reader to Lane et al. (2008), Metzger et al. (2010, 2011), Immer et al. (2011), Immer et al. (2011), Lane and Metzger (2012), Kaydash et al. (2011), Clegg et al. (2014), and Clegg-Watkins et al. (2016).

Using Lunar Reconnaissance Orbiter Camera narrow angle camera (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 19), 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.

Although exhaust plumes only excavate a few centimeters of regolith beneath each lander (Clegg et al., 2014; Shkuratov et al., 2013), 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.

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 engine or other system failure during landing. The exclusion zone is a 2-km radius centered on the site of interest; landing vehicles must approach this zone tangentially and may not fly directly toward it for the purpose of landing on its perimeter. Figure 20 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 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 spacecraft.

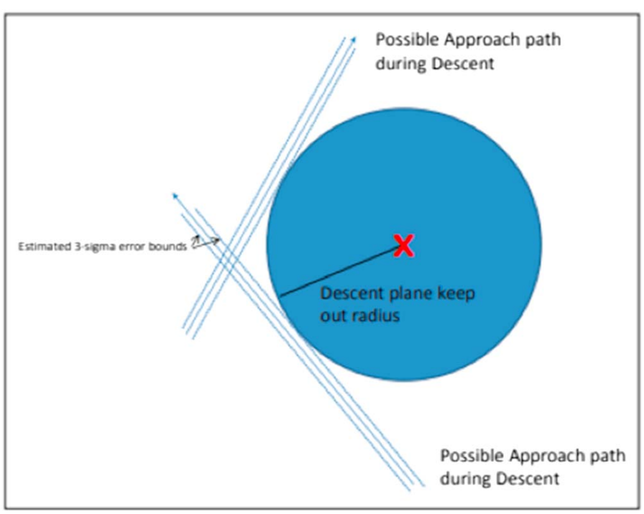

Figure 20. Schematic showing the exclusion zone (blue circle) centered on a site of interest (e.g., historic U.S. spacecraft). Future landed missions should approach this exclusion zone tangentially, as indicated by possible approach paths (blue lines).

4. Conclusions

As Earth's nearest neighbor, the Moon is the most readily accessible object in our Solar System. The lunar surface provides a convenient laboratory where human and robotic missions can advance our scientific knowledge of the Solar System as well as learn how to overcome the challenges of working and living in off-Earth environments. Recent advances in lunar science have developed new questions about geological processes such as volcanism, impact crater and basin formation, and the lunar water cycle (among many others), and continued exploration of the Moon will allow us to address fundamental questions about the Earth-Moon system as well as the formation and evolution of the Solar System as a whole. A robust, *sustainable* program of continuous surface exploration missions is required to fully outline goals described in the SCEM report, the

Planetary Decadal Survey, and the LEAG ASM-SAT. The Moon has enormous potential for the development of a vibrant commercial sector and for enabling human exploration in the near future. This report aims to provide guidance to commercial entities and government agencies as they select landing sites and plan both near- and far-term missions to the surface of the Moon.

Appendix A: Three-Phase Lunar Exploration Framework

A1. Introduction

Current engineering and technological capabilities allow access to a wide range of locations on the Moon, enabling access to a diversity of exploration zones and scientific analyses described in this report. However, certain locations are difficult to access given current engineering constraints due to steep slopes, blocky surfaces, insufficient sunlight (leading to extremely cold conditions), and/or lack of a direct communication pathway with Earth, as discussed in section 3. Due to these engineering constraints, missions launched with the currently available technology are limited to landing sites located on the central nearside at low latitudes that contain low slopes (~10°) and few surface hazards such as boulders or impact craters. These missions will have to be short lived (≤1 lunar day) until robust instrumentation can be developed that will enable surface exploration during the harsh conditions of the lunar night. Such technology was utilized for the Lunokhod missions by the Soviet space program in the 1970s, which depended on a nuclear energy source to power the Lunokhod rovers.

Despite the engineering constraints described above, there are numerous opportunities to perform cutting-edge science on a wide diversity of lunar targets based on the findings outlined in this report. This section describes a potential framework for a lunar exploration program by outlining a sequence of increasingly complex missions to a variety of landing sites on the Moon. Missions vary in location (nearside/farside/polar regions), duration (<1 lunar day/multiple lunar days), and mission type (static lander/rover/sample return). This lunar exploration program framework is outlined in three phases.

1. Phase 1—missions that could be launched with current engineering constraints. These missions are limited to static landers on the lunar nearside at low latitudes (nonpolar regions) that last <1 lunar day.
2. Phase 2—missions that incorporate mobility (i.e., rovers). Access to a wider diversity of locations including the polar regions and the lunar farside may also become available with the introduction of technologies enabling lunar farside communications, functionality in extreme thermal conditions, and sample return.
3. Phase 3—missions that could include longer duration (>1 lunar day) missions and sample return capabilities.

The landing sites and mission architectures outlined in this report are sorted into this exploration framework and presented below. It is important to note that this exploration framework is only an example to illustrate the potential of an extended lunar exploration program—the development of new and more efficient technologies may enable missions designated to later phases to be completed earlier.

Phase 1

Missions in the first phase of this recommended lunar exploration architecture would utilize currently available technological capabilities. Broad-scale landing site requirements for missions in Phase 1 include locations with (1) direct line-of-sight communications with Earth (i.e., on the nearside at nonpolar latitudes), (2) full solar illumination; (3) low slopes (<10°), and (4) low density of surface hazards (boulders, impact craters, etc.)

Mission architecture capabilities for Phase 1 include static landers that could operate for <1 lunar day, although longer-term instruments, such as geophysical packages or retroreflectors, could also be deployed.

Significant enhancing technology that could be incorporated into Phase 1 missions include (1) *autonomous hazard avoidance,* which would broaden the landing zone capabilities to include regions that contain a higher number of surface hazards; (2) *dust mitigation*, which would protect equipment and preserve fine-scale surface geologic features; and *mobility*, which would significantly enhance the variety of scientific analyses capable of being made at any given landing site

Note that these technologies are not required for Phase 1 missions but would significantly enhance the mission architecture and scientific data return.

Example Landing Sites for Phase 1 Missions (Static landers) are the following: (1) Aristarchus plateau, (2) Gruithuisen domes, (3) IMPs (e.g., Ina), (4) magnetic anomalies/swirls; (5) Orientale (nearside), and (6) Rima Bode.

Phase 2

Missions in the second phase of this recommended lunar exploration program would have the same capabilities of Phase 1 missions, specifically static landers, and several (formerly enhancing) technological capabilities are now available: (1) automated landing site hazard avoidance, (2) dust mitigation upon landing, and (3) mobility via roving.

The availability of these technologies allows access to locations with higher latitudes, steeper slopes, higher concentration of surface hazards, temporary shadow, and periods of no line-of-sight communication with Earth. In addition, if a temporary communications relay becomes available, locations on the lunar farside would also become accessible.

Significant enhancing technology that could be incorporated into Phase 2 missions include (1) a dedicated, long-lived communications satellite to facilitate persistent farside access, (2) technologies that ensure the ability to survive the lunar night, which would significantly enhance the quantity and variety of data gathered by static landers and rovers, and (3) sample return capabilities.

Examples of Phase 2 Missions are the following: (1) Aristarchus plateau rover, (2) Compton Belkovich lander/rover, (3) Gruithuisen domes rover, (4) IMP (Ina) lander/rover, (5) magnetic anomalies rover, (6) Marius Hills rover, (7) Moscoviense lander/rover, (8) Orientale lander/rover, (9) P60 basalt lander/rover, (10) pit crater rover, (11) Rima Bode lander/rover, (12) Schrödinger lander/rover, and (13) SPA lander/rover.

Phase 3

Phase 3 missions include all the technological capabilities and landing site access of Phases 1 and 2, with the additional capabilities of longer duration missions and sample return. These additional capabilities enable access to all locations on the lunar surface for multiple lunar days and allow for either static landers or rovers, and the option of sample return from the lunar nearside, farside, or polar regions. Additionally, Phase 3 could include a series of missions that repeatedly land at the same location and that build upon each subsequent mission. For example, a lander could be sent to do in situ science, then a rover to explore nearby areas, and then a mission to return samples from a region that has been identified as having high scientific value from the previous two missions.

A significant enabling technology for Phase 3 missions would be cryogenic sampling, storage, and return, which is particularly necessary for sample return from high-latitude or polar regions, or locations that may be enriched in volatiles such as pyroclastic deposits.

In addition, Phases 2 and 3 mission capabilities may be greatly enhanced by the presence of the Lunar Orbital Platform-Gateway. The gateway could potentially facilitate robotic missions on the lunar surface by acting as a communications relay and receiving samples returning from the farside of the Moon.

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