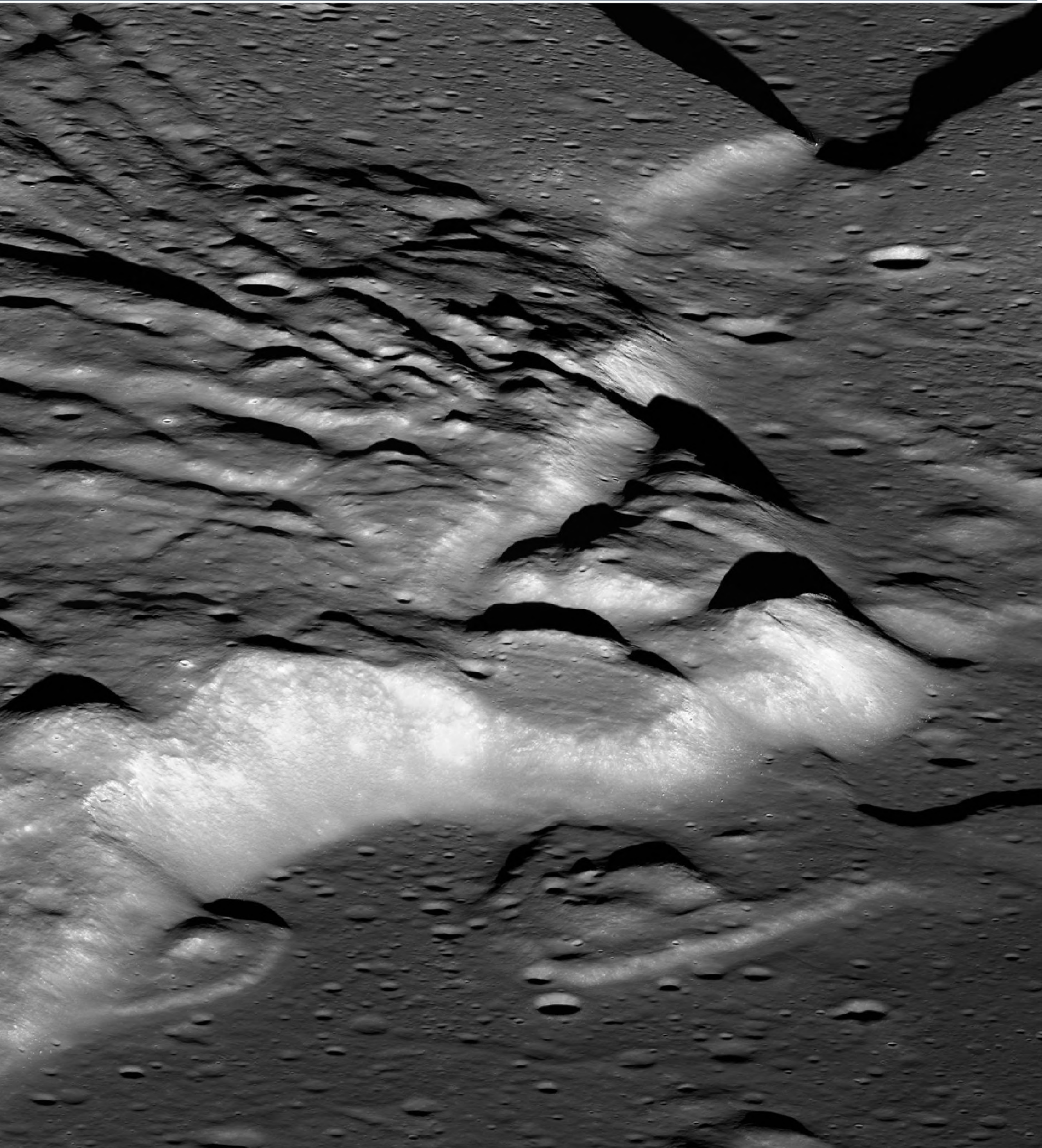
ADVANCING SCIENCE OF THE MOON

REPORT OF THE LEAG SPECIFIC ACTION TEAM



ON THE FRONT COVER: Orientale spectacular! The Moon is a stunning world, with stupendous vistas that no human being has seen with their own eyes. This is the interior of Orientale basin, the youngest basin on the Moon and a place where human beings will surely explore. NAC images M1124173129L & R, image centered at 24.23°S, 264.30°E, scene width is approximately 16 km and the cliff at center is 1.7 km high [NASA/Goddard Space Flight Center/Arizona State University]

Interim Report of the Advancing Science of the Moon Specific Action Team, Released February 2018.

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LEAG extends its appreciation to the staff of the Lunar and Planetary Institute for facilitating and hosting the in-person meeting for this Specific Action Team.

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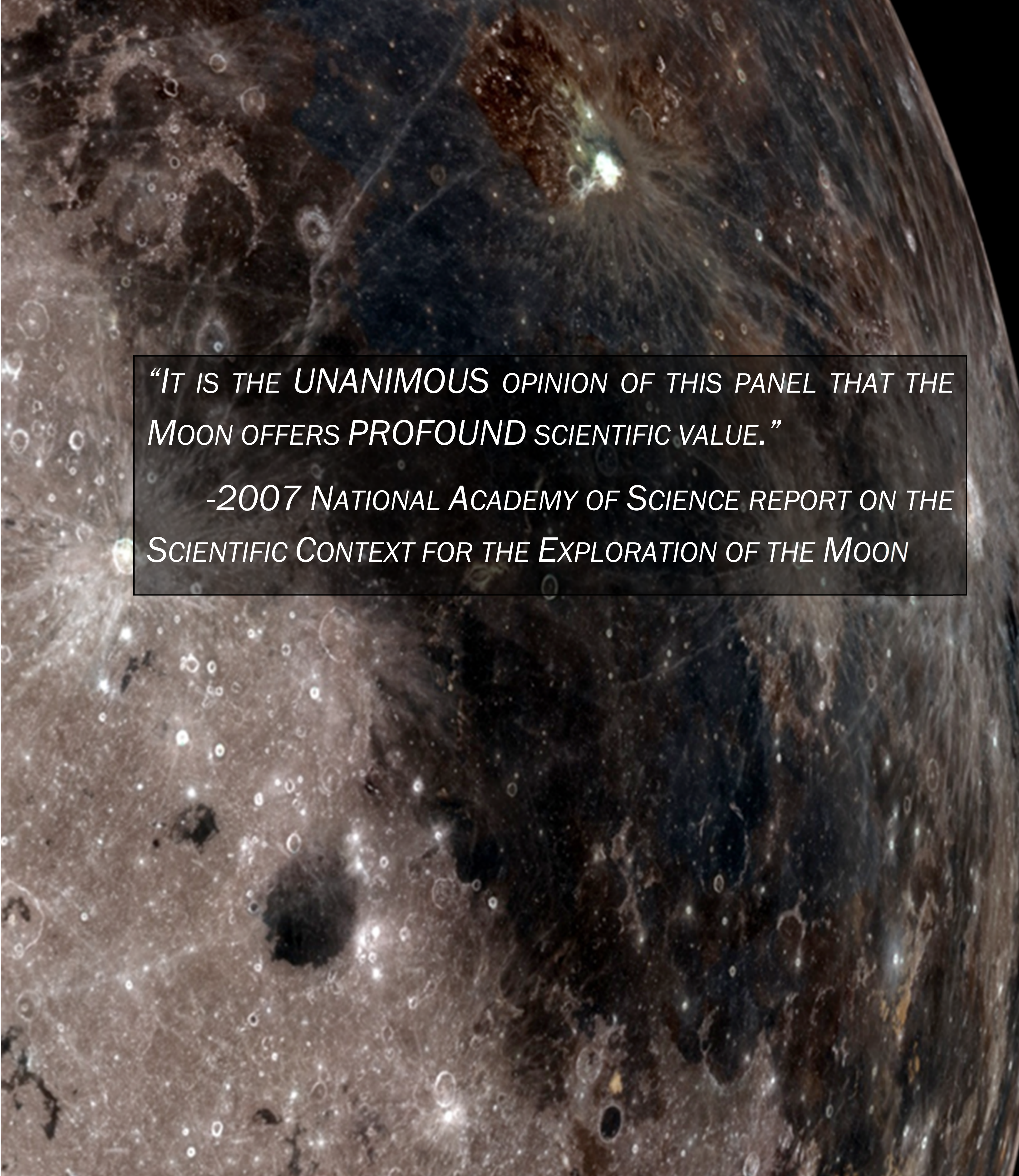


> "It is the UNANIMOUS opinion of this panel that the Moon offers PROFOUND scientific value."
>
> -2007 National Academy of Science report on the Scientific Context for the Exploration of the Moon

Lunar Reconnaissance Orbiter Camera Wide Angle Camera false color mosaic of the Moon demonstrating the compositional diversity of the Moon, overlain on the lunar GLD100 global topography dataset. The regional pyroclastic deposit of the Aristarchus Plateau, one of the Moon's largest and most accessible resource deposits, is visible near the top of this image [NASA/GSFC/Arizona State University].

PREFACE

The announcement of the Vision for Space Exploration (VSE) in 2004 ultimately resulted in a renaissance in lunar science. The VSE was a cohesive, step-by-step plan for the United States to use the resources found on the Moon to establish the capability for human voyages beyond low-Earth orbit. Establishing an outpost on the surface of the Moon by 2020, as originally envisioned, would have decisively provided the workforce, experience base, and technologies needed to enable the United States to move out into the Solar System in a sustainable fashion.

In the context of the VSE, in 2006 NASA Headquarters commissioned the National Research Council to undertake a study of the Scientific Context for the Exploration of the Moon in order to help guide the inclusion of scientific objectives in the lunar exploration program. The NRC report was delivered to NASA in 2007, and remains the definitive articulation of the scientific priorities and goals of lunar exploration.

It is unfortunate that the logical and expansive program of exploration envisioned in 2004 ultimately did not come to pass; the benefits of doing so would have been enormous. Nevertheless, an international flotilla of lunar missions reached the Moon between 2006 and the present and made profound new scientific discoveries about the Moon.

TAKEN COLLECTIVELY, THE NEW RESULTS ARISING FROM THESE MISSIONS HAVE REVOLUTIONIZED OUR UNDERSTANDING OF THE MOON AND REINFORCED THE MOON'S PRIMACY AS THE CORNERSTONE OF PLANETARY SCIENCE

These new advances arising from recent lunar mission results produced dramatic questions about lunar volcanism, volatiles, impact processes, lunar tectonics, and the lunar environment, and the discoveries have just begun. The lunar science and exploration communities continue active research and analysis of data from these missions. One mission, the NASA Lunar Reconnaissance Orbiter, remains functional in lunar orbit as of this writing in 2018, continuing to provide phenomenal new science and profound insights into the Solar System. In addition to new scientific advances, these new mission results also indicate that the resource potential of the Moon is vast, inarguably making a strong presence on the lunar surface a critical enabling asset for any goal the United States sets for human spaceflight, now and in the future.

In light of the stunning advances in lunar science over the past decade, it became evident that a community assessment of the progress made towards achieving the goals and objectives enumerated in the 2007 NRC report – written before any of these missions had been launched - should be carried out.

The Advancing Science of the Moon Specific Action Team (ASM-SAT) was formulated by LEAG specifically to encompass a diverse range of expertise amongst the science community to ensure a truly representative evaluation of progress made towards achieving the goals of the 2007 NRC Report. ASM-SAT met in person on August 6-7 at the Lunar and Planetary Institute in Houston, Texas, and the outcomes of its deliberations are summarized in this report.

A COHESIVE FRAMEWORK FOR PROFOUND DISCOVERY

In addition to ASM-SAT, LEAG also engaged in five other complementary activities in 2017 designed to synthesize the viewpoints of the large, diverse lunar exploration community. These activities included:

- The second Volatiles Special Action Team (VSAT2) at the request of NASA on behalf of the International Space Exploration Coordination Group (ISECG), intended to help facilitate coordination between lunar polar missions being undertaken by NASA and its international partners;
- The Next Steps on the Moon Special Action Team (NEXT-SAT), which developed concepts for future lunar exploration missions informed by the deliberations of ASM-SAT;
- The Lunar Science for Landed Missions workshop, sponsored by the Solar System Exploration Research Virtual Institute (SSERVI) and LEAG, prioritized destinations and solicited community input on the valuable high-priority science missions that could be carried out on the lunar surface.
- The "Back to the Moon" community grass-roots initiative, designed to identify potential commercial on-ramps for lunar exploration, viable architectures for reaching the surface with humans in the next 4-8 years, and a prioritized set of recommendations and goals for an expansive and credible program of lunar

exploration, culminating in a meeting in Columbia, Maryland, in October 2017 with a conference report summarizing the outcomes.

Taken collectively, these five activities have developed a cohesive framework for re-engaging in lunar exploration – making profound scientific discoveries, advancing American interests, and ensuring economic growth - available to both policymakers and the scientific community for implementation. Reports from these activities can be found on the LEAG web site – www.lpi.usra.edu/leag.

TOWARDS NEW FRONTIERS

The overarching sentiment of the lunar exploration community arising from ASM-SAT and all of the other LEAG activities of 2017 can be summarized simply: The Moon is a stunning world of wonder and opportunity that is only a few days away. With its tremendous bounty of accessible resources, stunningly beautiful vistas, and incredibly compelling scientific questions, the Moon continues to beckon us towards the next horizon as the stepping-stone to the rest of our Solar System.

EXECUTIVE SUMMARY

Overview

- The Moon is a resource-rich, readily accessible target for future United States human and robotic missions which will enable fundamental scientific advances impacting our understanding of the entire Solar System.
- Numerous lunar missions from the United States and other countries (Chang'e-1/2/3, Kaguya, Chandrayaan-1, LRO, LADEE, GRAIL) have been flown since the publication of the 2007 NRC Report on the Scientific Context for the Exploration of the Moon, vividly demonstrating the international interest in lunar exploration. Each of these missions has produced significant advances in lunar science, uncovered new science questions, defined locations for future exploration, and collected sufficient data to enable safe landings across the lunar surface.
- A robust program of ongoing surface exploration missions with robots and humans is required to fully address the goals outlined in the 2007 NRC Report, and follow-up on new mission discoveries, with in-situ investigations and/or sample return.

Background

In 2006, in the context of the expansive integrated program of lunar exploration envisioned under the Vision for Space Exploration, NASA HQ commissioned the National Research Council to produce the Scientific Context for the Exploration of the Moon report (NRC, 2007) which remains the definitive benchmark defining the scientific goals and investigation priorities for lunar exploration. These priorities were grouped into eight concepts, each with associated science goals:

Concept 1: The bombardment history of the inner Solar System is uniquely revealed on the Moon.

Concept 2: The structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated planetary body.

Concept 3: Key planetary processes are manifested in the diversity of lunar crustal rocks.

Concept 4: The lunar poles are special environments that may bear witness to the volatile flux over the latter part of Solar System history.

Concept 5: Lunar volcanism provides a window into the thermal and compositional evolution of the Moon.

Concept 6: The Moon is an accessible laboratory for studying the impact process on planetary scales.

Concept 7: The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies.

Concept 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.

Since the 2007 NRC report was published, numerous missions from the United States and other countries reached the Moon and made new discoveries. In fact, one of these missions, the Lunar Reconnaissance Orbiter, remains operational in lunar orbit, continuing to produce new science results. Therefore, an assessment of progress towards meeting the goals set forth in the 2007 NRC report was clearly needed. The Planetary Science Division, Science Mission Directorate, NASA Headquarters, requested that the Lunar Exploration Analysis Group assemble the Advancing Science of the Moon Specific Action Team (ASM-SAT) to assess the progress that had been made towards achieving the goals set forth in the 2007 NRC report by recent missions, reexamination of older lunar datasets, advances in modeling and studies of lunar meteorites and Apollo samples. ASM-SAT met in person at the Lunar and Planetary Institute,7-8 August 2017. For each of the Concepts and associated Goals from the 2007 report, ASM-SAT assessed progress and identified new concepts whose importance was not known when the 2007 report was formulated. The ASM-SAT did not attempt to reassess the prioritization set forth in the 2007 NRC report.

ASM-SAT Outcomes

Progress towards meeting goals from the 2007 NRC Report

While progress has been made in addressing many of the main concepts in the 2007 NRC Scientific Context for the Exploration of the Moon (SCEM) report, none of the goals outlined can be considered to be "complete". For example, while the LADEE mission and a variety of other instruments and missions have provided a new understanding of the lunar atmosphere and dust environment (Concept 8), the poleward migration of volatiles of the PSRs and the lofting of dust to <5 km heights have not been addressed. These new data allow us to constrain the questions and the parameters of future investigations. This situation is repeated throughout each of the other concepts, and the science goals associated with each concept remain relevant today. The recommendations for implementation given in the 2007 NRC report, with minor updates, provide guidance on how to achieve the progress that is still needed.

Concept 1: The bombardment history of the inner Solar System is uniquely revealed on the Moon. Achieving the science goals of this concept related to the bombardment history requires a combination of modeling of the composition of basin impact melt, petrology and geochemistry of samples to tie them to specific basins, and detailed geochronology of multiple samples, ideally with multiple geochronologic systems. Such studies could be accomplished by landing and in situ dating and/or sample return to Earth.

Concept 2: The structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated planetary body. Meaningful progress in expanding our knowledge of planetary differentiation can be made by the emplacement of equipment such as a simultaneous, globally distributed seismic and heat flow network and/or an expanded retroreflector network, and strategic collection of samples from terrains of different ages that can provide constraints on lunar geochemistry and new information on the history of the lunar dynamo.

Concept 3: Key planetary processes are manifested in the diversity of lunar crustal rocks. Recommendations for advancing our understanding of differentiation processes and the Moon's complex crust include obtaining compositional information at higher spatial resolutions, the return of samples from high-priority targets, in situ elemental and mineralogical analyses as well as regional seismic networks to determine vertical structure, and geologic fieldwork by astronauts. Data returned from recent orbital missions have allowed for the identification of many high-priority target sites for further exploration that would further our understanding of the lunar crust.

Concept 4: The lunar poles are special environments that may bear witness to the volatile flux over the latter part of Solar System history. . The last decade has provided substantial new information about the lunar poles, though achieving the goals related to this concept, such as understanding volatile source(s), detailed compositions, and the ancient solar environment, will require in the implementation of recommendations from the SCEM report, such as in situ analyses and the return of cryogenically preserved samples.

Concept 5: Lunar volcanism provides a window into the thermal and compositional evolution of the Moon. Critical advances in understanding planetary volcanism would come from subsurface sounding, sample return (for the youngest and oldest basalts, benchmark basalts, and pyroclastic deposits), in situ elemental and mineralogical analyses with investigation of geologic context, and astronaut field work that could include core drilling, active subsurface sounding, and sampling of a complete sequence of basalt flows. The implementation of these recommendations is now more feasible than ever, given new remote sensing data that has shown locations and accessibility of high priority sample sites.

Concept 6: The Moon is an accessible laboratory for studying the impact process on planetary scales. Fundamental questions remain in our goal to understand this fundamental planetary process. These could be addressed by: detailed studies to identify large-scale melt deposits at older basins, the establishment of regional seismic networks at multi-ringed basins to provide insight into basin structure, field studies and sample return of melt sheets and peak rings to shed light on their mode of formation and depth of origin, and long-duration orbital observations to detect newly formed impact craters larger than those seen to date.

Concept 7: The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies. The recommendations in the SCEM report for understanding the development and evolution of the surfaces of planetary bodies are still valid today, and include sounding to reveal the upper stratigraphy of the regolith, and regolith sample return from regions of diverse composition and age, of old regolith where it is stratigraphically preserved, and from paleoregoliths. The apparent conflict between remote sensing and sample studies as to the dominant space weathering agent could be resolved by in situ analyses and targeted sample return from areas such as lunar swirls.

Concept 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. The substantial progress made on Concept 8 has clarified areas where the most progress is still needed. These include: identify the sources of the mid-latitude surface hydroxyl and water; determine whether hydrogen products migrate poleward to the cold trap reservoirs; explore the near-surface electrostatic lofting of dust associated with plasma anomalies/voids in locations like polar craters, magnetic anomalies, and the night-side terminator; systematically detect trace volatile species (e.g., water, OH, hydrocarbon) in the exosphere; and search for evidence of prompt release of ^{40}Ar and other internal species following seismic events.

New Concepts

ASM-SAT also highlighted three important new concepts that must be considered as we move into the next phase of lunar exploration. These are:

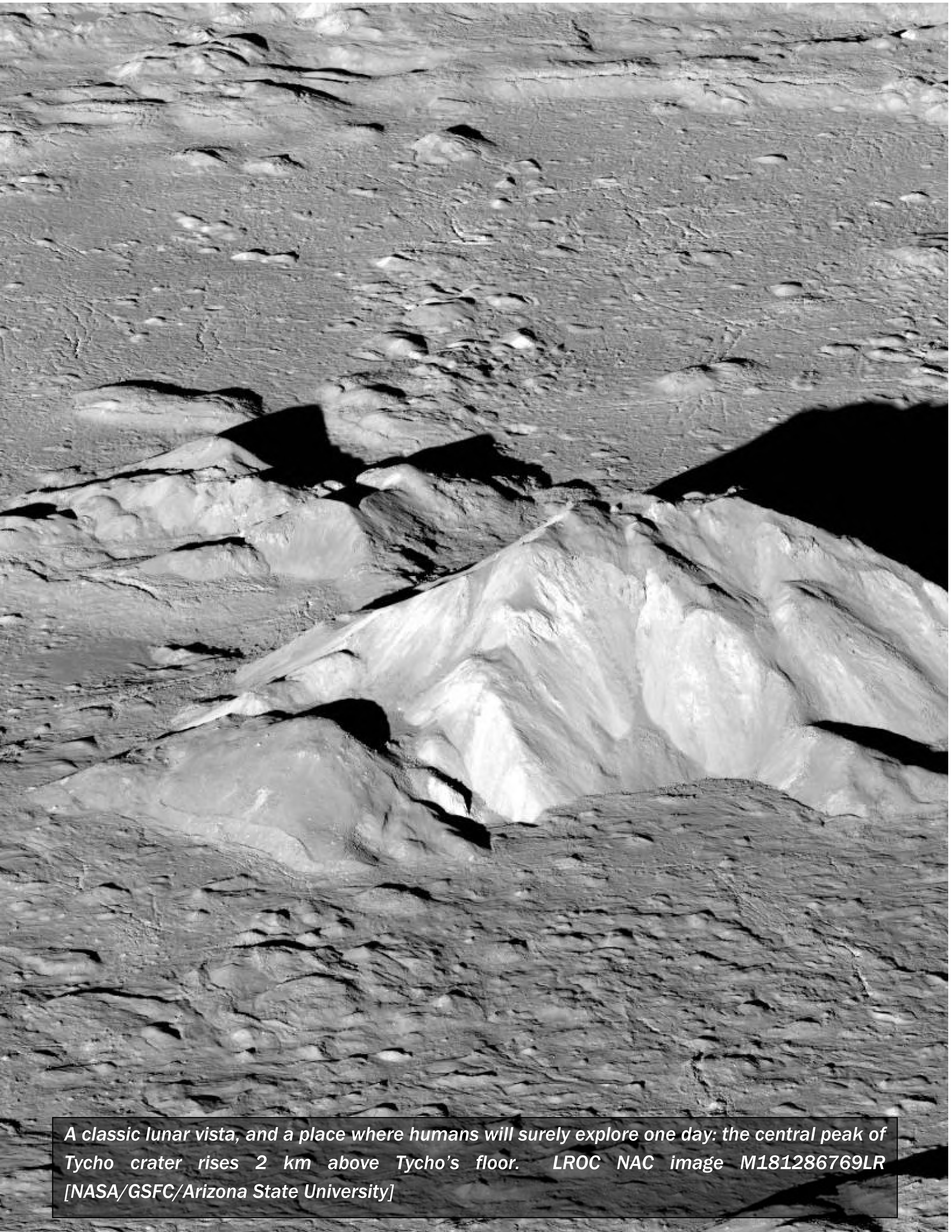
- The Lunar Volatile Cycle
- The Origin of the Moon
- Lunar Tectonism and Seismicity

Future Lunar Activities

The members of ASM-SAT unanimously agreed that exploring the Moon has enormous scientific value, and will provide incredible opportunities to make numerous fundamental advances in planetary science. ASM-SAT also noted that, as discussed in the LEAG Lunar Exploration Roadmap, the Moon could offer a valuable platform for other science investigations (such as farside radio astronomy) as a lunar exploration program is established.

The wealth of orbital data gathered since the 2007 NRC report allows important landing sites to be efficiently identified for in situ analysis and sample return robotic missions. Inclusion of humans to the lunar surface who could conduct detailed fieldwork would allow even more tremendous progress to be made in many of the concepts described above.

Making new advances in planetary science by addressing the vital questions highlighted and summarized in the ASM-SAT report requires a sustained, robust program of lunar exploration.



A classic lunar vista, and a place where humans will surely explore one day: the central peak of Tycho crater rises 2 km above Tycho's floor. LROC NAC image M181286769LR [NASA/GSFC/Arizona State University]

INTRODUCTION

In April 2017, the Planetary Science Division of the Science Mission Directorate, NASA HQ, requested that the Lunar Exploration Analysis Group (LEAG) form a Specific Action Team (SAT) to assess the advances made lunar science in the decade following the 2007 publication of the National Research Council Report on the Scientific Context for the Exploration of the Moon, also referred to as the SCEM report. Since the publication of the 2007 NRC report, numerous lunar missions have enabled many scientific discoveries that have furthered our knowledge of the Moon and how it can inform our understanding of Solar System history. Examining the larger implications of these new advances can now help to provide a basis for deciding about the next steps for lunar exploration.

To accomplish this task, LEAG and Headquarters worked together to develop a Charter (Appendix I) for the SAT. Following approval of the SAT Charter, the LEAG Chair and Vice-Chair assembled a distinguished panel of lunar exploration experts for ASM-SAT from around the United States. ASM-SAT membership (Appendix II) was specifically selected to encompass a diverse range of expertise and backgrounds from the science community in order to provide a comprehensive and balanced assessment. The ASM-SAT also included members of the original NRC study team in order to provide perspectives on the context for the decisions outlined in the 2007 report. The members of the SAT met in person on August 6 and 7, 2017, at the Lunar and Planetary Institute in Houston, TX.

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CONTENT AND STRUCTURE OF THE REPORT

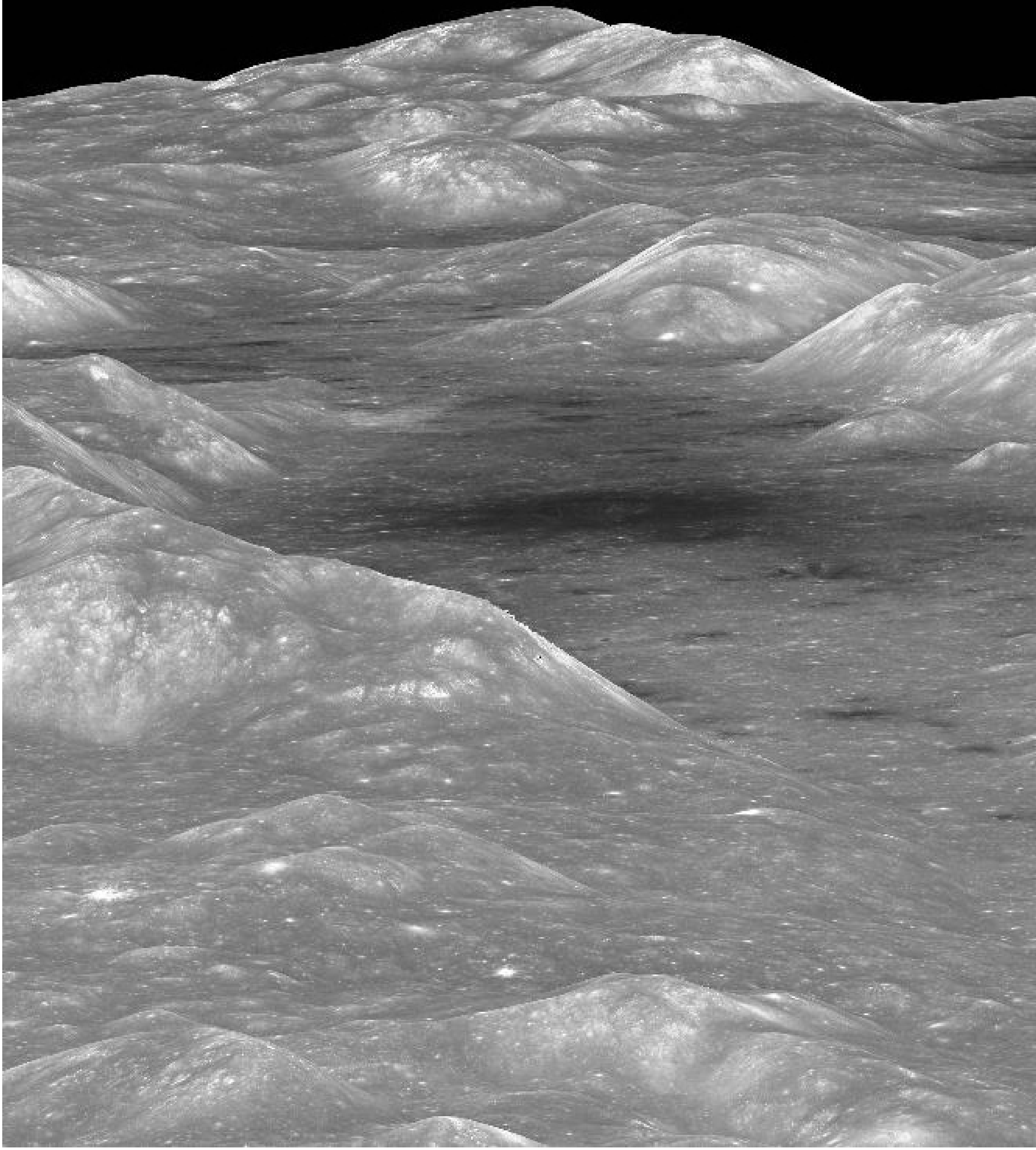
Per the SAT Charter, the ASM-SAT evaluated progress toward each of the original eight science concepts enumerated in the original 2007 NRC report, which were:

- *Concept 1:* *The bombardment history of the inner Solar System is uniquely revealed on the Moon.*
- *Concept 2:* *The structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated planetary body.*
- *Concept 3:* *Key planetary processes are manifested in the diversity of lunar crustal rocks.*

- *<u>Concept 4:</u> The lunar poles are special environments that may bear witness to the volatile flux over the latter part of Solar System history.*
- *<u>Concept 5:</u> Lunar volcanism provides a window into the thermal and compositional evolution of the Moon.*
- *<u>Concept 6:</u> The Moon is an accessible laboratory for studying the impact process on planetary scales.*
- *<u>Concept 7:</u> The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies.*
- *<u>Concept 8:</u> Processes involved with the atmosphere and dust environment of the Moon are accessible for scientific study while the environment remains in a pristine state.*

For each of these major science themes, the ASM-SAT systematically evaluated the progress made toward achieving the associated goals described in the SCEM report, and discussed progress still needed. These discussions are summarized in the following sections. No effort was made to reprioritize the science concepts and goals, though the ASM-SAT panel strongly agreed that they were all still important and relevant today. Following the content and structure of the original 2007 NRC report, the value of astronomical observations using the Moon as a platform was also discussed. Finally, during the course of discussions, new science concepts were identified that arise from results that had not been available when the NRC panel produced the report.

These mountains were formed in an instant by the impactor that created the Orientale basin. NAC image M1222023384LR.



CONCEPT 1: THE BOMBARDMENT HISTORY OF THE INNER SOLAR SYSTEM IS UNIQUELY REVEALED ON THE MOON

Establishing an absolute chronology has important ramifications for understanding the early structure of the solar system, to understand the evolution of both the of the dynamics and composition of the bodies. The concept of the Lunar Cataclysm, or broadened to the solar system as the Late Heavy Bombardment, would have affected whole Solar System. The dynamical models currently conceived to explain such a phenomenon encompass the gas-dust dynamics of forming disks and giant planet migration that now may be invoked to understand not only our Solar System, but systems of exoplanets around other stars. Such a phenomenon would also have affected the Earth at a point when other evidence shows that continents, oceans, and perhaps even life already existed. A high priority was placed on this topic in the SCEM report and both the 2003 and 2013 Planetary Science Decadal Surveys, where impact history is an important factor in the timing of delivery of volatile, organic, and siderophile elements, the possible role of impact stripping of atmospheres, and the geologic evolution of surfaces (National Research Council, 2003, 2011). In addition, The Astrophysical Context of Life emphasized bombardment history of the Earth-Moon system as a very high priority to astrobiology, finding that "the question whether the late heavy bombardment was an isolated episode or just a gradual, continuous decline in bolide impact frequency and intensity is unresolved, but the answer has important implications for both the timing of life's origin and for the types of organisms that might have existed at early times" (National Research Council, 2005)

Science Goal 1a. Test the cataclysm hypothesis by determining the spacing in time of the creation of lunar basins.

Until recently there has been a broad consensus among lunar geologists about the relationships of samples collected by the Apollo missions to the Imbrium (Apollo 14), Serenitatis (Apollo 17), and Nectaris (Apollo 16) basins (Stöffler et al., 2006). Today, most of these relationships have been questioned and are under active debate. The best available age for Imbrium appears to be 3.92 ± 0.01 Ga from KREEP-rich breccias and melt rocks collected at the Apollo 12 and 14 sites (Liu et al., 2012; Merle et al., 2017;

Nemchin et al., 2009; Snape et al., 2016). Analysis of LRO images of boulder tracks verified that the boulders that were samples at Apollo 17 originated in outcrops within the North Massif walls, which had been interpreted as Serenitatis ejecta (Hurwitz and Kring, 2016; Schmitt et al., 2017). However, the overlying Sculptured Hills deposits may be more closely related to Imbrium rather than Serenitatis (Fassett et al., 2012; Spudis et al., 2011), and U-Pb dating of Ca-phosphates in Apollo 17 melt breccias appears to support an Imbrium origin for these rocks, while the Ar distribution is less straightforward (Mercer et al., 2015; Thiessen et al., 2017). The aluminous Descartes breccias, which have been interpreted as either Imbrium or Nectaris ejecta, range in age from 3.9 to 4.1 Ga, leading to a proposed old age for Nectaris (Fernandes et al., 2013; James, 1981). However, subsequent studies showed that the youngest population of clasts in the Descartes breccias is coeval with the KREEP-rich, crystalline melt rocks that are the best candidates for Imbrium ejecta, supporting geological observations that favor emplacement of the Descartes breccias as Imbrium ejecta (Norman et al., 2010). Interpreting the Sculptured Hills and Descartes formation as Imbrium ejecta removes age constraints on basins older than Imbrium and reopens the pre-Imbrian impact history to debate.

The GRAIL gravity data have provided substantial new clarity about what basins exist and the size of individual basins. (Neumann et al., 2015) cataloged 43 basins with diameters greater than 300 km, more than conservative estimates from LOLA data but fewer than some other pre-GRAIL estimates suggested (Fassett et al., 2012; Frey, 2011). The population of basins with diameters less than 200 km is fitted well with the existing cumulative Hartmann-Neukum production function but this function underestimates the basin population with diameters between 300 and 1000 km. Efforts to resolve impacts that have either fully relaxed, have unusual gravity signatures, or been buried under mare deposits, have not significantly changed this distribution (Ishihara et al., 2011; Schultz and Crawford, 2016; Sood et al., 2017). A notable exception is Serenitatis, which has relatively few buried craters (Evans et al., 2016), supporting a young age for Serenitatis, contrary to the recent arguments of (Fassett et al., 2012; Spudis et al., 2011).

Models developed in the last decade explore both changing impactor populations and rearrangement driven by gravitational instability in the outer Solar System to aid in understanding lunar basin history (Bottke et al., 2012; Gomes et al., 2005; Morbidelli et al., 2010; Morbidelli et al., 2005; Morbidelli et al., 2012; Toliou et al., 2016; Tsiganis et al., 2005). In a recent review of the bombardment record of the terrestrial planets and asteroid belt, (Bottke and Norman, 2017) argued that a hybrid model, where there are both early and late components of bombardment, was best at matching constraints from the Moon and other bodies.

Science Goal 1b. Anchor the early Earth-Moon impact flux curve by determining the age of the oldest lunar basin (South Pole-Aitken Basin)

Although some ages of lunar basins may be known from radiometric age dating of lunar samples, we still do not know the age of the oldest basin on the Moon, the South Pole-Aitken (SPA) Basin. As the oldest stratigraphically recognizable basin on the Moon, SPA is a critical calibration point for relative age dating of the Moon and other planets, and an absolute age would anchor the flux curve very early in planetary history. New crater-counting results have attempted to constrain the age of SPA. Marchi et al. (2012) measured crater densities on SPA terrains, finding they are only a factor of 2 higher than Nectaris, implying that the SPA basin did not form during the period of the Lunar Cataclysm, but instead formed during an earlier phase of lunar history. Sample return of impact melt from the South Pole-Aitken Basin has been a recommended New Frontiers mission in both Planetary Science Decadal Surveys (National Research Council, 2003, 2011). Such a mission would establish the impact history of the SPA basin, including SPA itself and a suite of younger basins, distant from the Imbrium basin and its ejecta that bias our Apollo and Luna samples. Multiple proposals have been submitted and several have been downselected for further study (e.g., Jolliff et al., 2016; Jolliff et al., 2017), but none yet selected for implementation.

Science Goal 1c. Establish a precise absolute chronology.

Despite the lack of progress in establishing absolute ages for SPA and near side basins, lunar chronology is also constrained by mare basalt flows and younger benchmark craters where we have radiometric sample ages, including Copernicus, Tycho, North Ray, Cone, Autolycus and Aristillus craters (Stöffler and Ryder, 2001). Multiple authors have used the higher-resolution imaging of the Moon made available by LROC and Kaguya to update the crater-counting ages of these key lunar terrains (Haruyama et al., 2009; Hiesinger et al., 2003; Hiesinger et al., 2016; Hiesinger et al., 2012; Robbins, 2014; Williams et al., 2014). The derived model ages of the ejecta blankets of Cone, North Ray, Tycho, and Copernicus agree well with radiometric and exposure ages of the Apollo 12, 14, 16, and 17 landing sites, respectively (Hiesinger et al., 2012; Williams et al., 2014). However, the Robbins (2014) results differ by a factor of 2-3 for North Ray, and factoring in other landing sites, a lunar surface previously dated at 3 Ga may have an updated model crater age as young as 1.9 Ga. Recent U-Pb ages of zircon and phosphate grains of 1.4 and 1.9 Ga from sample 15405 have been interpreted by Grange et al. (2013) as the formation ages of Aristillus and Autolycus, which are slightly (200 Myr) younger than radiometric ages previously proposed for these craters. New Autolycus crater size-frequency distributions by Hiesinger et al. (2016) for individual parts of the ejecta blanket and crater floor yielded a range of model ages, none of which corresponded to either set of Apollo 15 impact melt ages. This implies either that the dated samples are not related to Autolycus or that the crater measurements are so heavily affected by resurfacing and secondary cratering from Aristillus that they no longer represent the formation age of Autolycus. An alternative method to crater counting for estimating the age of Copernican craters is the inverse relationship between rock abundance in large craters' ejecta, determined by LRO Diviner thermal radiometer data, and their age (Ghent et al., 2014). Results using this method suggest that the lunar cratering rate has increased by a factor of ~2-3 in the last ~250 Myr relative to the preceding ~750 Myr (Mazrouei and Ghent, 2017).

Science Goal 1d. Assess the recent impact flux

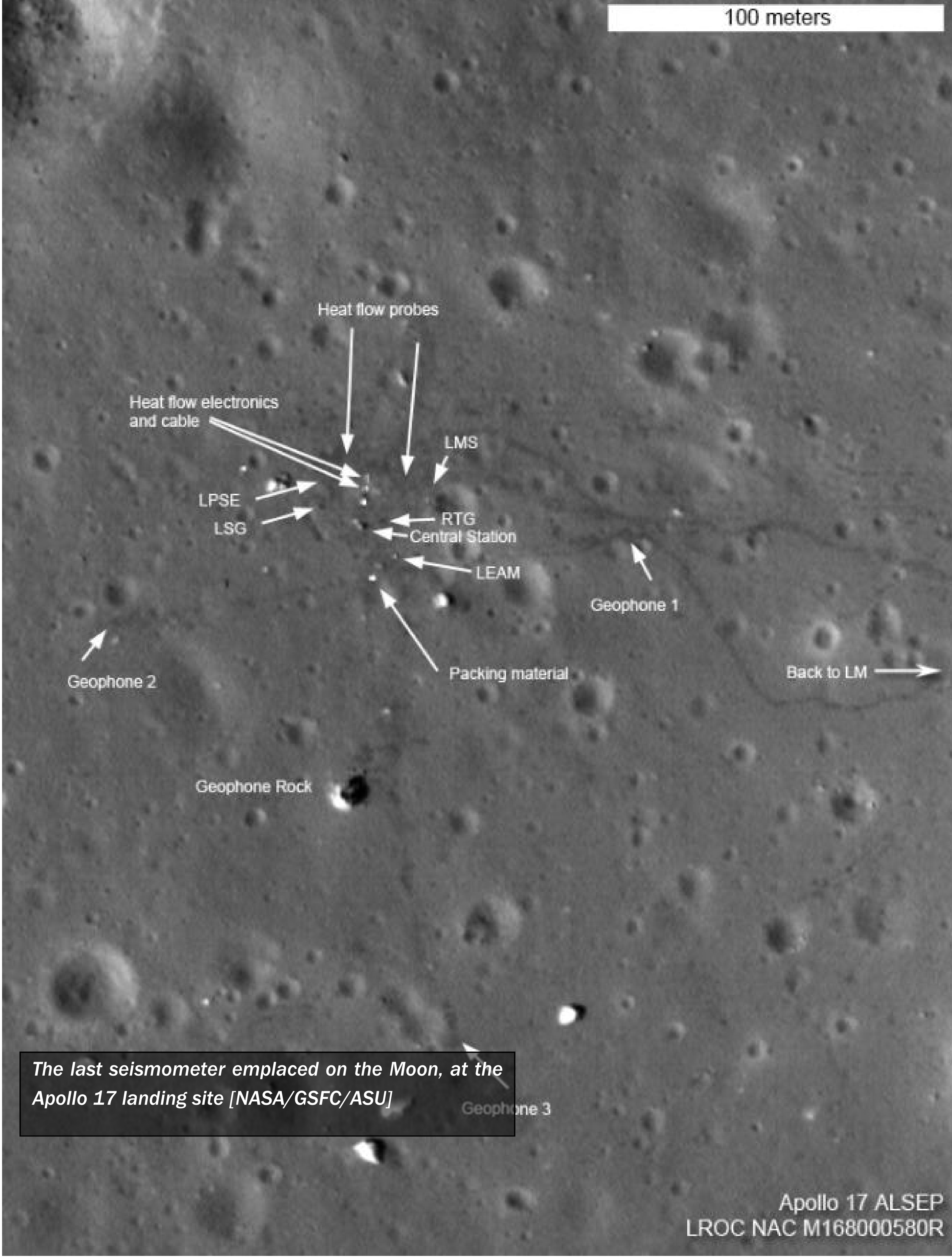
Amateur and professional observatories monitor the Moon for light flashes, interpreted to represent impact events. The NASA Lunar Impact Monitoring Program has recorded over 300 flashes (assumed to be meteoroid impacts) since 2006 (Suggs et al., 2014); the brightest recorded flash was associated with a new 18.8 m crater observed by the Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) (Robinson et al., 2015). LROC NAC temporal image pairs have also been used to quantify the contemporary rate of crater production on the Moon, revealing 222 new impact craters, higher than predicted by standard production functions for the Moon (Speyerer et al., 2016). During several of the known meteoroid showers, LDEX on LADEE observed temporary enhancements of the lunar dust cloud, localized to the hemisphere exposed to the incident meteoroid shower flux; approximately 40 μm per million years of lunar soil is estimated to be redistributed from meteoritic bombardment (Szalay and Horányi, 2016).

Science Goal 1e. Study the role of secondary impact craters on crater counts

High-resolution imaging from recent lunar missions has enabled investigations led to significant progress toward understanding the effects of secondary impact cratering on measured impact crater populations. For example, LRO Narrow Angle Camera (NAC) images have been used by multiple researchers to investigate the ejecta and secondary craters surrounding relatively young primary craters (Krishna and Kumar, 2016; Singer et al., 2014). Notably, Krishna and Kumar (2016) measured boulders and small, fresh craters surrounding Censorinus crater to find that the majority of craters superposed on the ejecta blanket were secondaries, with a minor component of small, superposed primary craters. Similarly, Singer et al. (2014) mapped secondary craters surrounding several lunar craters with the purpose of estimating the size and velocity of ejecta fragments that formed them. Hindrances to continued progress on this topic are largely related to the work effort involved; counting craters, especially secondary craters superposed on an ejecta blanket, is a tedious, time-intensive task. To date, there is no reliable alternative to the manual identification of craters, and the accurate and precise measurements of craters require substantial training of individuals involved. LROC and Kaguya images provide high-resolution data that is generally sufficient for these efforts since the sizes of secondaries are related to the size of the parent primary.

Concept 1: Summary of Progress Still Needed

The relationship of the nearside basins to one another is challenging for basin stratigraphy based on either cross-cutting relationships or visible crater statistics, because Imbrium basin's ejecta influenced the surrounding region so profoundly. Therefore, improvements to orbital remote sensing observations are unlikely to provide closure on this topic. A key test of this scenario is whether the terrestrial planets and asteroid belt experienced a relative "lull" in impacts between the early and late bombardment components described above. This will require a combination of modeling of the composition of basin impact melt, petrology and geochemistry of samples to tie them to specific basins, and detailed geochronology of multiple samples, ideally with multiple geochronologic systems. Such studies could be accomplished by landing and in situ dating and/or sample return to Earth. Prime targets known at this time include SPA, Orientale, Crisium, and Nectaris. Such missions must incorporate landing technologies such as terrain-relative navigation and hazard avoidance, sample-return missions need to carry a return launch motor to get the samples from the Moon to the Earth, and missions to SPA must establish a communications infrastructure for the lunar farside. New investments in communications, landing technology, and sample acquisition would be enabling across many landed mission concepts in this report. Expanding the absolute chronological framework for the post-basin era will require radiometric dating of samples with well-established provenance, including young mare basalts and key stratigraphic craters such as Copernicus. In addition, continued work to determine the geologic provenance of Apollo and Luna sampled units to understand sample ages, for example, understanding the Crisium lava flows and relating them to the Luna 24 samples. The longer LRO operates, the likelihood of finder more and larger impact events increases, helping better compare the recent flux with crater counting estimates. Lengthening the time difference between imaging sites under identical lighting conditions by LRO would improve the chances of imaging sites under different photometric geometries to help identify new craters.



The last seismometer emplaced on the Moon, at the Apollo 17 landing site [NASA/GSFC/ASU]

CONCEPT 2: THE STRUCTURE AND COMPOSITION OF THE LUNAR INTERIOR PROVIDE FUNDAMENTAL INFORMATION ON THE EVOLUTION OF A DIFFERENTIATED PLANETARY BODY

Apollo seismic data have proved to be a rich source of information on the structure and composition of the lunar interior for the central nearside of the Moon, and in the absence of new seismic data, have been continuously mined for new information. The NASA Gravity Recovery and Interior Laboratory (GRAIL) mission mapped the gravity of the Moon at the highest resolution for any Solar System body. However, the goals for Concept 2 outlined in the SCEM report remain relevant, particularly in terms of the absolute measurements of crustal thickness, the chemical and physical stratification of the mantle, and the thermal state of the Moon. Any new and global geophysical data that could be obtained would dramatically enhance the GRAIL dataset.

Science Goal 2a. Determine the thickness of the lunar crust (upper and lower) and characterize its lateral variability on regional and global scales.

Analysis of data from the twin spacecraft of the GRAIL mission has resulted in significant progress in the understanding of the lateral variability of the thickness of the lunar crust on regional and global scales (Zuber et al., 2013; Wieczorek et al., 2013) (Figure 1.1). The improved lunar gravity field map revealed features of the lunar crust in unprecedented detail, including fractures and other tectonic structures, mascons, lava tubes (Chappaz et al., 2017) and other volcanic landforms, impact basin rings (Neumann et al., 2015) and the shape and size of complex to peak-ring lunar craters (Baker et al., 2017). However, in terms of the thickness of the upper and lower lunar crust, GRAIL measurements use seismic estimates for their “ground truth,” and while relative lateral variability is known, absolute measurements of crustal thickness remain a priority.

The Apollo seismic data are still the only direct source of lunar crustal thickness information, and those values may have large errors owing to uncertainties in readings of seismic arrival times. One-dimensional crustal structure models thus span a range of plausible layers that fit these observations. Much of the "noise" in Apollo seismic signals is due to scattering effects introduced in the shallowest layers of the lunar regolith (meter scale). Recent studies have made progress quantifying these effects (e.g., Sens-Schönfelder and Larose, 2008; Lognonné et al., 2009; Blanchette-Guertin et al., 2012; Gillet et a., 2017).

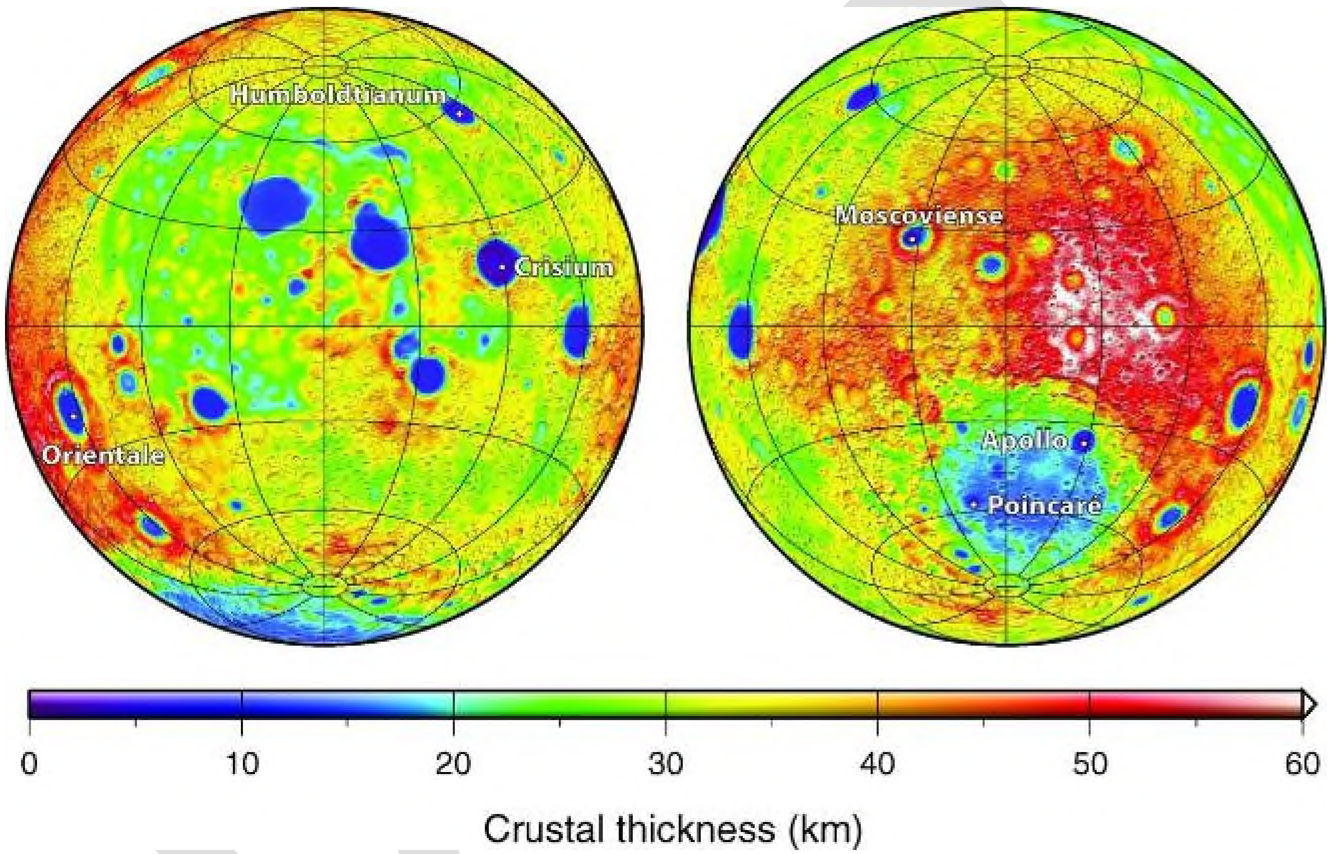


Figure 1.1. The crustal thickness of the Moon, derived from GRAIL and LOLA measurements (Wieczorek et al., 2013).

Science Goal 2b. Characterize the chemical/physical stratification in the mantle, particularly the nature of the putative 500-km discontinuity and the composition of the lower mantle.

The putative 500-km seismic discontinuity has been interpreted as indicative of chemical stratification in the mantle, and possibly the base of the lunar magma ocean. However, Nakamura (2005) explained this mantle "discontinuity" as an artifact in his original model (Nakamura, 1983). Later work (Logonné et al., 2003; 2006; Khan and Moosegaard, 2001, 2002; Khan et al., 2013) show that a constant velocity mantle can fit all observed constraints within uncertainty, with perhaps only a slight suggestion of an increase in velocity at mid-mantle depths. Thus, higher fidelity seismic data are required to determine if this discontinuity exists, with implications for the depth of melting in the magma ocean, and subsequent mantle overturn or whole-mantle convection.

New work on the physical nature of the mantle has proposed mechanisms for deep moonquakes (dehydration embrittlement, transformational faulting; Weber et al., 2009; Kawamura et al., 2017), operating on the assumption that tidal stress alone is not enough to cause failure under significant overburden pressure, and that these deep moonquakes occur in what should be a ductile regime. However, it has also been proposed that the stress release of deep quakes may be as low as the tidal stress (Kawamura et al., 2017). None of these studies can be confirmed or refuted with the presently available data. Seismic tomography studies reexamining both shallow and deep structure have also been performed (Zhao et al., 2008, 2012), but are not well constrained, again owing to the relatively uncertain nature of the Apollo arrival data.

Science Goal 2c—Determine the size, composition, and state (solid/liquid) of the core of the Moon

Recent work has put rough constraints on the structure of the core, which may include a solid inner core, a fluid outer core, and a partially molten layer (Williams et al., 2006; Garcia et al., 2011; Weber et al., 2011). The interpretation of the Apollo seismic data suggested the existence of these layers, but provides less explicit evidence for their depths. The average core density could imply either a large concentration of lighter alloying elements, or a large core temperature (Garcia et al., 2011). The existence of a partially molten layer was further examined with lunar geophysical data in combination with phase-equilibrium computations, and with a viscoelastic dissipation model (Khan et al., 2014; Nimmo et al. 2012); these studies yielded conflicting results. The GRAIL lunar gravity produced a family of core models all consistent with geodetic parameters (including constraints from lunar laser ranging - Williams and Boggs, 2015), all of which had partial melt layers (Yan et al., 2015).

Gravity data has not yet definitively identified the presence of an inner core. Laser ranging data suggest the lunar core is liquid (e.g., Williams et al., 2006; Williams and Boggs, 2015; Barkin et al., 2014), although combining gravity, topography and laser ranging data to model the deep interior of the Moon (Matsuyama et al., 2016) produces a solid inner core and total core size akin to the core modeled using Apollo seismic data (Weber et al., 2011).

Science Goal 2d—Characterize the thermal state of the interior and elucidate the workings of the planetary heat engine.

On the Moon's near side, heat-producing elements are concentrated in the Procellarum KREEP Terrane (PKT), and the cause for this large-scale asymmetry remains unknown. Modeling has attempted to understand the effects of this asymmetry, where crustal Th in the PKT would lead to asymmetric mantle temperatures and would effectively cause a giant "mantle plume" below the PKT (Laneuville et al., 2013); the influence of ilmenite on mantle overturn may have also permitted a single large upwelling plume (Zhang et al. 2017). GRAIL data revealed a thin crust and dyke system surrounding PKT (Andrews-Hanna et al., 2014), calling into question the long-standing theory that PKT is an ancient impact basin. Rather this work suggests it may be a magmatic-tectonic feature overlying the nearside "magma plumbing system" that supplied the mare with their basaltic infills. A thermal asymmetry that extended into the mantle may have produced true polar wander (Siegler, et al. 2016).

Heat flow measurements are necessary to understand the Moon's thermal history, and because the Apollo heat flow measurements were made at the boundary of the PKT and the surrounding feldspathic highlands, they are not truly representative of either terrane. Furthermore, installation procedures may have led to spurious conductivity observations (e.g., Saito et al., 2007, 2008). While no new measurements of heat flow have been made, work with Diviner measurements of PSRs are being used to place upper limits on heat flow in a region far from the PKT (Paige and Siegler, 2016). Future heat flow measurements with stations both well inside and outside of PKT could demonstrate whether the mantle is truly hotter beneath the PKT, and combining such heat flow measurements with seismic observations would enable the determination of whether there is a sub-crustal KREEP layer beneath the PKT (see Goal 3b).

Paleomagnetic studies of Apollo samples have demonstrated that the Moon had surface magnetic fields of ~30–100 μT between at least 4.2 and 3.56 Ga (Weiss and Tikoo, 2014; Garrick-Bethell et al., 2017). The widely accepted theory for the generation of this field is an ancient core dynamo. While large surface impacts can also generate transient magnetic fields, recent analyses of Apollo samples require a slow cooling timescale that excludes impact field origins (e.g., Tikoo et al., 2017). Subsequent to 3.56 Ga, the fields recorded in samples is drastically reduced, but not zero. Current studies are attempting to understand the timing and cause of this drop in recorded field strength and whether it is linked to total cessation of core dynamo activity, or persistence in an extremely weakened state. A single dynamo mechanism cannot explain the strong fields inferred for the period before 3.56 Ga while also allowing the dynamo to persist in a weakened state afterwards. Two distinct mechanisms may have been in play at different stages of lunar history (convective vs. mechanical convection).

Concept 2: Summary of Progress Still Needed

In order to make significant progress toward addressing the fundamental questions related to the lunar interior as raised in Concept 2, the recommendations for implementation in the SCEM report remain valid. These recommendations include emplacement of equipment such as a simultaneous, globally distributed seismic and heat flow network and/or an expanded retroreflector network, and strategic collection of samples from terrains of different ages that can provide constraints on lunar geochemistry and new information on the history of the lunar dynamo.

Looking down on the amazing compositional diversty of the central peak of Jackson crater, which rises 2000 meters above the crater floor NAC M1117602006LR [NASA/GSFC/Arizona State University].

CONCEPT 3: KEY PLANETARY PROCESSES ARE MANIFESTED IN THE DIVERSITY OF LUNAR CRUSTAL ROCKS

New data in the past decade from remote sensing and studies of lunar rocks from Apollo, Luna, and meteorite collections has provided a variety of new results that have highlighted the diversity of crustal rocks. How the feldspathic crust, Mg-suite rocks, KREEP, and evolved lithologies are tied together in the Moon's early crustal formation and evolution is still not known. However, with the remote sensing data of the past decade, we now know where to go to find out.

Goal 3a. Determine the extent and composition of the primary feldspathic crust, KREEP layer, and other products of planetary differentiation.

The progress made toward this goal has been principally through remote sensing analyses using data from recent orbital instruments. Extensive deposits of pure crystalline anorthosite (PAN) have been identified and mapped across the exposed inner ring of basins and elsewhere with spectroscopic data from Chandrayaan-1 (M3) and SELENE (MI and SP) (e.g., Ohtake et al., 2009; Pieters et al., 2009; Cheek et al., 2013; Donaldson Hanna et al., 2014) confirming the magma ocean concept of a massive cumulate plagioclase (flotation) primary crust. There is no new data concerning the distribution and nature of KREEP. Characterizing the lower crust and mantle is ongoing but data are limited: current Chandrayaan-1 (M3) and SELENE (MI and SP) spectroscopic data appear to indicate the lower crust/mantle is pervasively noritic (plagioclase + low Ca- pyroxene) in nature with pockets of troctolite (olivine + plagioclase) (Yamamoto et al., 2010; Isaacson et al., 2011; Klima et al., 2011b; Kramer et al., 2013; Lucey et al., 2014; Ohtake et al., 2014; Moriarty and Pieters, 2017).

Goal 3b. Inventory the variety, age, distribution, and origin of lunar rock types.

The progress made toward addressing this goal has been through the remote sensing analyses using spectroscopic data from orbital instruments: Chandrayaan-1 (M3), SELENE (MI and SP) and LRO (DIVINER, LROC WAC). In addition to primary rock types of the crust

(Greenhagen et al., 2010; Taylor, 2009; Dhingra et al., 2015), the orbital data have identified new rock types (not found in the samples) such as 'pink' Mg-rich spinel anorthosite from the lower crust (Dhingra et al., 2011; Pieters et al., 2011; Pieters et al., 2014), and water-rich KREEP-rich silicic volcanism (Glotch et al., 2010; Jolliff et al., 2011; Klima et al., 2013; Bhattacharya et al., 2013). Well-documented samples, however, are lacking to characterize these in detail. Such unusual components suggest processes are active that might lead to local concentrated resources. The diversity of rock types is now beginning to be understood at a basic level, but translating that into a coherent understanding of the sequence of how these rocks formed during early lunar history and the sequence of events post-differentiation remains a future goal.

Goal 3c. Determine the composition of the lower crust and bulk Moon.

Progress has been made evaluating the composition of the lower crust and upper mantle through analysis of data from orbital remote sensors focusing on compositional products excavated by large craters and basins (e.g., Lucey et al., 2014). Local exposures of troctolite (olivine with plagioclase) are found near several large basins. The largest lunar basin (SPA) has clearly excavated/exposed Mg-rich pyroxene, with no clearly detectible olivine (Ohtake et al, 2014; Moriarty and Pieters, 2015; 2017), and the breccia composition of the megaregolith is largely also dominated by Mg-pyroxene and plagioclase (norite) implying low-Ca pyroxene is the dominant mafic mineral of the lower crust/upper mantle.

New constraints on the thickness and porosity of the lunar crust from GRAIL have allowed for refined calculations of the Moon's bulk composition (Wieczorek et al., 2013; Taylor et al., 2013; Warren and Dauphas, 2014), suggesting the bulk Moon has abundances of refractory elements that are similar to the Earth. Major uncertainties in these in these calculations include the composition of the lower mantle and temperature; heat flow measurements would provide critical new constraints.

Goal 3d. Quantify the local and regional complexity of the current lunar crust.

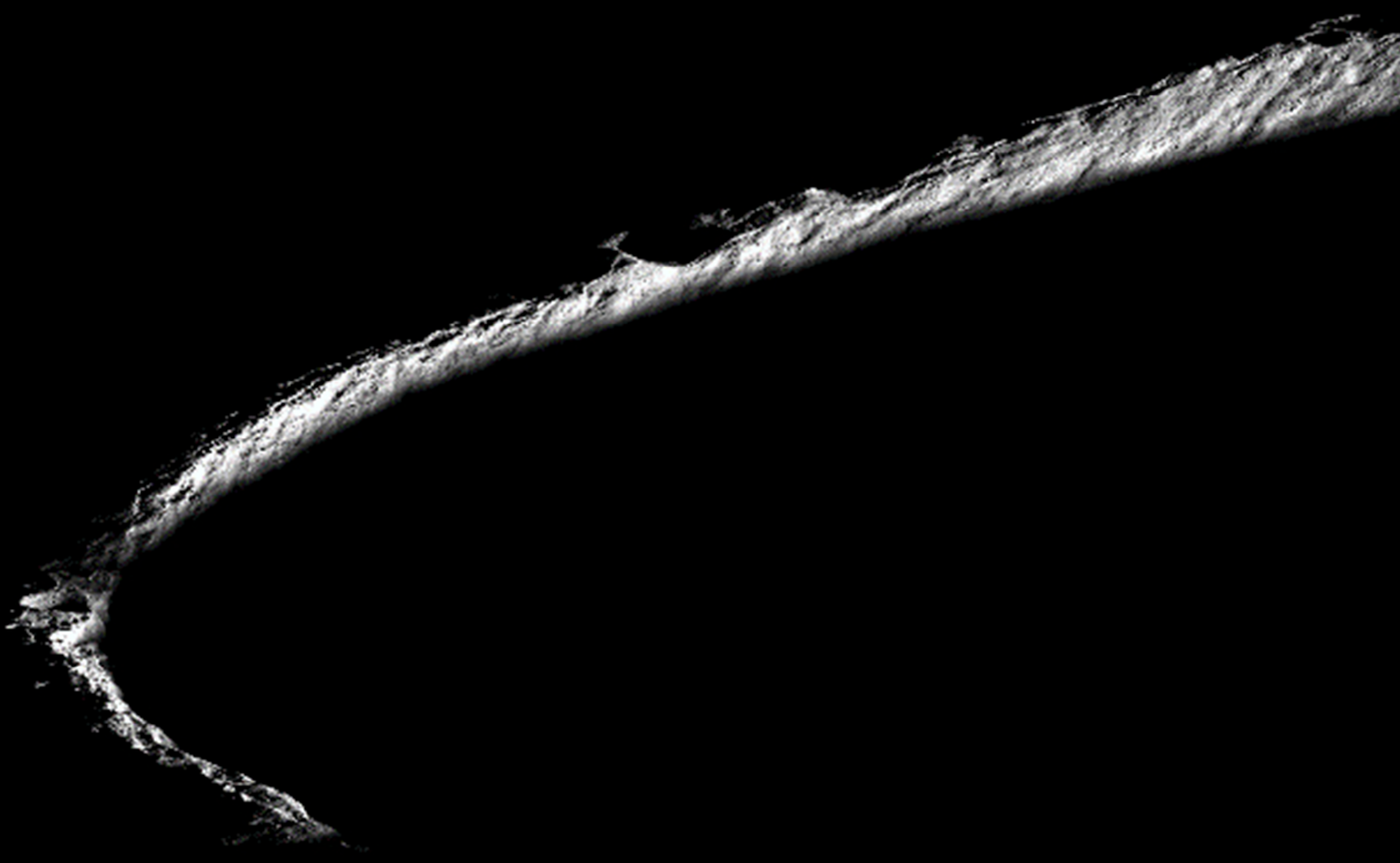
Aspects of the complexity of the lunar crust has been documented through a combination of compositional analyses using spectroscopic sensors on Chandrayaan-1 (M3), SELENE (MI and SP), and LRO (DIVINER, LROC WAC) coupled with detailed geologic information at high spatial resolution obtained by cameras on SELENE (TC) and LRO (LROC NAC). Although apparently unsampled, outcrops of coherent lunar lithologies are frequently exposed at craters and basins (e.g., Dhingra et al., 2011; Cheek et al., 2013; 2015; Kramer et al., 2013).

Goal 3e. Determine the vertical extent and structure of the megaregolith.

Although the properties of the megaregolith and their relationship to early lunar bombardment and the pristine crustal materials that lie within these mixed materials are important, no significant new understanding of their composition or relationship with a particular basin event has been made through recent orbital missions. Geophysical models of GRAIL data have shown that the initial porosity of the megaregolith is 10–20%, which decreases to zero at a depth of 10–20 km (Han et al., 2014).

Concept 3: Summary of Progress Still Needed.

With the success of recent remote sensing missions, both new and unusual rock types have been discovered across the Moon, as well as areas that have been shown to contain abundant endogenous volatiles; these represent new areas where future missions can reveal aspects of the Moon that were not known at the time of the SCEM report. The recommendations for implementation from the SCEM report included higher spatial resolution compositional information, the return of samples from high-priority targets, in situ elemental and mineralogical analyses as well as regional seismic networks to determine vertical structure, and geologic fieldwork by astronauts. Each of these recommendations remains valid and returns from orbital missions have identified many high-priority targets that would further our understanding of key planetary processes as manifested in the diversity of lunar crustal rocks.



The "Most Valuable Real Estate in the Solar System" - oblique view of the rim of Shackleton crater near the South Pole. While no location on the Moon stays continuously illuminated, three points on the rim of Shackleton remain collectively sunlit for more than 90% of the year, making this a prime location for a lunar outpost. These points are surrounded by topographic depressions that never receive sunlight, creating cold traps that can capture ices, NAC M1224655261LR [NASA/GSFC/Arizona State University]

CONCEPT 4: THE LUNAR POLES ARE SPECIAL ENVIRONMENTS THAT MAY BEAR WITNESS TO THE VOLATILE FLUX OVER THE LATTER PART OF SOLAR SYSTEM HISTORY

The past decade has provided a wealth of new data and an abundance of research focused on understanding polar volatiles. Interest in the special environment of the lunar poles has grown dramatically, but an understanding of polar volatiles and the fundamental questions about their origin and evolution remain unanswered and will remain unanswered without in situ analysis and returned samples.

Goal 4a. Determine the compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and depth) of the volatile component in lunar polar regions.

Progress in this goal has been made through additional analyses of existing datasets (e.g., Lunar Prospector) as well as new measurements from the SELENE, LRO, and LCROSS missions. The LCROSS mission showed that water and other volatile species (e.g., light hydrocarbons, sulfur bearing species, and CO_2) are present in the large permanently shaded region (PSR) within Cabeus crater (Colaprete et al., 2010, 2012; Gladstone et al., 2010; Schultz et al., 2010). LCROSS data indicate somewhat higher water abundances (5.9±2.9 wt.%) than suggested by Lunar Prospector (LP) neutron data of 1.5±0.8 wt.%; although new analyses of LP data suggest the neutron-derived values could be revised upwards (Eke et al., 2015). Passive ultraviolet (UV) and active (laser) near-infrared measurements indicate the possible presence of non-uniformly distributed water frost within PSRs (Hayne et al., 2015; Lucey et al., 2014) (Figure 4.1). Visible images of the inside of PSRs do not show evidence of any macroscopic water ice or volatile materials (Haruyama et al., 2008; Haruyama et al. 2013 et al., 2013; Koeber et al., 2014), as are seen in similar images of the volatile-rich deposits of Mercury's PSRs (Chabot et al., 2014), despite the fact that LOLA observations at 1064 nm indicate PSRs have ~10% higher reflectance (Lucey et al., 2014), and increases in reflectance correlate with the temperatures at which some volatiles are stable (Fisher et al., 2017). Spatial reconstruction analyses of Lunar Prospector (LP) data indicate that the neutron-detected hydrogen enhancements are mostly from PSRs (Eke et al., 2009), albeit LRO neutron data

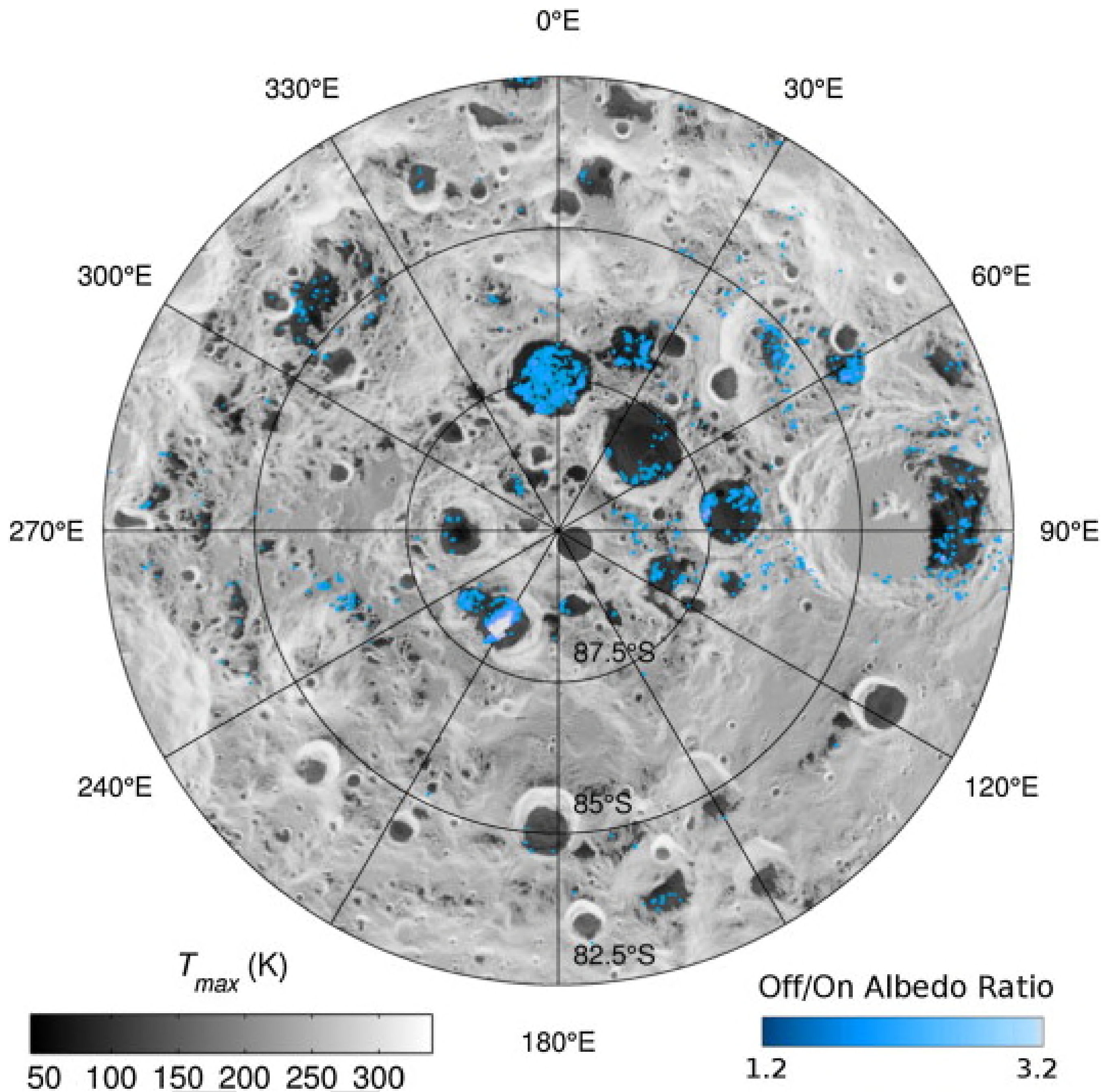


Figure 4.1. Locations of anomalous UV albedo consistent with water ice. Colors indicate points with off/on-band albedo ratio values >1.2 and Lyman-α albedo <0.03, increasing from deep orange (1.2) to white (>3.2). The average Moon outside of the cold traps has a ratio of ~0.9. Ratio values in the range 1.2–4.0 are consistent with water ice concentrations of ~0.1–2.0% by mass. If patchy exposures of pure water ice are mixed by area with dry regolith, the abundance could be up to ~10%. From Hayne et al. (2015).

suggest some amount of hydrogen both inside and outside PSRs (Mitrofanov et al., 2010). Finally, radar data from Chandraayan-1 and LRO suggest that relatively pure water ice is present in multiple PSRs (Spudis et al., 2013; Patterson et al., 2016), although some interpretations of these data suggest surface roughness may also be the cause of some portion of the radar signatures (Fa and Cai, 2013). To date, there is still not uniform agreement regarding how the hydrogen distribution in and around PSRs, especially in regards to the hydrogen abundances within individual PSRs (Lawrence, 2017). While substantial progress has been made toward this goal, our understanding of the compositional state of volatiles and their distribution is far from complete.

Goal 4b. Determine the source(s) for lunar polar volatiles.

To determine the source for lunar polar volatiles, it is generally required that isotopic measurements be made of lunar polar material. Since there is no current means of making such measurements from orbit, and since there have been no landed missions to lunar PSRs, there has been no substantial progress made for this goal. Understanding the lunar volatile cycle could be investigated by deployment of static, long-lived networks around the poles that monitor the lunar exosphere. These could monitor the migration of volatile species to the cold traps in the polar regions.

Goal 4c. Understand the transport, retention, alteration, and loss processes that operate on volatile materials at permanently shaded lunar regions.

Very little progress has been made on this goal because understanding these processes generally require in situ measurements to be made either nearby or inside PSRs. Since there have been no landed missions to such locations, there has been no progress. Future missions will need to sample a wide range of sizes of PSRs in order to understand how transport, retention, and loss processes operate. Moderate progress has been made through models and measurements for the transport of lunar volatiles across the lunar surface (see Science Goal 8d). Since the PSRs are a key volatile sink, then the results from those studies provide indirect assistance towards understanding processes operating within PSRs. In addition, new data from PSRs at Mercury (e.g., Lawrence, 2017) provide generalized information regarding volatile processes within PSRs; however, applications of Mercury measurements to the Moon may be limited given the significant differences between the mercurian and lunar PSRs.

Goal 4d. Understand the physical properties of the extremely cold (and possibly volatile rich) polar regolith.

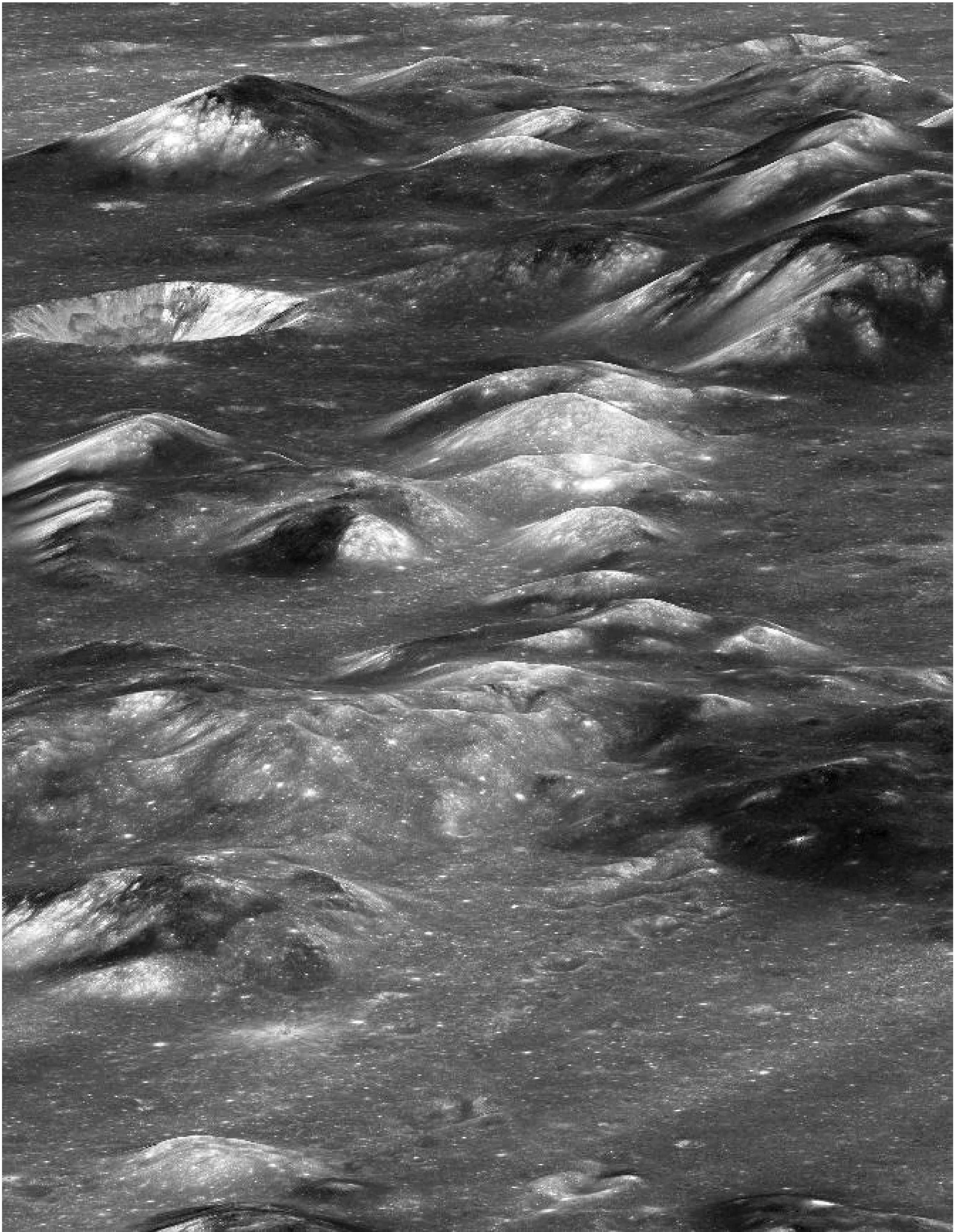
Progress toward understanding the physical properties of polar regions been made through new measurements from the SELENE, Change'E-1 and LRO missions, such as detailed measurements of lunar polar topography (Ping et al., 2009; Araki et al., 2009; Smith et al., 2010), the thermal environment (Paige et al., 2010; Siegler et al., 2016), and lighting conditions in and around PSRs (Mazarico et al., 2011; Speyerer and Robinson, 2013; Speyerer et al., 2016). However, in terms of understanding the geotechnical properties of the regolith, which will affect any efforts to extract volatiles for utilization, no new information is available.

Goal 4e. Determine what the cold polar regolith reveals about the ancient solar environment.

Addressing this goal requires samples to be acquired of the cold polar regolith and then analyzed. There has been no substantial progress made on this goal.

Concept 4: Summary of Progress Still Needed.

Information is still needed regarding the: 1) detailed elemental, mineralogic, and isotopic compositions of lunar volatiles, 2) volatile source(s), 3) transport, retention, alteration, and loss processes for volatiles in PSRs, 4) geotechnical properties of the polar regolith, and 5) ancient solar environment. Recommendations for implementation from the SCEM report remain relevant. Further information about the distribution and abundance of polar volatiles can still be gained from high-spatial resolution orbital measurements. Landed missions can provide information about the physical properties of the regolith, vertical and lateral distribution of volatiles, and in situ measurements of chemical, isotopic, and mineralogic characteristics of polar deposits, and cryogenic sample return could provide a wealth of details on the origin and complexity of lunar volatiles.



CONCEPT 5: LUNAR VOLCANISM PROVIDES A WINDOW INTO THE THERMAL AND COMPOSITIONAL EVOLUTION OF THE MOON

Remote sensing datasets from the past decade have provided a refined understanding of the compositions of volcanic deposits, and relative ages have been estimated for a wide variety of near and far side basalts. The lack of new returned samples at known locations from previously unsampled deposits, including from the far side or from cryptomare, and the absence of new constraints on the volumes of volcanic deposits and their absolute ages limit our understanding of the thermal and compositional evolution of the Moon.

Goal 5a. Determine the origin and variability of lunar basalts.

Incremental progress has been made on determining the origin and variability of lunar volcanic rocks through the analysis of new lunar meteorites, Chang'E-3 data, and isotopic studies of lunar materials. Studies of lunar meteorite NWA-032 show compositional ranges beyond those of Apollo samples (e.g., Borg et al., 2009; Elardo and Shearer, 2014), and data from the Chang'E-3 rover indicated an unsampled basaltic composition at its landing site in northern Mare Imbrium (medium-Ti and high-Al, e.g., Ling et al., 2015; Neal et al., 2015). Isotopic studies of lunar zircons and mare basalts shed information on the origins of their source regions, yielding source region model ages similar to those of the highlands crust and KREEP, suggesting they reflect primordial differentiation or a secondary event that affected the lunar nearside (see Borg et al. 2015).

Data from the JAXA SELENE and NASA LRO missions have resulted in discoveries of "skylights" or "pits" in mare basalts (Figure 5.1) that have been interpreted as breached lava tubes (Haruyama et al., 2009a; Robinson et al., 2012; Wagner and Robinson, 2014), and the walls of these pits provide new information about mare basalt emplacement as a series of thin flows. Such pits provide a site in which a stratigraphic sampling of mare basalt lava flows could occur (along with paleoregolith; Goal 7a).

Kaguya data analyses also indicate that volcanism on the far side of the Moon was long-lived (Haruyama et al., 2009b). As we have no volcanic samples from known locations on the far side, we cannot compare compositional and source region differences with the near side.

While this goal addresses lunar basalts, the diversity of lunar volcanic compositions is reflected in results from the LRO mission that have shown the presence of silicic/felsic volcanic features on the lunar surface at the Gruithuisen and Marian Domes, Aristarchus, Hansteen Alpha, Montes Riphaeus, and the Lassell Massif on the lunar nearside, and Compton Belkovich on the farside (e.g., Glotch et al., 2010, 2011; Jolliff et al., 2011).

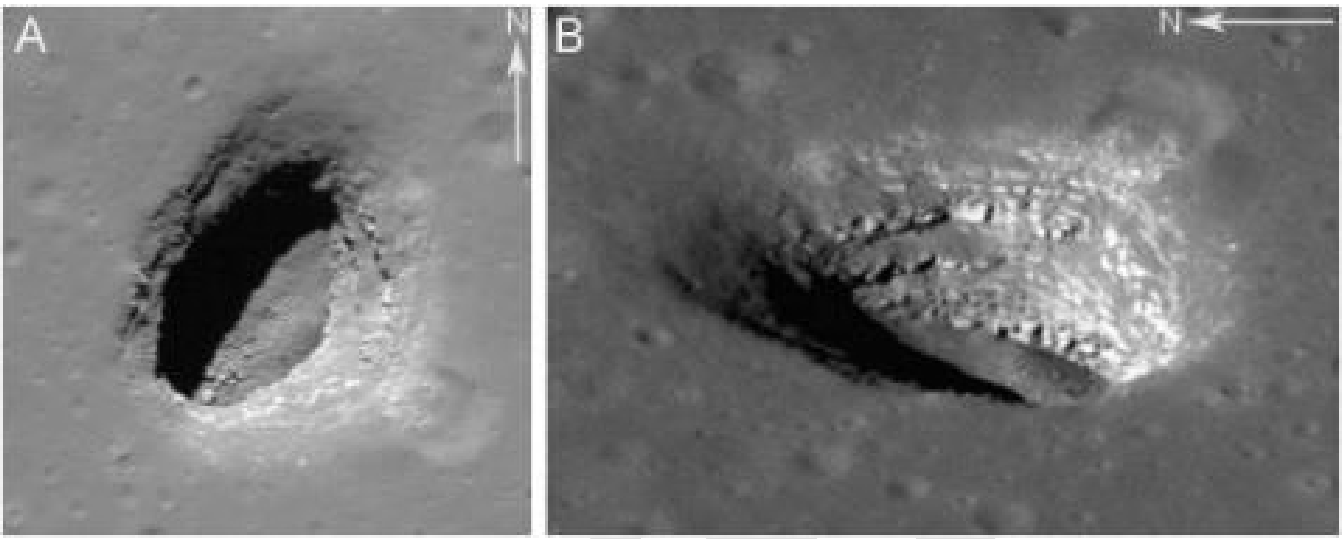


Figure 5.1. A pit in Mare Ingenii showing layering of basalt flows (Robinson et al., 2012).

Goal 5b. Determine the age of the youngest and oldest mare basalts.

Progress toward understanding the ages of lunar volcanism comes from remote sensing and lunar meteorites, though true advances are limited by the lack of accurate sample-based age information to constrain the former, and lack of known provenance and context in the case of the latter. Controversial new results from the LRO mission suggest basaltic volcanism may have continued much longer than previously thought in the form of Irregular Mare Patches (IMPs) (Figure 5.2) located at ~70 sites on the lunar near side. These unusual deposits exhibit sharp, meter-scale morphology, steep slopes, and a paucity of superposed impact craters suggesting ages younger than 100 million years (Braden et al., 2014). However, it has alternately been suggested that IMPs represent volcanic deposits with unusual formation mechanisms and physical properties, and are instead billions of years old (Qiao et al., 2017; Wilson and Head, 2017). Surface exploration and likely isotopically determined age determinations of IMP materials are needed to resolve this controversy.

While lunar meteorites indicate mare basalts exist with ages beyond the range of basalts returned by Apollo and Luna (e.g., Borg et al., 2009), they do not encompass the span of ages identified by crater size–frequency distributions (Hiesinger et al., 2011). A number of old basalts (i.e., >4.2 My) have been identified in lunar meteorites (Terada et al., 2007; Shih et al., 2008; Shaulis et al., 2016). Some of these meteorites have been described as samples of ancient, buried mare basalt (cryptomare), but as with all lunar meteorites, broader interpretations are limited by the lack of known provenance and geologic context. At least 20 cryptomaria sites cover ~2% of the lunar surface (Whitten and Head, 2015), indicating that ancient volcanism is still underrepresented in the sample suite.

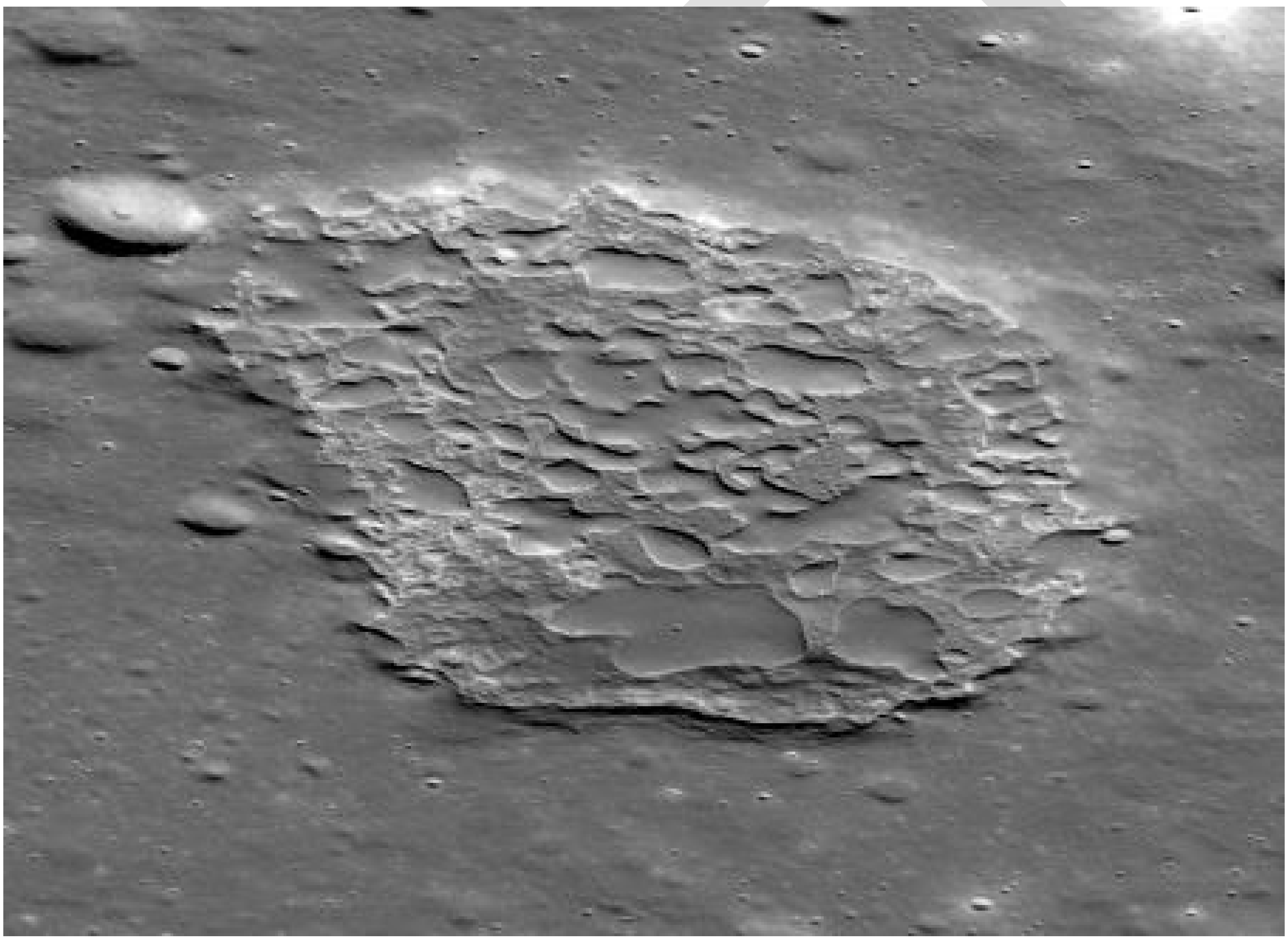


Figure 5.2. Ina, a 2-km wide Irregular Mare Patch that may be younger than 100 million years or older than 3 billion years. NAC image M1108203502LR [NASA/GSFC/Arizona State University].

Goal 5c. Determine the compositional range and extent of lunar pyroclastic deposits.

Lunar pyroclastic glasses were derived from distinct (deeper) source regions compared to the crystalline mare basalts and thus have added significance for examining mantle heterogeneity of the Moon. A search for previously unrecognized pyroclastic deposits (e.g., Gustafson et al., 2012) focused on use of the Clementine color data and these were largely confirmed with M^3 data (Besse et al., 2013). The high spatial resolution of the Kaguya Terrain Camera (TC, ~10 m/pixel), Multiband Imager (MI, ~20 m/pixel) and LRO Narrow Angle Camera (NAC, 0.5 m/pixel) data make them ideal for use in searching for additional undiscovered pyroclastic deposits and to complete an updated global inventory (e.g., Gaddis et al., 2011, 2013, 2018; Kramer et al., 2015). Data from MI, SP, and M^3 for mature soils on lunar pyroclastic deposits provide information on the shape, position and strength of the 1- and 2- μm bands and indicate the frequent presence of volcanic glass among the mafic minerals (high- and low-calcium pyroxenes, and olivine) typically present (e.g., Bennett et al., 2015; Gaddis et al., 2014, 2016; Jawin et al., 2015) in lunar small pyroclastic deposits. In addition, analyses of the Chandrayaan-1 Moon Mineralogy Mapper (M^3) data reveal the presence of an unusual spinel-rich material (pleonaste, $[Mg,Fe]Al_2O_4$) associated with the largely buried pyroclastic deposit at Sinus Aestuum (Weitz et al., 2017).

Pyroclastic deposits have also been observed in association with sites of silicic volcanism on the Moon, including at the Compton-Belkovich thorium anomaly (Jolliff et al., 2011; Clegg-Watkins et al., 2017), the Lassell Massif (Ashley et al., 2016), and at Aristarchus (Glotch et al., 2010; Milliken & Li, 2017). This indicates a range of lunar volcanic compositions that is certainly beyond that represented in the Apollo collection. Work published since the SCEM report has demonstrated there is indigenous water and other volatiles in the lunar mantle (Saal et al., 2008; Hauri et al., 2011, 2015; Anand, 2010; Anand et al., 2014; Boyce et al., 2010, 2014; McCubbin et al., 2011; Barnes et al., 2016). New work using M^3 data has also shown that there is a widespread occurrence of water in pyroclastic deposits, with localized abundances up to 300-400 ppm (Milliken and Li, 2017). These orbital observations need to be verified through sample analysis.

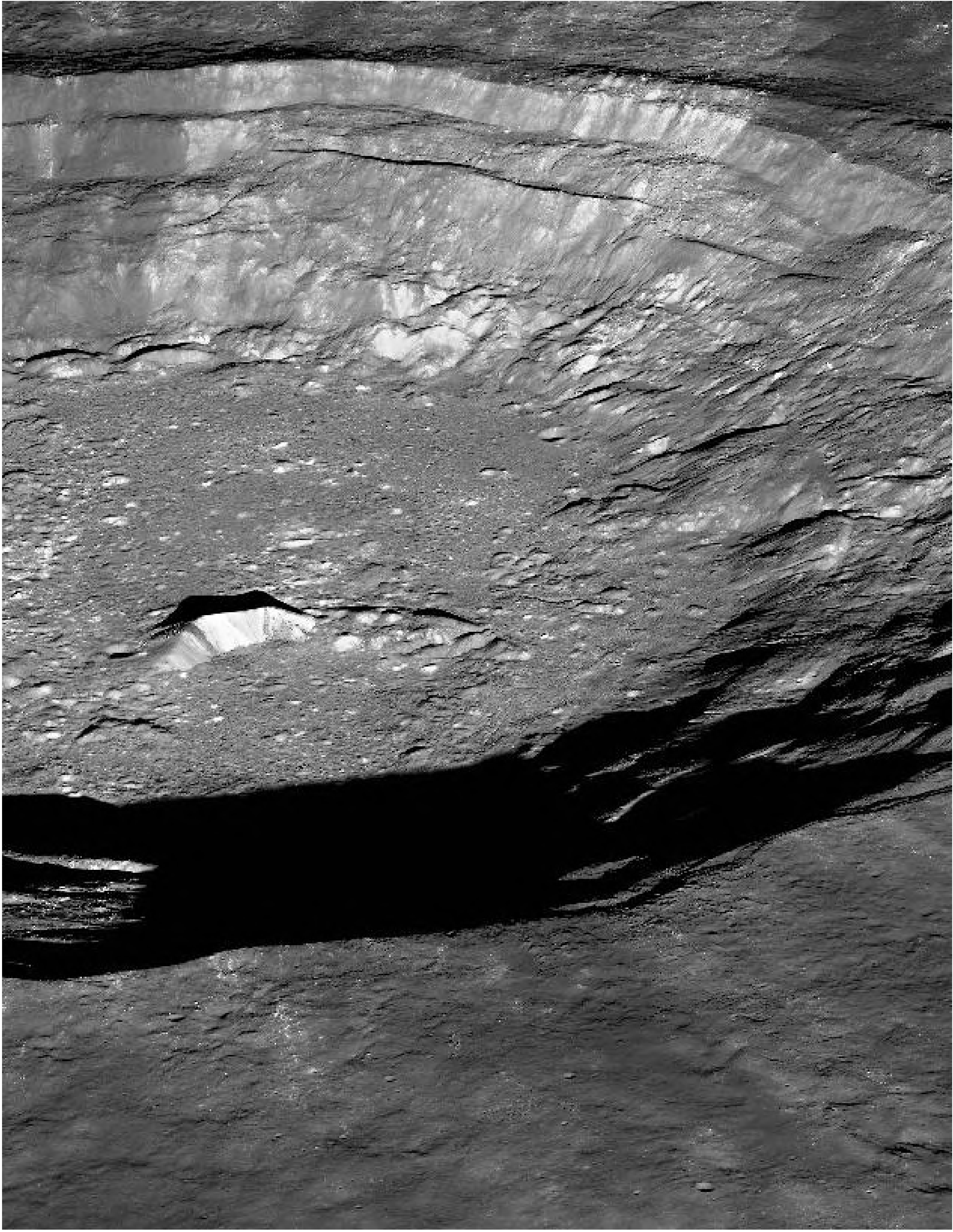
Goal 5d. Determine the flux of lunar volcanism and its evolution through space and time.

Major unknowns remain in terms of both the volume and timing of volcanic eruptions that limit our ability to understand the evolution of the flux of lunar volcanism through time. However, with currently available data, fluxes have been estimated (e.g., Needham and Kring 2017; Neal, 2017) on the basis of the surficial extent of volcanism and estimates of their absolute ages determined from crater size–frequency results (e.g., Hiesinger et al., 2011). Advances have been made in our understanding of the distribution of cryptomare deposits (cf. Whitten and Head, 2015), which represent some of the earliest basaltic volcanism on the Moon, however their volume and range of ages is also unknown, limiting our ability to constrain the volume and duration of pre-4 Ga volcanism. Better constraints on the ages of basaltic deposits (through sample return and radiometric dating, e.g., Goals 1b, 3b, 5b) and their volumes (as determined with, for example, local and global geophysical networks) are both required for true progress toward achieving this goal.

Concept 5: Summary of Progress Still Needed

With the broader understanding of the variability of lunar volcanic rocks, including cryptomare, emphasis should extend to the understanding the composition, eruption styles, and variability of lunar volcanism. The importance of endogenous volatiles entrained in lunar volcanic products was unappreciated at the time of the SCEM report. The composition and variability of these volatiles represent an important new area of research ripe for future exploration. Recommendations for implementation from the SCEM report included subsurface sounding, sample return (for the youngest and oldest basalts, benchmark basalts, and pyroclastic deposits), in situ elemental and mineralogical analyses with investigation of geologic context, and astronaut field work that could include core drilling, active subsurface sounding, and sampling of a complete sequence of basalt flows. As with Concept 3, the implementation of these recommendations is now more feasible than ever, given new remote sensing data that has shown locations and accessibility of high priority sample sites. For example, in situ geochemical analysis and age dating at Ina would yield a resolution to the current controversy regarding the origin of IMPs; targeted sample return from regions identified as the youngest mare basalts would yield information about the flux of volcanism through time, the mantle source, and the crater flux used to estimate ages across the Solar System; targeted sample return from

cryptomare sites would help constrain the nature, type, and mantle sources of the oldest mare deposits.



CONCEPT 6: THE MOON IS AN ACCESSIBLE LABORATORY FOR STUDYING THE IMPACT PROCESS ON PLANETARY SCALES

A wide variety of new datasets and model results are informing our understanding of the numerous variables that affect the impact cratering process and final crater morphology, as well as the way in which impact ejecta is distributed and results in vertical and lateral mixing. Gravitational acceleration data from GRAIL has provided unprecedented information on the structure of multi-ring basins, though consensus is lacking on a model for their formation that can explain all observations. New observations have provided conflicting results for the extent to which impact melts differentiate.

6a. Characterize the existence and extent of melt sheet differentiation.

Debate continues about the extent of melt sheet differentiation in large lunar basins, particularly those where the impact melt sheet is most clearly identified: the Orientale, Schrödinger, and SPA basins. Remote sensing observations of the Orientale melt sheet have been interpreted to suggest that upper ~2 km is homogeneous in its anorthositic norite composition, and heterogeneities seen at greater depths are inconsistent with compositions expected from melt sheet differentiation (Spudis et al., 2014). However, petrologic modeling suggests that differentiation would occur at Orientale (Vaughan et al., 2013), though the size of crystals within the melt may determine whether differentiation in fact occurs because convective processes in the melt sheet inhibit settling of small crystals (Cassanelli and Head, 2016). Within SPA, remote sensing observations suggest kilometers-thick layers with distinct compositions may be the products of melt-sheet differentiation (Uemoto et al., 2017), while the upper noritic composition can be explained by differentiation in petrologic models where the SPA impact event occurred before cumulate overturn (Hurwitz and Kring, 2013; Vaughan and Head, 2014). Ground truth data and sample analysis is needed to determine the extent of melt sheet differentiation at these basins, perhaps at locations where impact craters probe the subsurface (e.g., Maunder crater at Orientale).

6b. Determine the structure of multi-ring impact basins.

High-resolution lunar gravity data from GRAIL and topography data LOLA have provided critical new observations of the structure of multi-ring basins. Peak-ring basins are observed to have a characteristic central positive free-air gravity anomaly (mascon), surrounded by a negative annulus, and an outer positive annulus. The inner mascon is attributed to the impact process rather than any later infill by mare basalts. No clear consensus has been reached between two distinct models that have been proposed to explain these observations.

The simplest model for the formation of peak-ring basins infers a continuation of processes as craters get larger (Grieve et al., 1981). Whereas a central uplifted peak is characteristic of complex craters, in a dynamic collapse model (e.g., Collins et al., 2002; Ivanov, 2005) and displaced structural uplift model (Kring et al. 2016), an over-heightened central uplift, without sufficient strength to uphold uplift against gravity, collapses downward and flows outward to form a peak ring. That model is consistent with recent mapping of the Schrödinger peak-ring basin on the Moon (Kring et al. 2016) and with a >1.3 km deep borehole drilled into the Chicxulub peak-ring crater on Earth (Morgan et al. 2016; Kring et al. 2017).

An alternative model emerged from a study of the non-linear growth in impact melt volume as a function of increasing crater diameter (Cintala and Grieve 1994). The model, currently described as a nested melt cavity model (Head 2010; Baker et al. 2011, 2012, 2016), suggest the peak ring is uplifted not from the base of a transient crater, but from the walls of a transient crater. Thus, in this model, an uplifted peak ring has a fundamentally different origin than do central peaks.

Because the competing models can generate peak ring lithologies from different depths and that the rocks in them may be affected by different levels of shock, samples from peak rings can be used to test the models.

The largest basins may have other features: significant uplift of deeper (e.g., mantle), a thickened subsurface annulus of crustal material, and one or more additional rings can form beyond the traditional basin walls. Those features, in addition to relatively low-density impact breccias and relatively dense impact melt fill, generate gravity anomalies. Moreover, the consequences may be a function of the temperature of the Moon at the time of impact.

Those types of features and the processes that produced them are better understood now than they were in 2007, because they have been re-examined with LRO-LOLA, LRO-LROC, M3, and GRAIL data and with a series of computer models that have been evaluated in light of that data (e.g., Potter et al. 2012, 2012, 2013, 2013, 2015; Melosh et al. 2013; Miljkovic et al. 2013, 2016; Cheek et al. 2013; Nahm et al. 2013; Freed et al. 2014; Johnson et al. 2016; Zuber et al. 2016). Yet, consensus eludes the community and to confidently sort through the complicated processes involved, in situ measurements and surface samples are required. The two youngest basins, Orientale and Schrödinger, are prime targets for that type of exploration, because they have not been altered by later basin-forming events.

6c. Quantify the effects of planetary characteristics (composition, density, impact velocities) on crater formation and morphology.

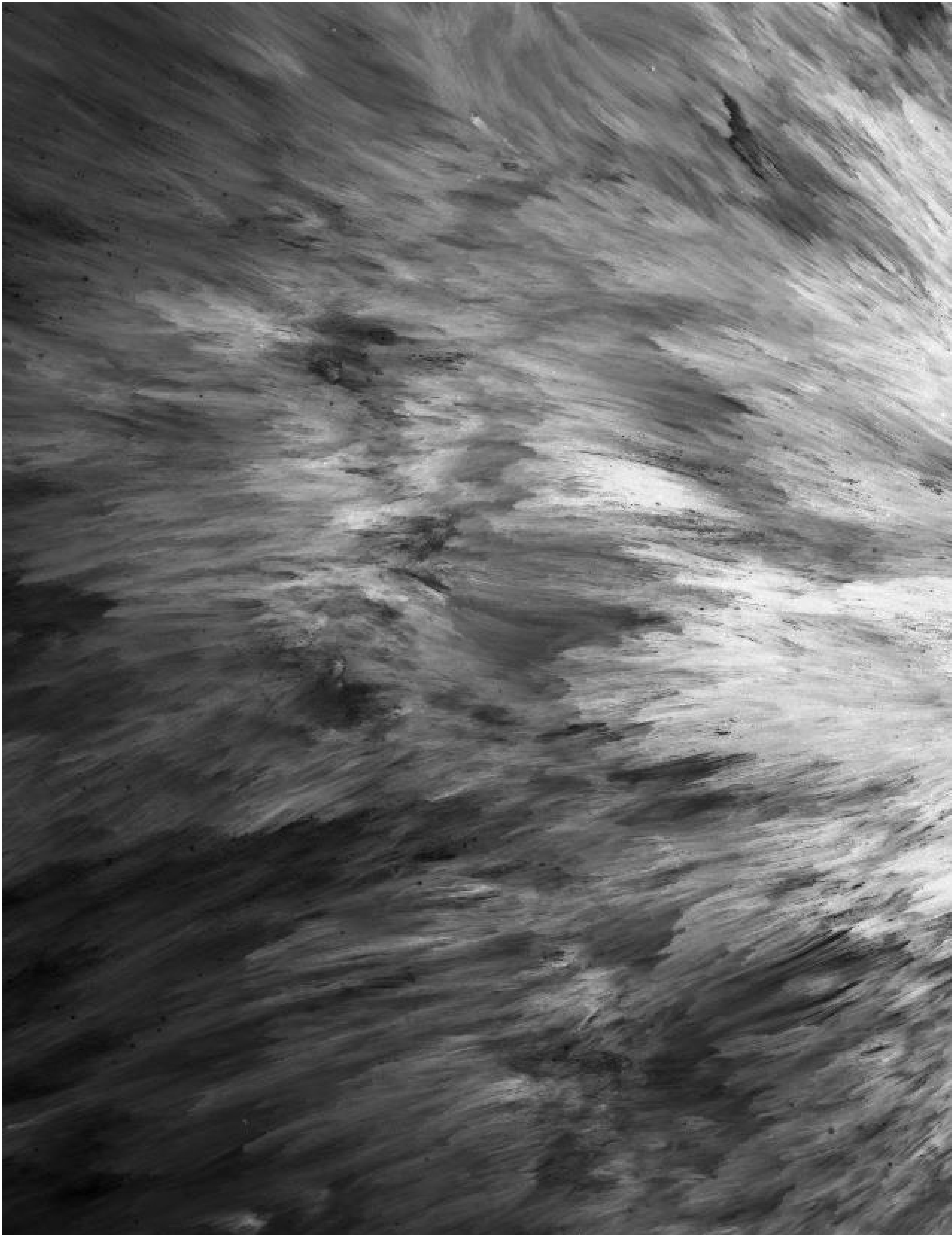
The lack of typical degradation processes, apart from impacts themselves, means that the Moon is the premier location for studying the crater formation process. Observations of craters that formed on the Moon within the last ten years have shown that ejecta from the formation of even small craters (tens of meters) affects the surface tens of kilometers away and provides evidence of jetting that occurs at high-velocities and ground-hugging trajectories (Robinson et al., 2015; Speyerer et al., 2016). These observations coupled with those of a population of craters seen as "cold spots" in Diviner nighttime data show that distal disturbances of the upper regolith occur and are preserved only short periods of time (tens of thousands of years) in comparison to the timescale of modification of other impact deposits (Bandfield et al., 2015; Williams et al., 2016). Further, pond-like deposits of impact melt discovered antipodal to Tycho crater indicate the impact process may be possible of transporting material across the globe (Robinson et al., 2016; Bandfield et al., 2017). New observations have also highlighted the effects of target properties on simple craters (e.g., van der Bogert et al., 2017); at a larger scale the discrepancy between the population of near- and far-side basins suggests that target temperature can affect basin diameter by up to a factor of two (Miljković et al., 2013). For the Imbrium basin, the non-radial distribution of its sculpture provides new evidence for the effects of impactor angle (Schultz and Crawford 2016).

6d. Measure the extent of lateral and vertical mixing of local and ejecta material.

New datasets have allowed for the detailed mapping and compositional analysis of ejected materials, while the development of three-dimensional models for regolith transport provides a means for interpreting these datasets. Detailed mapping of light plains has indicated that deposits up to four basin radii likely originated in the Orientale-forming impact, and that most of the material is locally derived (Meyer et al., 2016). Observations of the density and rate of formation of "splotches" of ejecta associated with craters formed during the LRO mission have shown that vertical mixing of the upper centimeters of regolith is dominated by the effects of distal ejecta emplacement (Speyerer et al., 2016). The importance of distal ejecta is also highlighted in the results from a new model of regolith transport that indicates crater rays are critical for distal transport of material and the resultant heterogeneity of surface materials (Huang et al., 2017).

Concept 6: Summary of Progress Still Needed.

To understand the extent of melt sheet differentiation, progress could be made with knowledge of chemical and mineralogical details of melts derived from various locations within a melt sheet. Additionally, work is needed to identify the large-scale melt deposits at older basins, which can be difficult to unambiguously discern due to their high degree of degradation. Regional seismic data would provide insight into multi-ring basin structure, and observations of the lithologies within peak rings can help assess their mode of formation, while particularly samples that could shed light on depth of origin. The details of ejecta and ray thickness and emplacement mechanisms can be aided by long-duration orbital observations that would enable the detection of newly formed impact craters larger than those seen to date; field studies would provide a critical advance.



CONCEPT 7: THE MOON IS A NATURAL LABORATORY FOR REGOLITH PROCESSES AND WEATHERING ON ANHYDROUS AIRLESS BODIES

Substantial progress has been made on understanding lunar regolith processes, and includes a new understanding of the physical properties of the regolith, the understanding of the rapid rate of regolith gardening, and a wide variety of laboratory and remote sensing studies of space weathering. However, key goals identified as part of this Concept, such as characterizing ancient regolith, knowledge of polar regolith properties and volatile deposition, an understanding of the role of the solar wind vs. micrometeoroid bombardment in the space weathering process, and identifying and characterizing rare materials in the lunar regolith, have not been met.

Goal 7a. Search for and characterize ancient regolith.

Ancient regolith has accumulated information about the history of solar activity, the composition of ancient impactors, and what material was being ejected from lunar petrologic provinces in the past. This information may have been preserved if the regolith was subsequently buried by lava flows. Newly discovered lunar pits in the maria provide potential new sites for future sampling of such paleoregolith (Haruyama et al. 2009; Wagner and Robinson 2014), and laboratory and theoretical studies have constrained the degree to which this regolith may have been affected by heat from the lava flows during their emplacement (Fagents et al. 2010; Crawford et al. 2010; Rumpf et al. 2013). However, no direct progress has been made on this goal with its aim to sample ancient regolith sequestered by lava flows due to lack of sample return missions.

Goal 7b. Determine physical properties of the regolith at diverse locations of expected human activity.

Some aspects of the regolith have now been characterized Moon-wide via orbital missions. Maps of the thermal inertia of the regolith (Hayne et al., 2017; Figure 7.1), abundance of cm-scale surface rocks, and information about the compaction of the upper several centimeters of regolith were derived from Diviner data (Bandfield et al., 2011), information about the regolith porosity and particle-size distribution has been interpreted from photometric and polarimetric studies (Sato et al., 2014; Jeong et al., 2015), block abundance at the >0.5 m-scale relevant for assessing landing hazards is available from LROC, and Mini-RF revealed regolith properties of the upper 1–2 m of the surface (Nozette et al., 2010) across much of the Moon. Whereas Mini-RF data have complete polar coverage, less is known about the physical properties of polar regolith properties from Diviner or LROC owing to the weak temperatures variations and poor illumination conditions, respectively. No new data regarding classical geotechnical properties are available.

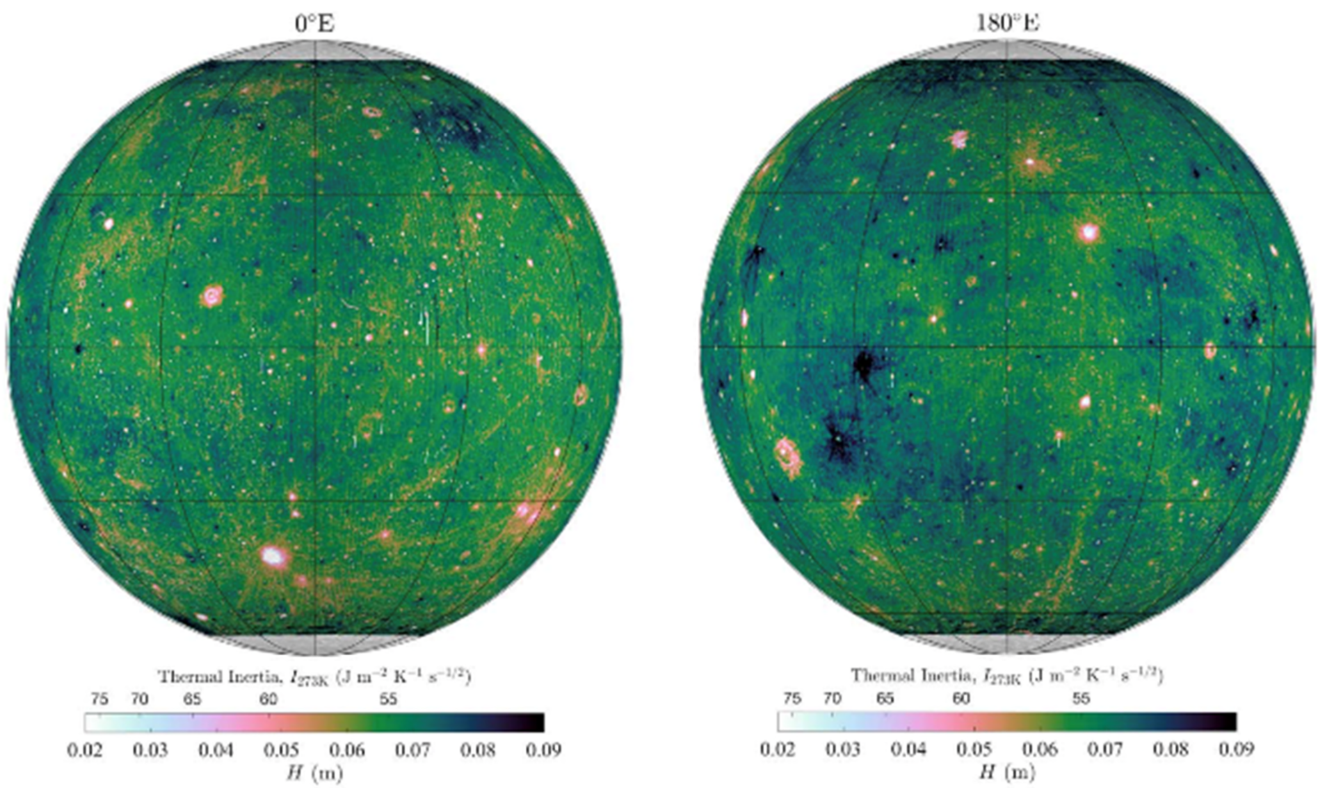


Figure 7.1 Thermal inertia of the Moon derived from Diviner data (Hayne et al. 2017).

Goal 7c. Understand regolith modification processes (including space weathering), particularly deposition of volatile materials.

Both laboratory and orbital data have shed significant light on how solar wind sputtering and micrometeorites produce the observed space weathering effects. Vapor deposits containing the spectral reddening agent nanophase iron, and have been interpreted as largely due to micrometeoroid bombardment rather than solar wind sputtering (Zhang and Keller, 2012). However, a variety of remote sensing data show that solar wind must play a role in space weathering. Lunar swirls show strong albedo and spectral effects associated with magnetic fields that drastically modulate the local solar wind flux (Kramer et al., 2011a,b; Denevi et al., 2014, 2016; Glotch et al., 2015; Hendrix et al., 2016). A gradient in albedo in the lunar maria with latitude also suggests solar wind is playing an important role in the accumulation of space weathering products (Hemingway et al. 2015; Lemelin et al. 2016). The detection of a longitudinal asymmetry in the albedo and spectral properties of east and west facing walls of a large sample of moderate and large craters can be explained by the bias of intensity of solar wind caused by the passage of the Moon through the Earth's magnetotail (Sim et al., 2017), and also suggests the solar wind is critically important in weathering. Nominally, the sample and remote results appear to be in conflict regarding the relative roles of solar wind and impact vaporization.

Modification of the polar regolith, including that in permanent shadow, is beginning to be revealed. LRO LAMP shows that regions of permanent shadow display low UV albedos, and this has been attributed to anomalously high porosity of the uppermost surface (Gladstone et al. 2012). Reflectance measurements derived from the LOLA laser altimeter and Diviner temperature have revealed an inverse correlation of surface reflectance and the maximum surface temperature (Fisher et al. 2017). This increase in albedo at high latitudes and in permanent shadow may be evidence of reduced weathering due to the lower solar wind flux in these regions, or a temperature dependence of the space weathering process (Lucey et al. 2014; Corley et al. 2016, 2017).

Extensive modification has been found around newly formed craters observed by LROC (Robinson et al. 2015; Speyerer et al. 2016) and some fresh craters observed by Diviner (Bandfield et al., 2014) extending to tens of crater radii or more (Figure 7.2). The thermophysical properties that indicate the regolith has been substantially decompressed to a depth of several centimeters, and the size and frequency distribution of newly modified surface suggest that modification of the uppermost regolith (regolith gardening) occurs on a timescale of ~70,000 years, more rapidly than previously thought.

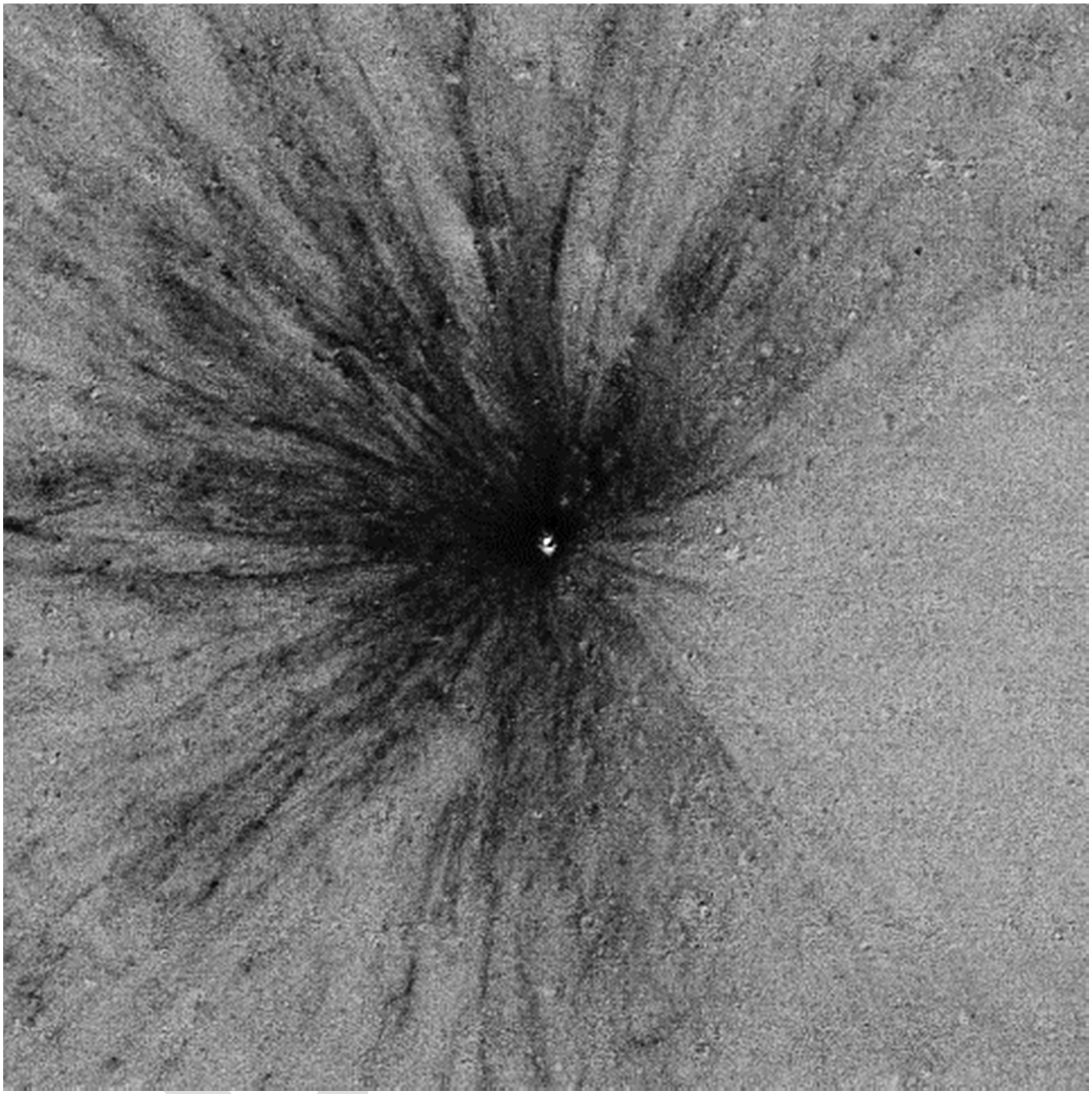


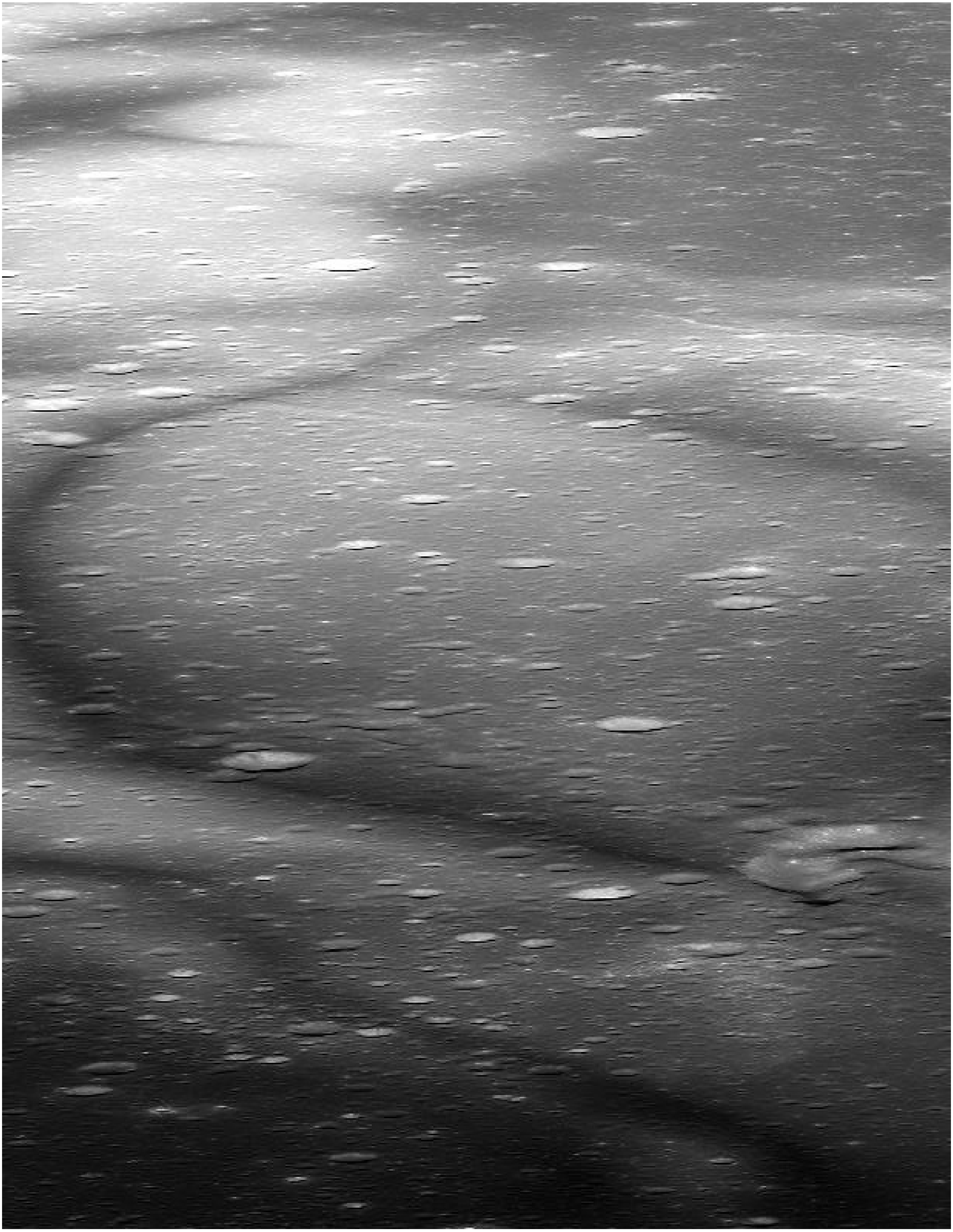
Figure 7.2. A new 12-m impact crater and its extensive rays that formed between October 2012 and April 2013, seen in an image acquired after the impact divided by an image taken before the crater formed (NAC images M1121160416R and M1105837846R) [NASA/GSFC/Arizona State University].

Goal 7d. Separate and study rare materials in the lunar regolith.

The identification of projectile fragments in lunar soils proves that the regolith preserves extra-lunar materials (Joy et al. 2012). While a body of theoretical studies continue to build regarding the probability of identifying a variety of extralunar materials, no comprehensive, systematic effort to search for such material has been reported.

Concept 7: Summary of Progress Still Needed.

Recommendations in the SCEM report included sounding to reveal the upper stratigraphy of the regolith, and regolith sample return from regions of diverse composition and age, of old regolith where it is stratigraphically preserved, and from paleoregoliths. These recommendations are still applicable toward progress in understanding the history of solar activity, the composition of ancient impactors, space weathering, and the search for ancient rare materials such as Earth meteorites that could be preserved in the regolith. The apparent dichotomy between remote sensing and sample studies as to the dominant space weathering agent could be resolved by targeted sample return from areas noted by remote sensing as those being dichotomous with the study of the existing sample collection.



CONCEPT 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

LADEE and a variety of other instruments and missions have provided a new understanding of the lunar atmosphere and dust environment, including a transformational new understanding of the lunar volatile cycle and conclusive measurements showing the absence of electrostatically levitated dust at altitudes above 5 km. These new results have attuned researchers to critical new questions such as the source(s) of mid-latitude surface hydroxyl and water and their relation to volatiles in PSRs.

Goal 8a. Determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further human activity.

Substantial progress has been made toward this goal as a result of the LADEE mission. LADEE NMS and UVS identified the primary atmospheric constituents, their density, and variability (Benna et al., 2015, Colaprete et al., 2016). LADEE UVS detected hydroxyl and regolith species enhancements during meteor streams (Colaprete et al., 2015), highlighting the variability that can be tied directly to micrometeoroid bombardment. The detection of some of the trace volatile species, like water and OH, is ambiguous under nominal conditions (Benna et al., 2015) and the data and its interpretation is still being examined. Follow-on missions may require specialized detectors for further progress regarding these species, both in orbit and distributed over the lunar surface.

Science Goal 8b. Determine the size, charge, and spatial distribution of electrostatically transported dust grains and assess their likely effects on lunar exploration and lunar-based astronomy.

The LADEE mission also contributed to our understanding of lunar dust: LADEE LDEX obtained a comprehensive data set of dust detections at altitudes >5 km (Horanyi et al., 2015). This set consists almost exclusively of particulates associated with impact ejecta, contrary to the expectation that electrostatically lofted dust would be an important contribution. While electrostatically transported dust was not detected at these altitudes, it likely occurs nearer to the surface in regions where there are strong surface charging and anomalously large E-fields, such as at the low-density plasma void that forms at and near obstacles in the terminator, in polar regions, and at magnetic anomalies. Progress is still needed to understand how dust is lofted in these regions, which will also be locations where any charging human system (rover, walking astronaut) will have longer charging dissipation times, possibly leading to an anomalously high charge state.

Science Goal 8c. Use the time-variable release rate of atmospheric species such as ^{40}Ar and radon to learn more about the inner workings of the lunar interior.

LADEE NMS measured a ~140-day baseline of ^{40}Argon, and reported the development of an Argon bulge over the western KREEP terrane, thought to be due to the surface enhancement in the ^{40}Ar parent product, ^{40}K (Benna et al., 2015; Hodges and Mahaffy, 2016). LADEE NMS also reported on the beginning large-scale variability in the ^{40}Ar baseline, which may be due to annual variations in shadowing and sequestering. However, a mission with a longer baseline would be required to investigate occurrences such as the release of ^{40}Ar and other internal species that could follow seismic events. Having such a mission in conjunction with a global lunar geophysical network would allow significant progress to be made in this area.

Science Goal 8d. Learn how water vapor and other volatiles are released from the lunar surface and migrate to the poles where they are adsorbed in polar cold traps.

Transformational progress has been made in this goal due to LADEE, the two ARTEMIS spacecraft, LRO LAMP, M^3, and new modeling tools. This progress has created both a greater understanding of the volatile cycle (including a water system and hydrogen cycle) but also creates more questions on the hydrogenation, hydroxylation, and hydration occurring on the lunar surface. Key observations include the reports of concentrations of hydroxyl in the mid-latitude surfaces as detected in the 2.8-micron absorption feature in the IR reflectance spectrum (Pieters et al., 2009; Sunshine et al., 2009; Clark, 2009; McCord, 2011; Li and Milliken, 2017) (Figure 8.1). This surface reflectance feature may even exhibit a diurnal effect (Sunshine et al., 2009; Li and Milliken, 2017), suggesting a dynamic surface hydroxylation, but more observational evidence is needed to confirm this possibility. Both solar wind and meteoritic infall have been considered as a source for this hydroxylation. LAMP UVS reflectance at 160–170 nm suggest surficial water content exhibits a diurnal effect (Hendrix et al., 2012). The LADEE NMS and UVS have detected exospheric water and OH enhancements during meteor showers, suggesting the external delivery of water/OH to the surface during such events. Consistent with this concept, LAMP also detected a surface frost with 1-2 wt% water residing on the floors of PSRs (Gladstone et al., 2012; Hayne et al., 2015). It was argued that this frost could be in dynamic equilibrium with competing environmental processes: local delivery of water via meteoritic infall and surficial losses including photon stimulated desorption via Lyman and prompt fractional loss via meteoritic vaporization. In 2007, the possibility of surface volatiles like water and OH forming at mid-latitudes and the poles was mostly speculative, but now in the LRO/LADEE era there exists solid observational evidence for their presence. However, important work remains to identify the sources of this mid-latitude hydroxyl and water, and to definitively determine if this component varies diurnally. Because LADEE was in an equatorial orbit, no progress has been made in terms of determining whether this (possibly) migrating component is transported to PSRs or whether this could be the source of the frost and deeper hydrogen layers observed within the PSRs (e.g., Goal 4b).

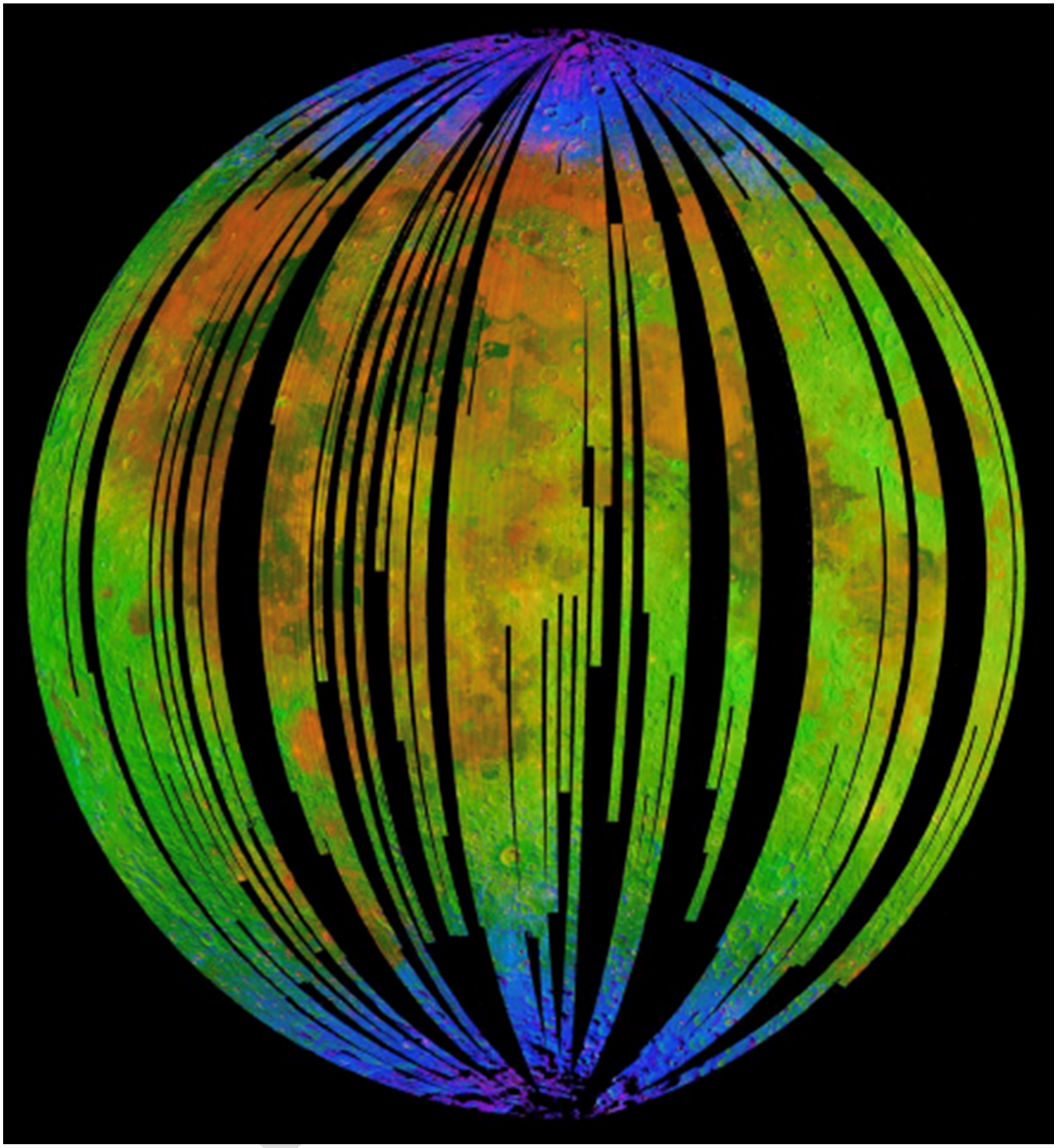


Figure 8.1. A color composite produced from M³ spectra where blue areas have a stronger 3-μm absorption related to the presence of OH/H_2O (Pieters et al., 2009).

Concept 8: Summary of Progress Still Needed.

The substantial progress made on Concept 8 has clarified areas where the most progress is still needed. These include: 1) identify the sources of the mid-latitude surface hydroxyl and water; 2) determine whether hydrogen products migrate poleward to the cold trap reservoirs in order to understand how the dynamic modern hydrogenation system connects to the deeper, possibly ancient, concentrations of hydrogen observed in the polar cold traps by neutron detection systems; 3) explore the near-surface electrostatic lofting of dust associated with plasma anomalies/voids in locations like polar craters, magnetic anomalies, and the night-side terminator; 4) systematically detect trace volatile species, like water, OH, and hydrocarbon in the exosphere; and 5) search for evidence of prompt release of ^{40}Ar and other internal species following seismic events. Future landed volatile-sensing stations could detect volatile transport from mid- to high-latitudes as a function of driving space environmental (solar storm, meteor stream) conditions, as well as near-surface dust lofting, with orbital assets serving to provide a global context.

NEW GOALS IN LUNAR EXPLORATION

In the decade since the 2007 NRC report was compiled, new data and analyses have resulted in both unexpected new concepts in lunar science as well as new ways of thinking about old problems. While this list is not comprehensive, we note several high-priority topics that were not included in the original report in 2007, or were scattered throughout such that their priority and importance for lunar science was not sufficiently emphasized given what we know now, 10+ years later.

The lunar volatile cycle

Polar volatiles were included in the SCEM report as part of Concept 4, the deposition of volatiles by the solar wind was mentioned in Goal 7c, and the migration of surficial water to cold traps was included in Goal 8d. However, work from the last decade has pointed to a lunar 'water' cycle with three principal components: primordial (interior) water, surficial water (linked to solar wind), and polar (sequestered) water. While lunar samples were once thought to have water concentrations of less than 1 ppb, new work, since the SCEM report was published, on the existing sample collection has demonstrated that primordial volatiles are present in the mantle source regions, which has implications for both the origin and evolution of the lunar mantle. Water has been found in samples of pyroclastic glasses (Saal et al., 2008; Hauri et al., 2011) and crystalline mare basalts (e.g., Boyce et al., 2010; McCubbin et al., 2011), and evidence in remote sensing data extends the detection of volatiles to unsampled lithologies such as KREEP-rich magmatic sources (Klima et al., 2013) and pyroclastic glasses (Milliken and Li, 2017). New evidence for the importance of surficial volatiles in lunar soils was found through observations of fundamental OH vibrations in the near-infrared (Clark et al., 2009; Pieters et al., 2009; Sunshine et al., 2009), with volatiles found at both low and high latitudes, and larger abundances in colder regions near the terminator that suggested there may be a diurnal volatile cycle. OH has also been directly measured in regolith samples, and linked to interaction with the solar wind (Liu et al., 2012). What relationship these primordial and surficial volatiles have to those that are cold-trapped as frost or ice in polar regions is currently unknown.

Identifying and characterizing the lunar volatile reservoirs and evaluating the interrelations of the primordial, surficial, and polar 'water' cycle is thus a high priority for lunar science.

Specific goals include: determine the composition and variability of endogenous volatiles entrained in lunar volcanic products; identify the sources of the mid-latitude surface hydroxyl and water, and determine how this component migrates; and determine the source(s) for lunar volatiles. While the latter two goals are included in Concepts 3, 5, 7, and 8, their importance and possible interconnection merits special mention here, specifically regarding the origin of the primordial (interior) water.

The origin of the Moon

One of the key motivations for studying the Moon is to better understand the origin and accretion of planets in the inner Solar System in general, and that of Earth in particular. The origin of the Moon is inextricably linked to that of Earth. The precise mode of formation affected the early thermal state of both bodies and, therefore, affected their subsequent geologic evolution. The leading hypothesis at present is that the Moon formed as the result of the impact of a Mars-sized object (Theia) with growing Earth (proto-Earth). However, the details of the process are still not clear, including the composition of Theia in comparison to the proto-Earth. These details can be further constrained by studies of lunar samples and improvements in numerical models. The Moon's internal geologic engine largely shut down long ago, and its deep interior is a vault containing a treasure-trove of information about its initial composition during and immediately after accretion. Through studies of lunar samples, the timing of the collision and the chemical signatures of lunar formation, the proto lunar disk, and perhaps Theia itself, can be investigated.

The origin of the Earth-Moon system and the geologic processes that operate during high-temperature planetary accretion are thus recorded within the lunar rock record and could be used to: constrain the timing of the collision between Theia and the proto Earth; establish the mechanisms, timing, and extent of volatile depletion in the Moon; establish isotopic similarities and differences between the Earth and Moon to constrain the composition of Theia; constrain the physicochemical conditions and processes that operated in the protolunar disk; and constrain the physicochemical conditions and processes that operated at the surface of the lunar magma ocean, and determine the composition and longevity of an early atmosphere (Saxena et al., 2017).

Lunar tectonism and seismicity

In the last decade, greatly expanded high-resolution image coverage of the lunar surface has led to explosive growth in the number of observations of tectonic landforms on the Moon (e.g., Watters et al., 2010, 2012; Banks et al., 2012; Williams et al., 2013). Many of these features, such as wrinkle ridges and rilles, are associated with mare basin formation and evolution. Lobate scarps, however, are found in both mare and non-mare regions and compared to other types of tectonic faults, surface-cutting thrust faults such as lobate scarps require the largest amount of stress to form and/or slip. These structures are thought to have formed in part as a response to compressional stress resulting from late-stage global cooling and contraction. In the absence of plate tectonics, the number and distribution of tectonic faults, as well as their level of seismicity, are important factors to consider when investigating planetary formation and evolution. The interior structure, thermal history, and mechanism(s) of heat loss of a planet are all related to the resulting distribution of surface tectonic features.

Lobate scarps on the Moon have additionally been found to have a non-uniform distribution. This implies that they cannot be entirely driven by late-stage global contraction, which would have caused isotropic stresses. Instead, they may be controlled by a combination of contractional stress, tidal stress, and orbital recession stress (Watters et al., 2015). Because these drivers persist to the present day, it may be possible that lobate scarps are still active (and some have been found to be younger than 50 My; Watters et al. 2012). Current studies are attempting to determine whether lobate scarps could reasonably provide an explanation for the existence of shallow moonquakes (or high-frequency teleseismic events), the largest (but rarest) class of naturally occurring seismic signals. If a positive link can be identified, this would have important implications for both future scientific and human exploration of the Moon: regions with active scarps would be targeted for seismic analyses, but avoided for landed assets such as outposts.

SCIENCE FROM THE MOON

While the focus of ASM-SAT was on what advances have been made, and still need to be made, in lunar science, lunar exploration will indisputably advance other science as well. It has long been evident that establishing infrastructure on the surface of the Moon - broadly speaking, human-tended outposts on the lunar surface and all of the associated infrastructure required to support that outpost, particularly cargo delivery systems, robotics, and human EVA capabilities - would provide immense value to all scientific disciplines and establish a platform from which many types of scientific investigations could be undertaken.

During the Space Exploration Initiative, many studies and proposals were made for activities that could be undertaken at a lunar base, including fundamental research in materials science, astronomy, and biomedicine, among others (e.g., Burns, 1988). In 2005, building upon the conceptual work done during SEI in the context of Vision for Space Exploration, LEAG performed an exhaustive evaluation of the kinds of scientific investigations that could be performed at a lunar surface outpost, all of which remains valid today (Taylor et al., 2005). This was followed in 2007 by the NASA Advisory Council workshop to determine the science that would be enabled by robust surface infrastructure (NASA Advisory Council, 2007). In the context of the Vision, the 2007 NRC report also assessed opportunities for science beyond planetary science, including heliophysics, astronomy and astrophysics, astrobiology, and earth observation and remote sensing:

> *Finding 5: The Moon may provide a unique location for observation and study of Earth, near-Earth space, and the universe. The Moon is a platform that can potentially be used to make observations of Earth (Earth science) and to collect data for heliophysics, astrophysics, and astrobiology. Locations on the Moon provide both advantages and disadvantages. There are substantial uncertainties in the benefits and the costs of using the Moon as an observation platform as compared with alternate locations in space. The present committee did not have the required span and depth of expertise to perform a thorough evaluation of the many issues that need examination. A thorough study is required.*
>
> *Recommendation 5: The committee recommends that NASA consult scientific experts to evaluate the suitability of the Moon as an observational site for studies of Earth,*

heliophysics, astronomy, astrophysics, and astrobiology. Such a study should refer to prior NRC decadal surveys and their established priorities.

Since the publication of the 2007 NRC report, some of additional studies responsive to this recommendation have been carried out.

- The publication of the LEAG Roadmap in 2012 (https://www.lpi.usra.edu/leag/roadmap/) involved experts from the Earth Observing, Heliophysics, Astrophysics, and fundamental Physics communities over the 4 years the initial draft took to be formulated.
- The 2010 NRC Astrophysics Decadal Survey (NRC 2010) identified the question of "When and how did the first galaxies form out of cold clumps of hydrogen gas and start to shine - when was our cosmic dawn?" as a community priority.
- The 2013 NASA Astrophysics Division Roadmap identified a role for lunar orbital missions and radio telescopes emplaced on the lunar surface to address this question through mapping using the 21-cm radio wavelengths, and concept studies regarding missions to make these measurements (e.g. Lazio et al, 2010) have been carried out. Missions of this type are viable candidates for inclusion in future lunar surface activities.

What is Needed: ASM-SAT echoes the 2007 NRC report in stating that establishing the capabilities and infrastructure to explore the lunar surface, particularly establishing regular and repeated access to the surface, could enable advances across a broad array of scientific disciplines. As the capability to reach the surface is re-established, opportunities for scientific investigations using the Moon as a platform should be fully evaluated for implementation using the LEAG Roadmap as a basis.

CONCLUSIONS

While progress has been made in addressing many of the main concepts in the 2007 Scientific Context for the Exploration of the Moon report, none of these goals can be considered to be "complete".

Concept 1: The bombardment history of the inner Solar System is uniquely revealed on the Moon. Achieving the science goals of this concept related to the bombardment history requires a combination of modeling of the composition of basin impact melt, petrology and geochemistry of samples to tie them to specific basins, and detailed geochronology of multiple samples, ideally with multiple geochronologic systems. Such studies could be accomplished by landing and in situ dating and/or sample return to Earth.

Concept 2: The structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated planetary body. Meaningful progress in expanding our knowledge of planetary differentiation can be made by the emplacement of equipment such as a simultaneous, globally distributed seismic and heat flow network and/or an expanded retroreflector network, and strategic collection of samples from terrains of different ages that can provide constraints on lunar geochemistry and new information on the history of the lunar dynamo.

Concept 3: Key planetary processes are manifested in the diversity of lunar crustal rocks. Recommendations for advancing our understanding of differentiation processes and the Moon's complex crust include obtaining compositional information at higher spatial resolutions, the return of samples from high-priority targets, in situ elemental and mineralogical analyses as well as regional seismic networks to determine vertical structure, and geologic fieldwork by astronauts. Data returned from recent orbital missions have allowed for the identification of many high-priority target sites for further exploration that would further our understanding of the lunar crust.

Concept 4: The lunar poles are special environments that may bear witness to the volatile flux over the latter part of Solar System history. . The last decade has provided substantial new information about the lunar poles, though the achieving the goals related to this concept, such as understanding volatile source(s), detailed compositions, and the ancient solar environment, will require in the implementation of recommendations from the SCEM report, such as in situ analyses and the return of cryogenically preserved samples.

Concept 5: Lunar volcanism provides a window into the thermal and compositional evolution of the Moon. Critical advances in understanding planetary volcanism would come from subsurface sounding, sample return (for the youngest and oldest basalts, benchmark basalts, and pyroclastic deposits), in situ elemental and mineralogical analyses with investigation of geologic context, and astronaut field work that could include core drilling, active subsurface sounding, and sampling of a complete sequence of basalt flows. The implementation of these recommendations is now more feasible than ever, given new remote sensing data that has shown locations and accessibility of high priority sample sites.

Concept 6: The Moon is an accessible laboratory for studying the impact process on planetary scales. Fundamental questions remain in our goal to understand this fundamental planetary process. These could be addressed by: detailed studies to identify large-scale melt deposits at older basins, the establishment of regional seismic networks at multi-ringed basins to provide insight into basin structure, field studies and sample return of melt sheets and peak rings to shed light on their mode of formation and depth of origin, and long-duration orbital observations to detect newly formed impact craters larger than those seen to date.

Concept 7: The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies. The recommendations in the SCEM report for understanding the development and evolution of the surfaces of planetary bodies are still valid today, and include sounding to reveal the upper stratigraphy of the regolith, and regolith sample return from regions of diverse composition and age, of old regolith where it is stratigraphically preserved, and from paleoregoliths. The apparent conflict between remote sensing and sample studies as to the dominant space weathering agent could be resolved by in situ analyses and targeted sample return from areas such as lunar swirls.

Concept 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. The substantial progress made on Concept 8 has clarified areas where the most progress is still needed. These include: identify the sources of the mid-latitude surface hydroxyl and water; determine whether hydrogen products migrate poleward to the cold trap reservoirs; explore the near-surface electrostatic lofting of dust associated with plasma anomalies/voids in locations like polar craters, magnetic anomalies, and the night-side terminator; systematically detect trace volatile species (e.g., water, OH, hydrocarbon) in the exosphere; and search for evidence of prompt release of ^{40}Ar and other internal species following seismic events.

New Concepts: The ASM-SAT deliberations also highlighted three important new concepts that must be considered as we move into a new phase of lunar exploration. These are:

- The Lunar Volatile Cycle
- The Origin of the Moon
- Lunar Tectonism and Seismicity

Science from the Moon: Establishing a robust lunar surface access capability for a variety of payload types will enable advances across a wide variety of scientific disciplines. As one example, radio telescope observations emplaced on the lunar far side by robots and/or human explorers offer great potential for new discoveries. As the United States re-establishes a credible capability, observations enabled by a presence on the lunar surface should be evaluated for implementation using the LEAG Roadmap as a basis.

Enabling Surface Access: The wealth of orbital data gathered since the SCEM (2007) report allows important landing sites to be identified for in situ analysis and sample return robotic missions. Inclusion of humans to the lunar surface who could conduct detailed fieldwork would allow tremendous progress to be made in many of the concepts described above. The capability for the United States to access the surface needs to be re-established.

An Exciting Future for Lunar Exploration

Despite the progress made in the last decade, there remain profoundly important and compelling science questions that require new missions to the surface of the Moon to be addressed. But that is the nature of exploration – the more we explore, the more questions we have to answer. A decade after it was produced, the objectives and goals of the 2007 NRC Report on the Scientific Context for the Exploration of the Moon, which established that exploring the Moon would enable quantum leaps in our understanding of fundamental Solar System processes, remain wholly relevant today. The outcome of the ASM-SAT deliberations demonstrated that the 2007 NRC report is still the benchmark describing the scientific importance and rationale for exploring the Moon in the 21st century, but also highlighted exciting new questions for further investigation. **Addressing all of these questions will require a robust lunar exploration program that takes**

advantages of new technologies and commercial paradigms to produce a regular cadence of landed missions – and profound new discoveries.

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APPENDIX I: ASM-SAT TERMS OF REFERENCE

The Lunar Exploration Analysis Group (LEAG) has been tasked by the Planetary Science Division (PSD) of NASA's Science Mission Directorate (SMD) to conduct a review of progress made to address the major lunar science priorities described in the 2007 National Academies report "The Scientific Context for the Exploration of the Moon," commonly referred to as the SCEM Report. These priorities are a comprehensive, well-validated, and prioritized set of scientific research concepts for a program of exploration of the Moon.

This Specific Action Team will produce the Advances in Science of the Moon Specific Action Team (ASM-SAT) report that will evaluate progress on each of the eight scientific concepts and goals previously articulated in the SCEM Report. This assessment will consider recent data from US and international missions, as well as modeling and sample analysis, which have become available since 2007. The ASM-SAT report will also consider concepts related to science implementation, as well as secondary science opportunities, outlined in the original SCEM Report. Finally, ASM-SAT will also note any new lunar science concepts that have become apparent since 2007.

The ASM-SAT will be led by Co-Chairs with broad experience in astromaterials, lunar science, NASA strategic planning, lunar mission flight operations, and astronautics. The ASM-SAT itself will be comprised of lunar scientists with expertise in at least one of the eight original concepts outlined in the SCEM Report and some which participated in the formulation of the SCEM report. At least one face-to-face meeting at the Lunar and Planetary Institute will be held over the summer of 2017.

APPENDIX II: ASM-SAT MEMBERSHIP

SAMUEL LAWRENCE, NASA Lyndon B. Johnson Space Center, *Co-Chair*
BRETT DENEVI, Johns Hopkins University Applied Physics Lab, *Co-Chair*
JACK BURNS, University of Colorado
BARBARA COHEN, NASA Goddard Space Flight Center
AMY FAGAN, Western Carolina University
WILLIAM FARRELL, NASA Goddard Space Flight Center
LISA GADDIS, United States Geological Survey
JOSEPH HAMILTON, NASA Lyndon B. Johnson Space Center
KRISTEN JOHN, NASA Lyndon B. Johnson Space Center
GEORGIANA KRAMER, Lunar and Planetary Institute
DAVID KRING, Lunar and Planetary Institute
DAVID LAWRENCE, Johns Hopkins University Applied Physics Lab
PAUL LUCEY, University of Hawaii
FRANCIS McCUBBIN, NASA Lyndon B. Johnson Space Center
CLIVE NEAL, University of Notre Dame
LILLIAN OSTRACH, United States Geological Survey
NOAH PETRO, NASA Goddard Space Flight Center
CARLE PIETERS, Brown University
MARK ROBINSON, Arizona State University
CHARLES SHEARER, University of New Mexico
G. JEFFREY TAYLOR, University of Hawaii
RENEE WEBER, NASA George C. Marshall Space Flight Center
D. BENJAMIN J. BUSSEY, NASA Headquarters, *ex officio*
SARAH NOBLE, NASA Headquarters, *ex officio*

ABOUT THE LUNAR EXPLORATION ANALYSIS GROUP

The Lunar Exploration Analysis Group (LEAG) was established in 2004 to support NASA in providing analysis of scientific, commercial, technical, and operational issues to further lunar exploration objectives. LEAG was jointly established by the Science Mission Directorate (SMD) and the Human Exploration and Operations Mission Directorate (HEOMD) and blends members of both communities, building bridges between science, exploration, and commerce whenever and however possible. LEAG is led by a Chair and a Vice-Chair who serve as the principal representatives of the United States lunar exploration community to stakeholders, including NASA and the international community. LEAG has a standing Commercial Advisory Board (CAB) to offer programmatic insights into the capabilities provided by industry. LEAG is a community-based, volunteer-driven, interdisciplinary forum. Membership is open to all members of the lunar exploration community and consists of lunar and planetary scientists, life scientists, engineers, technologists, human system specialists, mission designers, managers, policymakers, and other aerospace professionals from government, academia, and the commercial sector.

ABOUT THE LEAG LUNAR EXPLORATION ROADMAP

The LEAG Lunar Exploration Roadmap (LER) is the cohesive strategic plan for using the Moon and its resources to enable the exploration of all other destinations within the Solar System by leveraging affordable investments in lunar infrastructure. The LER is a living document developed over four years through a comprehensive community-based process and was released in 2012. The roadmap lays out a sustainable plan for Solar System exploration that allows NASA to use its lunar surface infrastructure to explore small bodies, Mars, and beyond. Following the LER will enable commercial development, through early identification of commercial opportunities that will create wealth and jobs to offset the initial investment of the taxpayer. The roadmap will also, with careful planning, enable international cooperation to expand our scientific and economic spheres of influence while enabling an expansion of human and robotic space exploration. The Roadmap is located at: https://www.lpi.usra.edu/leag/roadmap/ and the implementation plan is located at: https://www.lpi.usra.edu/leag/reports/RoboticAnalysisLetter.pdf

ON THE BACK COVER: A vast amount of molten rock splashed over the Tycho crater rim and flowed tens of kilometers before creating this "frozen falls" of rock on the Moon - a prime target for future astronaut exploration! [NASA/GSFC/Arizona State University].


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