LUNAR EXPLORATION IN THE 21ST CENTURY

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Presentation to KARI, 26 April 2022

WHAT I HOPE YOU LEARN TODAY

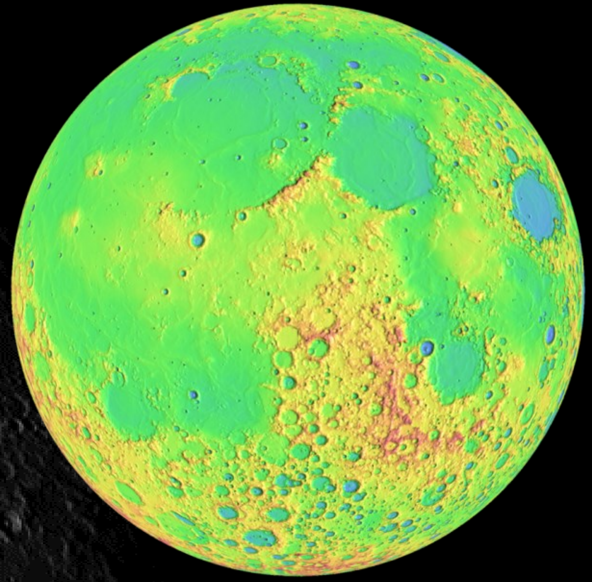
- The Value of the Moon
- US Planetary Community Overview
- The Past: Foundational Documents for Lunar Exploration
  - Previous major studies
  - NRC Scientific Context for the Exploration of the Moon Report
  - LEAG United States Lunar Exploration Roadmap
  - LEAG Advancing Science of the Moon Report
  - LEAG/SSERVI Lunar Science for Landed Missions Workshop Report
- The Future: Artemis III Science Definition Team Report

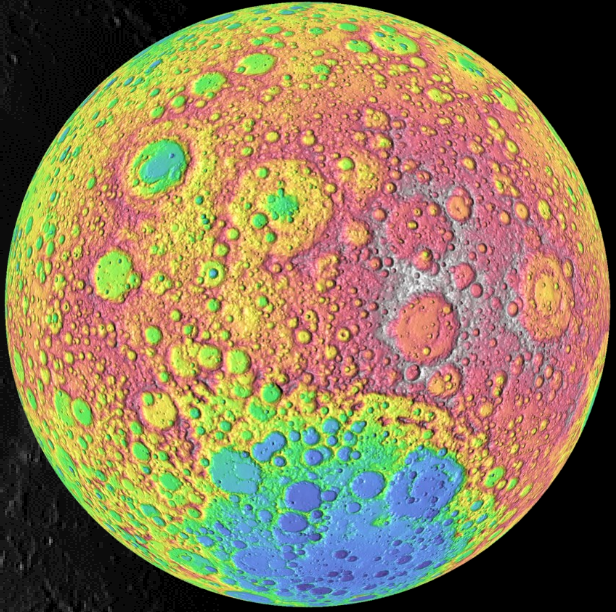
WHAT WE LEARNED FROM APOLLO

- The Moon is a rocky planetary object, differentiated into a crust, a mantle, and core
  - "Smallest terrestrial planet"
- The Moon has a heavily cratered surface
  - ***Only remaining record of first billion years of Earth history***
- The Moon was partially flooded by voluminous lava flows over 3 billion years ago
- Since that point, dominant lunar surface processes is impacts, which churned up the surface into a chaotic upper layer of debris (regolith)
  - Regolith is easily accessed and processed, for scientific investigation and resource utilization

A LUNAR RENAISSANCE

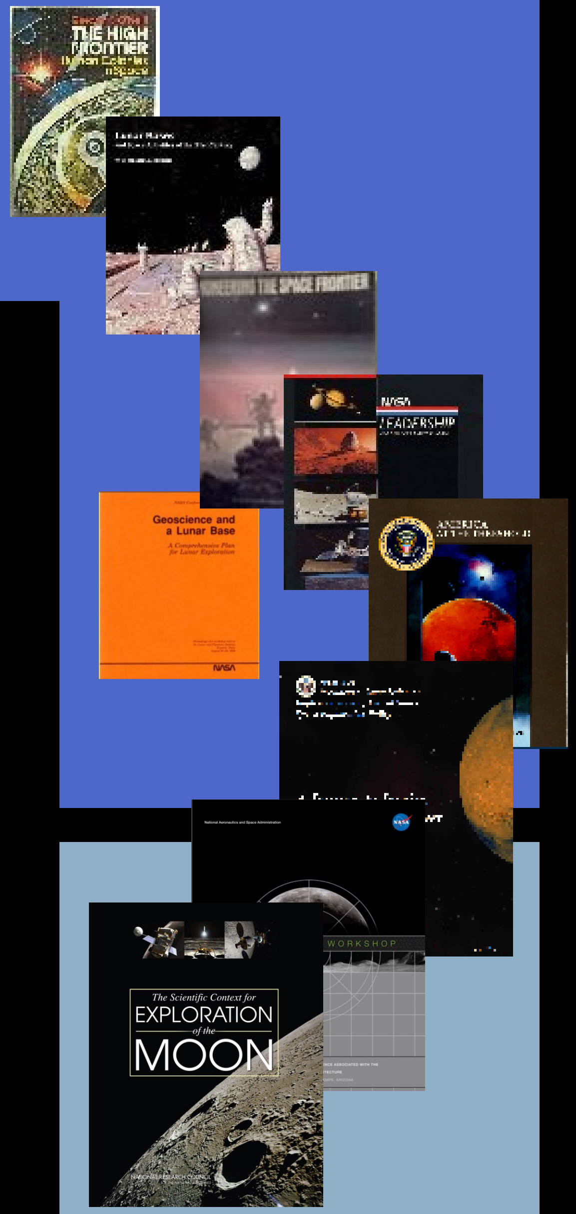
- USA: Clementine (1994)
  - First global multispectral map
- USA: Lunar Prospector (1998)
  - H2O at the lunar poles
- ESA: Smart-1 [2003]
- Japan: Kaguya [2007]
- China: Chang`e-1 [2007]
- India: Chandrayaan-1 [2008]
- USA: LCROSS [2009]
  - Direct observation of H2O at the lunar poles
- USA: Lunar Reconnaissance Orbiter [2009]
  - Ongoing – Largest dataset returned by United States
- China: Chang’e-2 [2010]
  - Ongoing
- LADEE (2013)
- China: Chang’e-3 [2013]
- China: Chang’e-4 [2018]
- Israel/SpaceIL: Beresheet [2019]
- India: Chandryaan-2/Vikram/Pragyan [2019]
- China: Chang’e-5 [2020]





PERSPECTIVE: A CONSISTENT STORY

We have a consistent story over five decades of reports, amplified by results from 21st Century lunar missions, that conclusively demonstrates the importance of lunar exploration



1986

Report on the National Commission on Space (Paine Commission

- "As revisits to the Moon become more frequent, the need will certainly grow for larger permanent "base camps," to serve as supply centers, local research laboratories, and medical centers for explorers taken ill or injured."

1988

Leadership and America's Future in Space (Ride Report

- "The Moon's unique environment provides the opportunity for significant scientific advances; the prospect for gains in lunar and planetary science is abundantly clear. Additionally, since the Moon is seismically stable and has no atmosphere, and since its far side is shielded from the radio noise from Earth, it is a very attractive spot for experiments and observations in astrophysics, gravity wave physics, and neutrino physics, to name a few. It is also an excellent location for materials science and life science research because of its low gravitational field (one-sixth of Earth's)."

1991

America at the Threshold (Stafford Report)

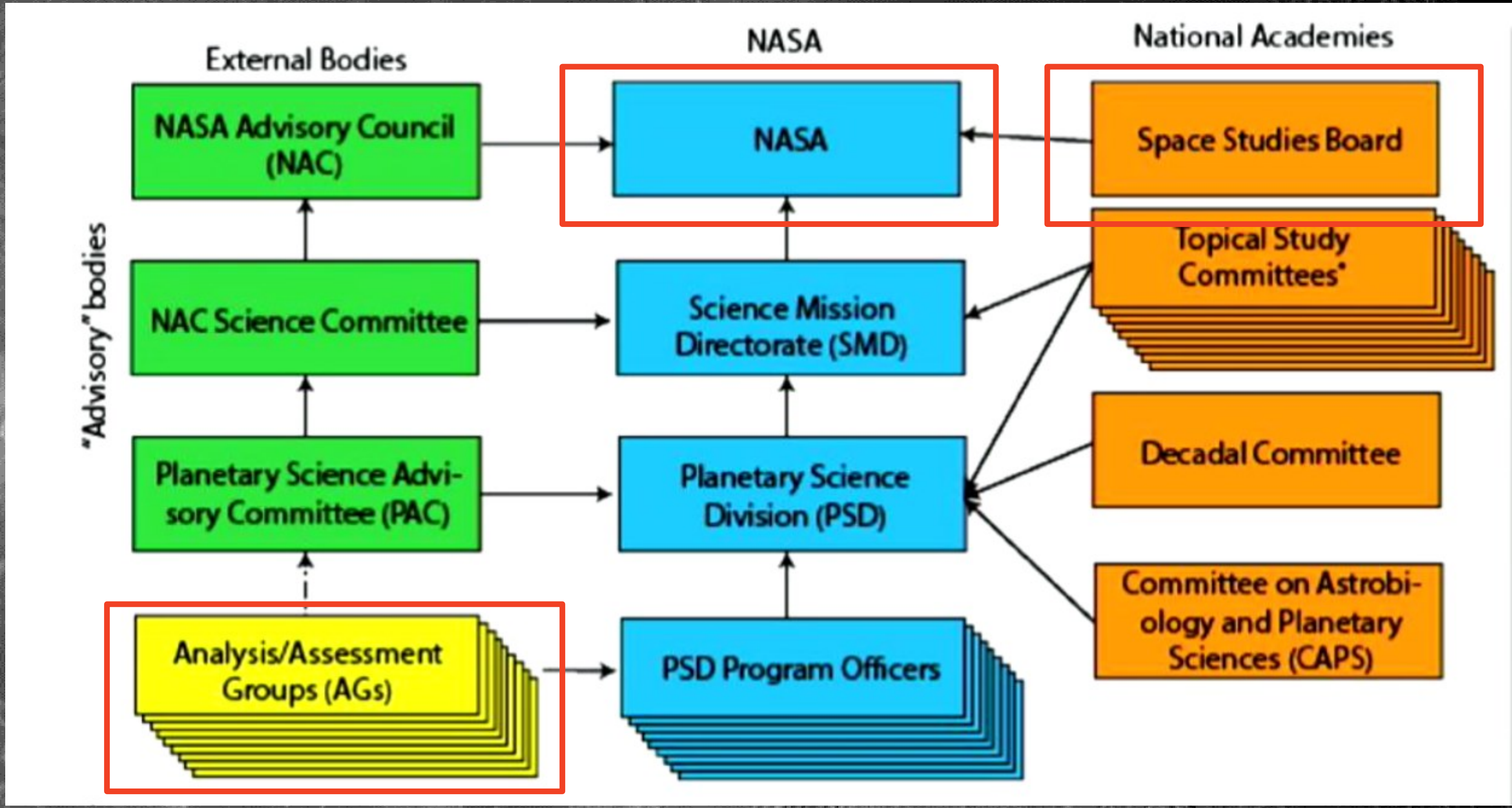
- "Earth's closest neighbor in space, the Moon, is an object for detailed exploration, a platform from which to observe and study the universe, a place to live and work in the environment of space, and a natural source of materials and energy for an emerging space-based economy".

2004

Vision for Space Exploration

- Extend human presence across the solar system, starting with a human return to the Moon
- Develop the innovative technologies, knowledge, and infrastructures
- Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests".

THE US PLANETARY SCIENCE COMMUNITY



US LUNAR EXPLORATION ANALYSIS GROUP

LEAG
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 in support of lunar exploration objectives, as well as their implications for lunar architecture planning and activity prioritization.

LEAG is chartered by the Science Mission Directorate (SMD). LEAG is responsive to the needs of ESDMD, SOMD, and STMD and blends members of all communities, building bridges and synergies between science, exploration, and commerce whenever and however possible. The LEAG Chair is selected by the Executive Committee and confirmed by Headquarters.

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.

LEAG: LEADING THE COMMUNITY

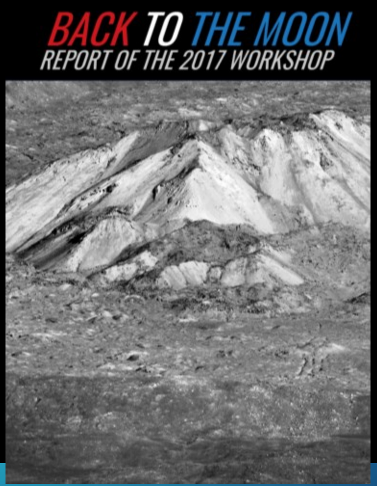
- Annual LEAG Meeting
  - SSERVI Sponsors the LEAG Bernard Ray Hawke Next Lunar Generation Awards to positively encourage early-career networking and participation, and the Larry A. Taylor Awards to support undergraduates
  - Annual meetings tend to have 200+ attendees
- LEAG Chair and Vice-Chairs represent lunar exploration community to stakeholders as needed
  - E.g., Lawrence LEAG presentation at the Vision 2050 meeting: “The Opened Gateway: Lunar Exploration in 2050”
- LEAG Hosts Town Halls at key community meetings
- Headquarters or field centers can request that LEAG form Special Action Teams to study topics of interest, if resources are provided

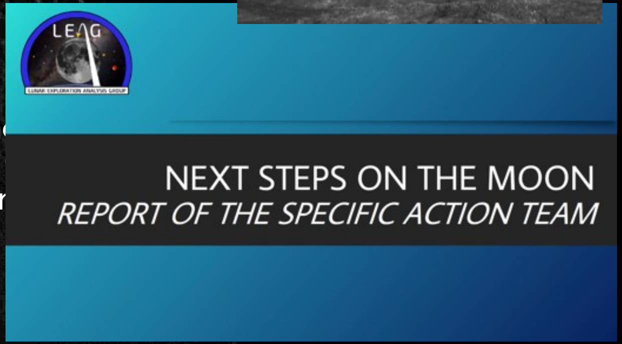
LEAG 2016

Vision 2050

LEAG SPECIAL ACTION TEAMS SINCE 2010

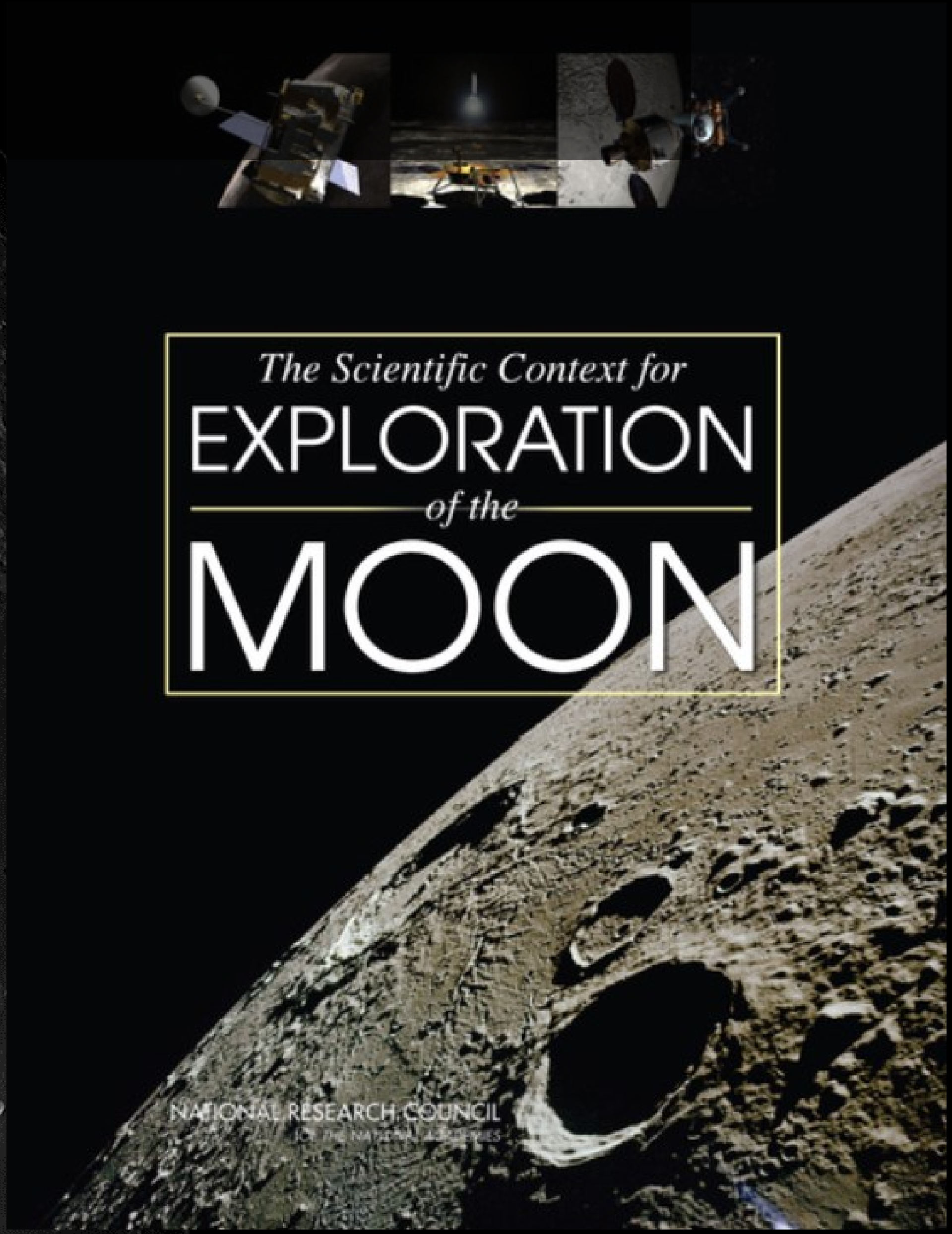
- January 2022: Lunar Critical Data Products [A. Stickle and J. Stopar]
- July 2020: COSPAR Rapid Response Special Action Team [S. Lawrence, B. Cohen, B. Denevi]
- Feb. 2018: Advancing Science of the Moon Special Action Team (Requestor: SMD) [B. Denevi and S. Lawren
- July 2017: ISECG International Polar Mission Coordination VSAT2 (Requestor: HEOMD/ISCEG) [D. Hurley ar
- August 2016: Strategic Knowledge Gaps for the “Moon First” Human Exploration Scenario V2
- September 2015: European Response to the Volatile Specific Action Team Report
- January 2015: Volatiles Special Action Team
- March 2014: LEAG Resource Prospector Mission Special Action Team
- September 2012: Mapping the SKGs to the Lunar Exploration Roadmap
- March 2012: Strategic Knowledge Gaps for the “Moon First” Human Exploration Scenario
- March 2012: Science Value of a Cislunar Hab Research Facility Special Action Team
- June 2011: LEAG Robotic Campaign
- June 2011: LEAG Response to the Decadal Survey





2007 SCIENTIFIC CONTEXT FOR THE EXPLORATION OF THE MOON REPORT

- National Research Council study performed at the request of the SMD Associate Administrator
- Provide guidance on the science enabled by the newly established Vision for Space Exploration
- "NASA needs a comprehensive, well-validated, and prioritized set of scientific research objectives for a program of exploration of the Moon"

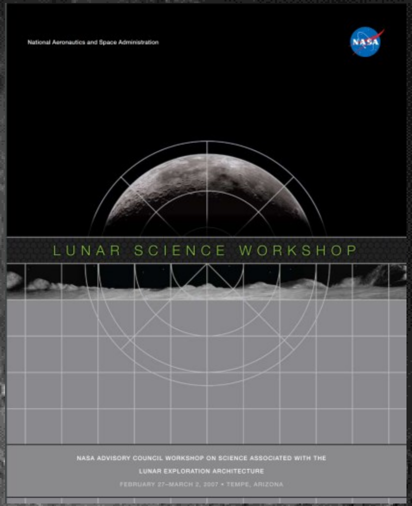


SCIENTIFIC PRIORITIES FROM THE 2007 NRC REPORT

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

LEAG UNITED STATES LUNAR EXPLORATION ROADMAP

- Developed at the request of the NASA Advisory Council (NAC) beginning in 2009
  - Builds on NAC Tempe Workshop and TOP-SAT
- First published in complete form in 2012, updated frequently
- Incorporates inputs from over 200 individuals
- Put simply, represents what the US lunar community wants to do on the Moon



LEAG UNITED STATES LUNAR EXPLORATION ROADMAP HTTP://WWW.LPI.USRA.EDU/LEAG/ROADMAP

Why should we go to the Moon?

Science (Sci) Theme: Pursue scientific activities to address fundamental questions about the solar system, the universe, and our place in them

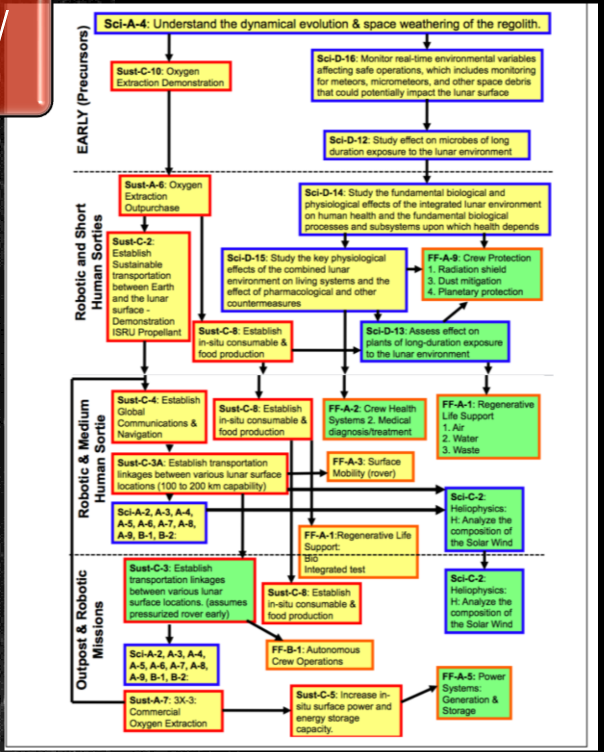
Feed Forward (FF) Theme: Use the Moon to Prepare for Future Missions to Mars and Other Destinations

Sustainability (Sust) Theme: Extend Sustained Human Presence to the Moon to Enable Eventual Settlement

LEAG UNITED STATES LUNAR EXPLORATION ROADMAP

THEMES → **GOALS** → **OBJECTIVES** → **INVESTIGATIONS/ INITIATIVES**

3 Themes: Science (Sci), Feed Forward (FF), Sustainability (Sust)



Example - Feed Forward to Mars:

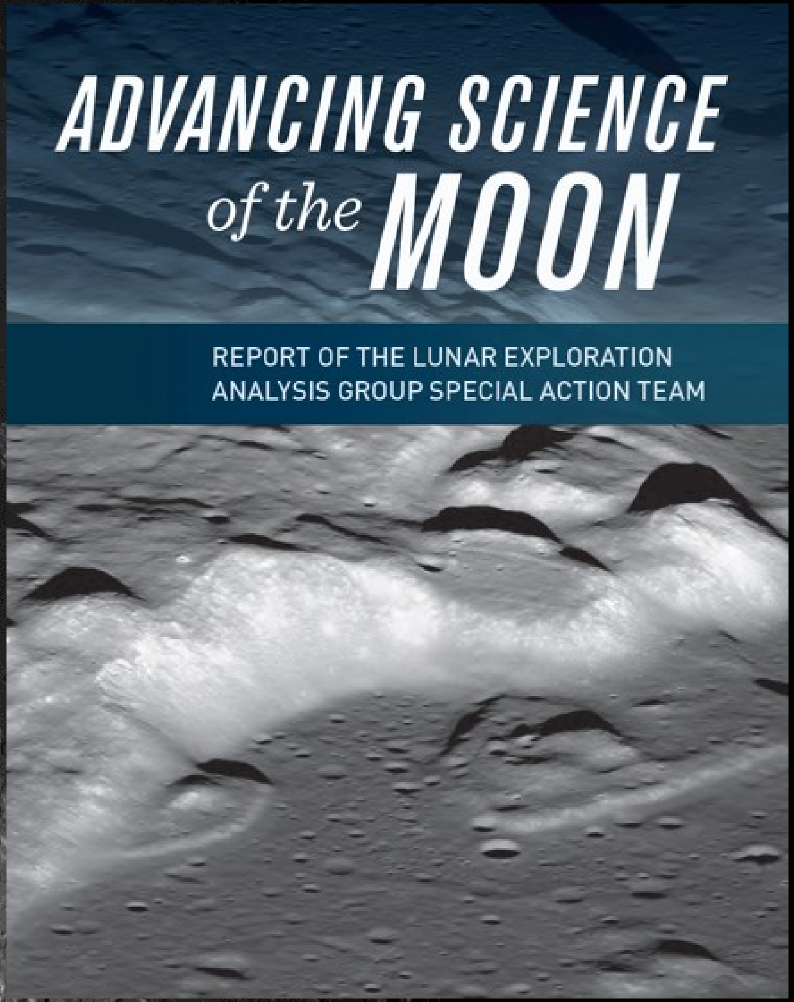
Goal FF-A: Identify and test technologies on the Moon to enable robotic and human solar system science and exploration. 9 Objectives, 31 Investigations of different priorities: 8 High, 10 Medium, 13 Low.

Goal FF-B: Use the Moon as a test-bed for missions operations and exploration techniques to reduce the risks and increase the productivity of future missions to Mars and beyond. 3 Objectives, 13 Investigations of different priorities: 2 High, 2 Medium, 9 Low.

http://www.lpi.usra.edu/leag/roadmap

2018: LEAG ADVANCING SCIENCE OF THE MOON REPORT

- ASM-SAT requested by Planetary Science Division
  - Evaluate progress on lunar science goals since the 2007 NRC Report
  - Consider concepts related to science implementation, and secondary science opportunities, outlined in the original SCEM report
  - Note any new lunar science concepts evident since 2007
- Each section ends with progress needed
- No effort to reprioritize



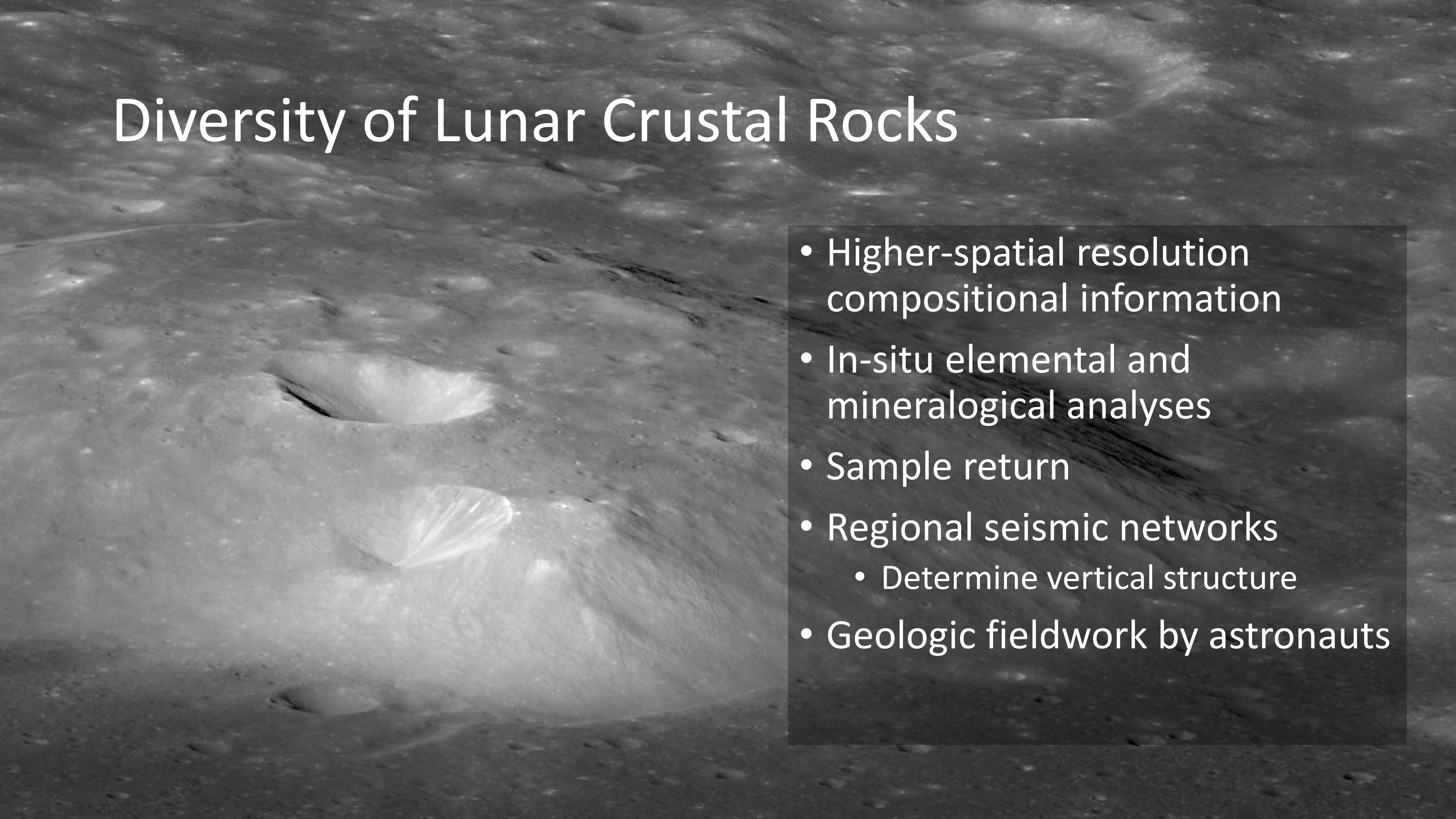
Lunar Bombardment History

- Requires surface exploration to fully address
  - In-situ investigations
  - Sample Return from exposed impact melt sheets
    - Geochronology of multiple samples with multiple isotopic systems
- Continuing and new orbital observations to increase temporal resolution

Structure and Composition of the Lunar Interior

- Emplacement of a simultaneous, globally distributed seismic and heat flow network and/or an expanded retroreflector network
- Strategic sample collection from terrains of different geologic ages
  - Constrain geochemical evolution

Diversity of Lunar Crustal Rocks



- Higher-spatial resolution compositional information
- In-situ elemental and mineralogical analyses
- Sample return
- Regional seismic networks
  - Determine vertical structure
- Geologic fieldwork by astronauts

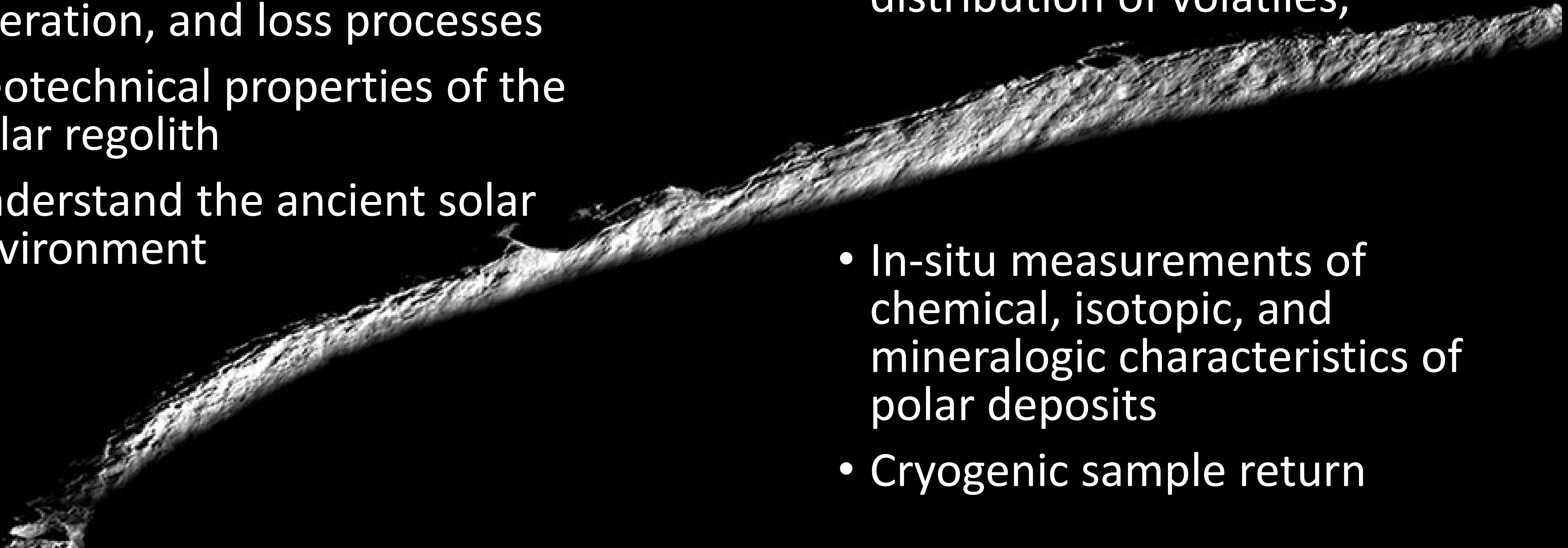
EXPLORING THE POLAR REGIONS

- Grazing sun angles cause some areas to be permanently shaded while nearby regions remain persistently illuminated
- Lighting conditions change very often and very rapidly
- Polar cold traps harbor volatiles, possibly including water ice
- Prime destination for lunar activity

The Lunar Poles are Special Environments

- Obtain detailed elemental, mineralogical, and isotopic compositions of lunar volatiles
- Determine volatile sources
- Determine transport, retention, alteration, and loss processes
- Geotechnical properties of the polar regolith
- Understand the ancient solar environment

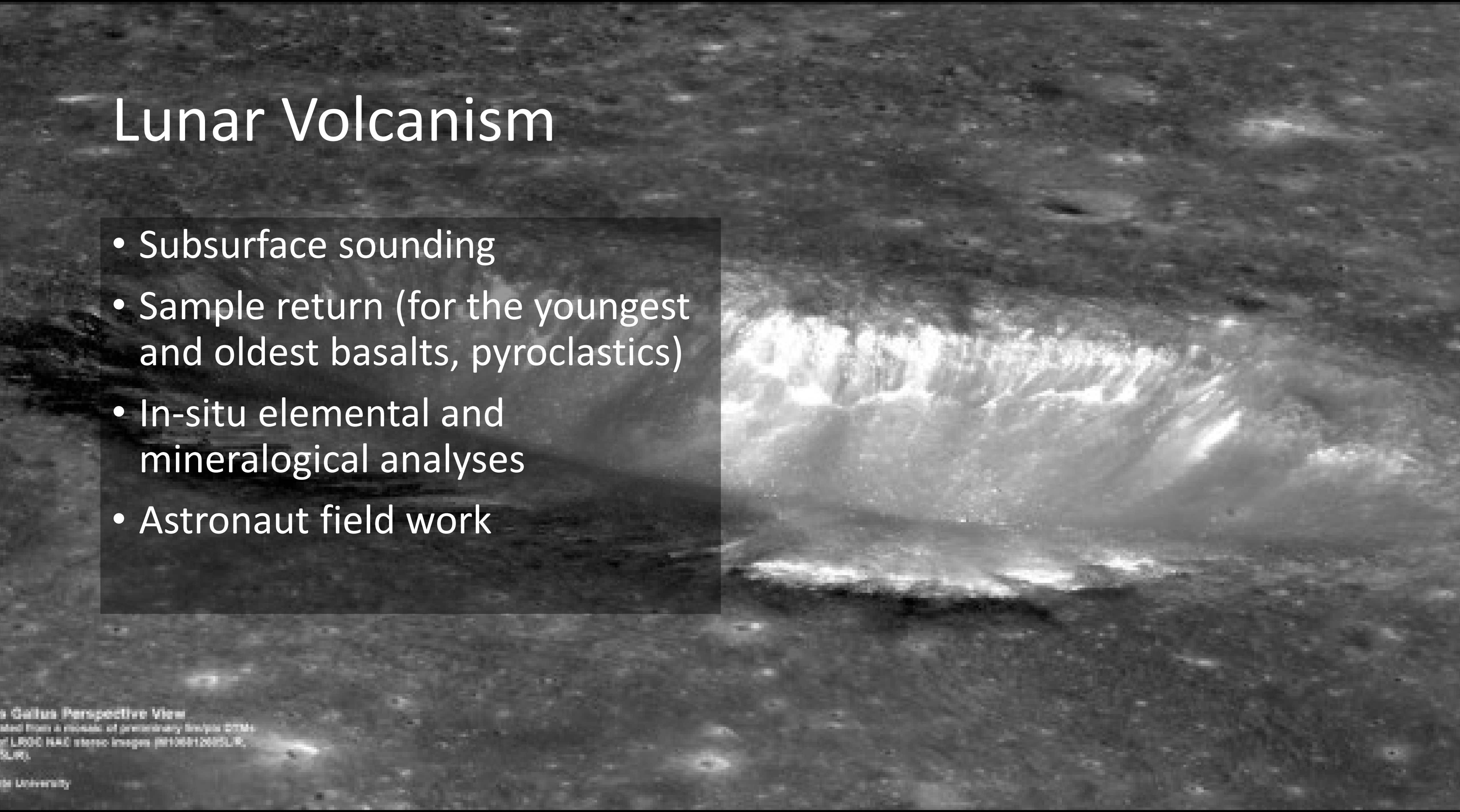
- High-spatial resolution orbital measurements
- Landed missions to understand the physical properties of the regolith, vertical and lateral distribution of volatiles,

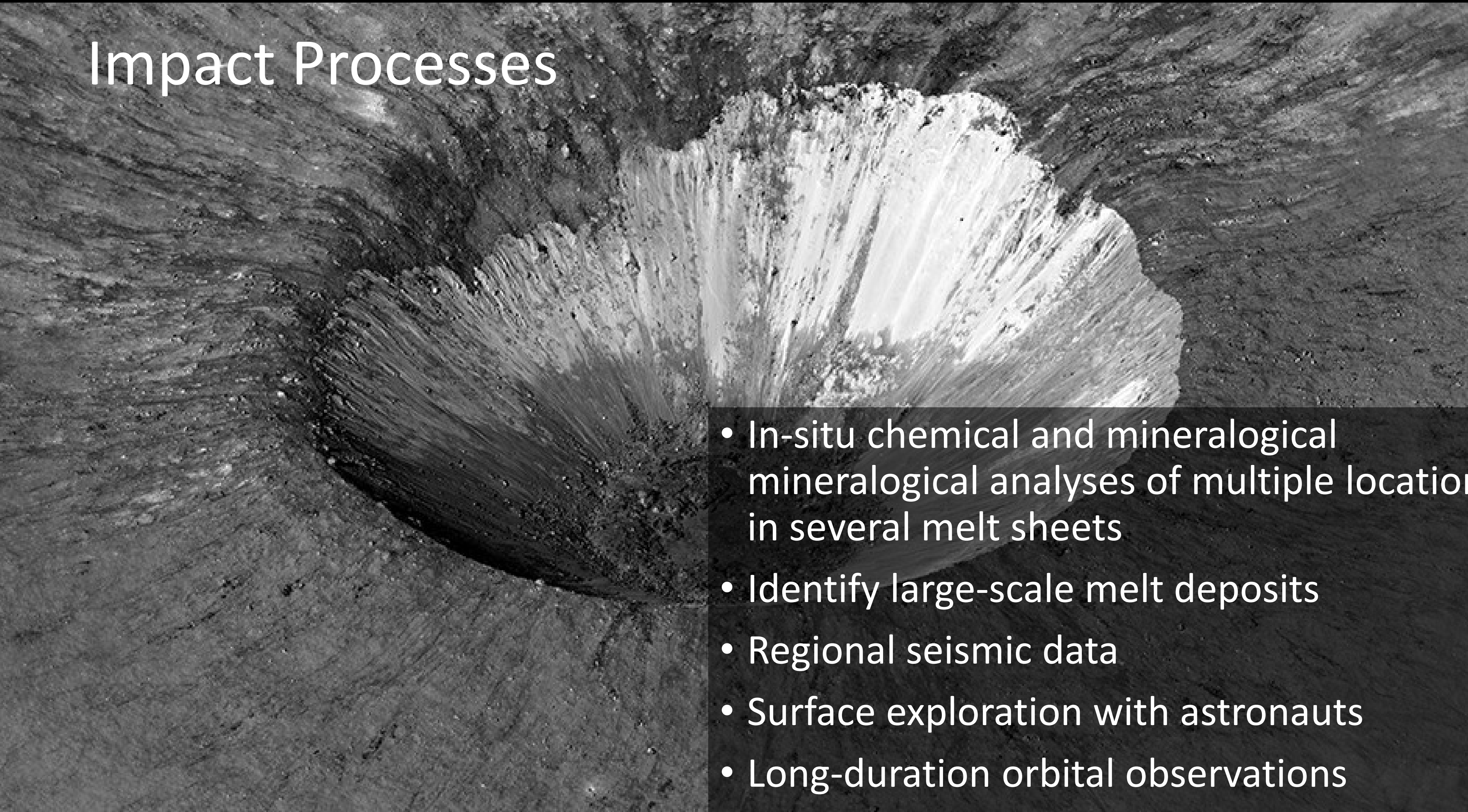


- In-situ measurements of chemical, isotopic, and mineralogic characteristics of polar deposits
- Cryogenic sample return

Lunar Volcanism

- Subsurface sounding
- Sample return (for the youngest and oldest basalts, pyroclastics)
- In-situ elemental and mineralogical analyses
- Astronaut field work





Impact Processes

- In-situ chemical and mineralogical mineralogical analyses of multiple locatio in several melt sheets
- Identify large-scale melt deposits
- Regional seismic data
- Surface exploration with astronauts
- Long-duration orbital observations

Regolith Processes

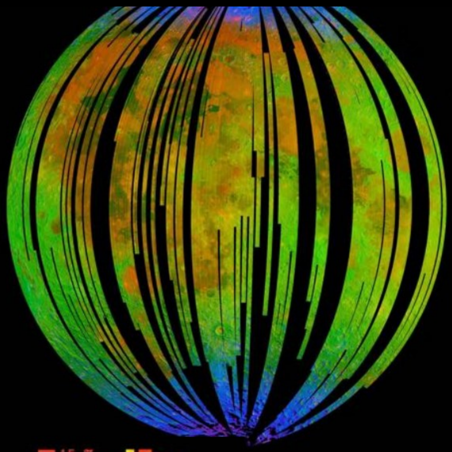
- Sounding to reveal upper stratigraphy of the regolith
- Regolith sample return from regions of diverse composition and age

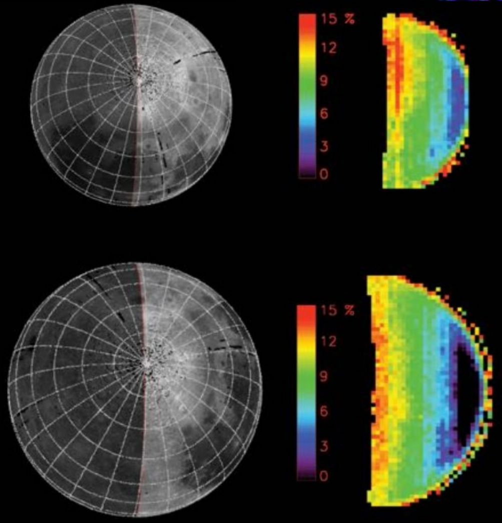
Lunar Exosphere

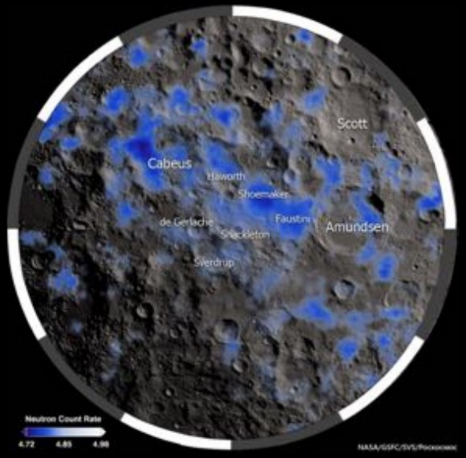
- Understand the sources of mid-latitude surface hydroxyl
- Determine whether hydrogen products migrate poleward
- Ascertain near-surface electrostatic lofting
- Detect trace volatile species in the exosphere
- Search for evidence of noble gas release following seismic events
- Long-lived volatile sensing stations on the surface and in orbit

The lunar ‘water’ cycle

- Volatiles scattered across four Concepts of SCEM report
- Work from the last decade points to cycle with three components:
  - Primordial (interior) water
  - Surficial water (linked to solar wind)
  - Polar water (sequestered)
- Identify and characterize these lunar volatile reservoirs and evaluate their interrelations
  - Composition and variability of endogenous volatiles entrained in volcanic products
  - Sources of mid-latitude surface hydroxyl and water, determine how it migrates
  - Determine source(s) of polar volatiles

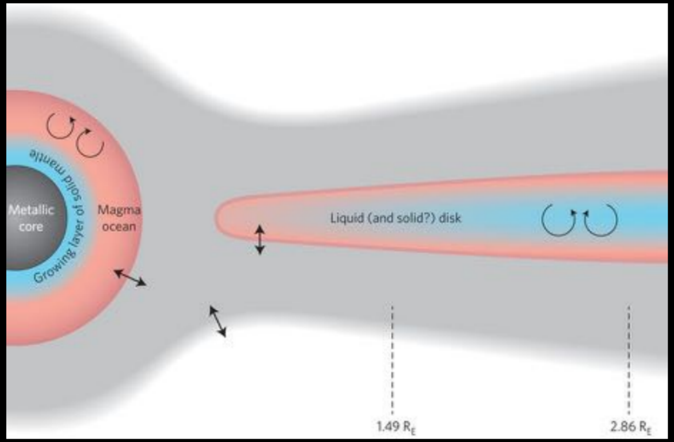






The origin of the Moon

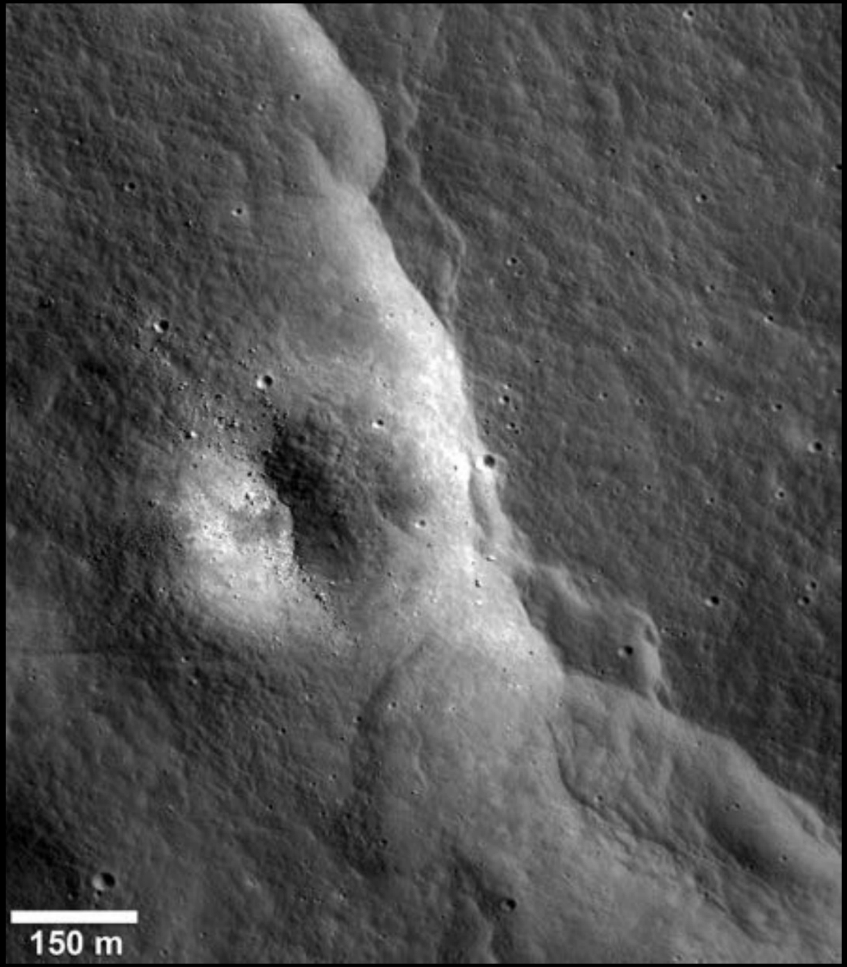
- A key goal of studying the Moon: better understand the origin and accretion of planets
- Moon's deep interior is a vault containing critical information about its initial composition during and immediately after accretion
- Specific goals:
  - timing of the collision
  - mechanisms, timing, extent of volatile depletion in the Moon
  - composition of the impactor
  - conditions and processes in the protolunar disk
  - conditions and processes at the surface of the lunar magma ocean, composition and longevity of an early atmosphere



Elkins-Tanton, 2013

Lunar tectonism and seismicity

- Greatly expanded high-res imaging led to discovery of abundance of lobate scarps
- Without plate tectonics: number, distribution, level of seismicity of lobate scarps, provide information on Moon's interior structure, thermal history, and mechanism(s) of heat loss
- In addition to global contraction, may be due to stresses from tides and recession – active today
  - Lobate scarps explain shallow moonquakes?
  - If so, regions with active scarps would be targeted for seismic analyses, but avoided for landed assets such as outposts



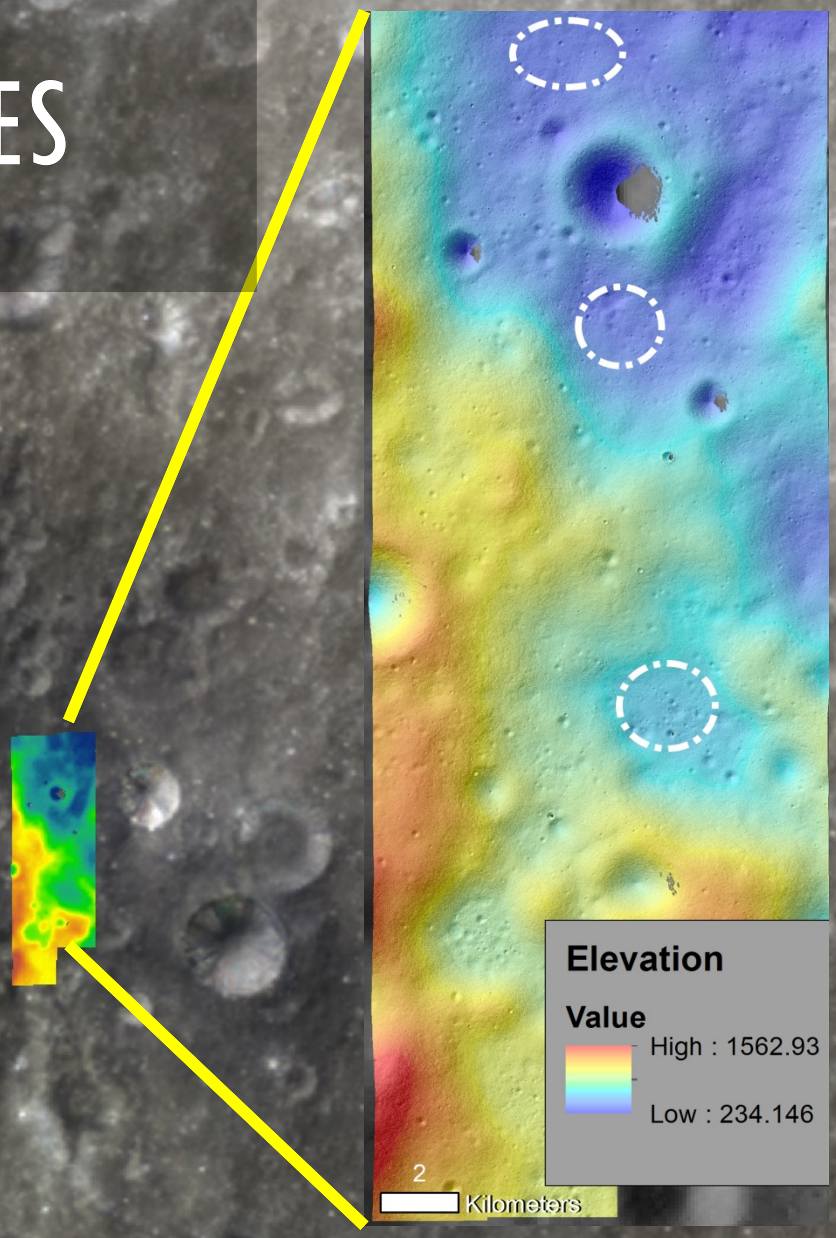
ASM-SAT Outcomes

- Concepts and goals outlined in the SCEM report remain relevant after a decade of progress in lunar science
- All goals had at least some progress, none were “done
- New concepts have emerged
- Landed missions are <u>required!</u>
- <u>Lots learned, lots to do</u>

- New concepts from ASM-SAT
  - Understand the lunar water cycle
  - Understand the origin of the Moon
  - Understand lunar tectonism and seismicity
- Science from the Moon has enormous potential
  - Astrophysics, heliophysics

HOW DO WE SELECT LANDING SITES

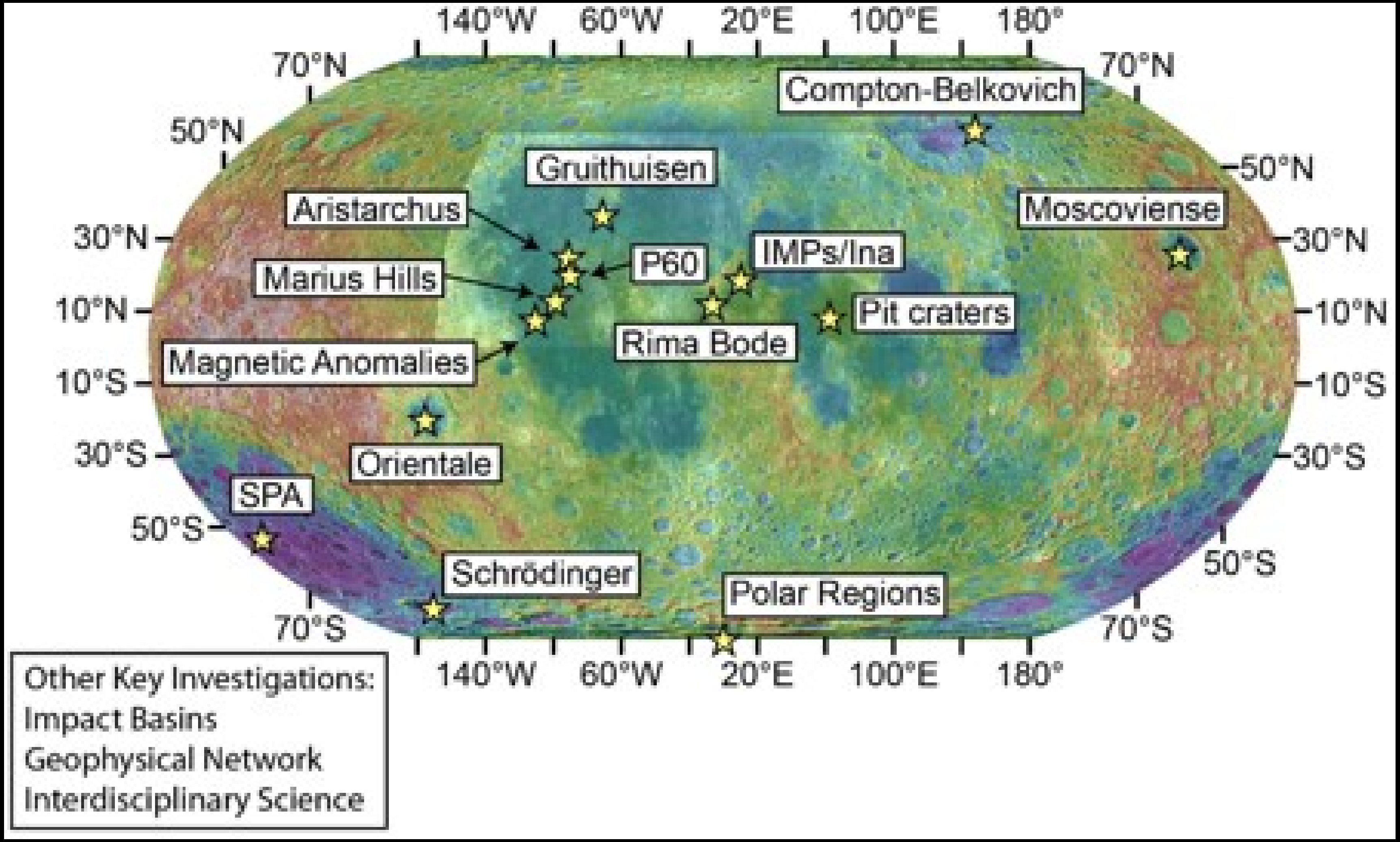
- Most important: we <u>must</u> ensure a <u>safe</u> landing
  - Level slope, low ruggedness, minimized submeter hazards
- Landing site must be in a region where we can
  - find new knowledge or
  - new economic opportunity for the United States and our allies



2018: LUNAR SCIENCE FOR LANDED MISSIONS REPORT

- Building on ASM-SAT Report, NASA Headquarters requested a prioritized list of landing sites for CLPS missions
- Solicited community abstracts for in-situ science, network science, and sample return
- Following workshop, focused analyses were done by early career researchers for the highest priority sites
- Workshop outcomes published here:
- https://lunar-landing.arc.nasa.gov/downloads/LunarLandedScience_Publication.pdf

2018 LANDING SITE WORKSHOP OUTCOMES



- https://lunar-landing.arc.nasa.gov/downloads/LunarLandedScience_Publication.pdf

THE ARTEMIS MISSIONS

Artemis is the twin sister of Apollo and goddess of the Moon in Greek mythology. Now, she personifies our path to the Moon as the name of NASA's program to return astronauts to the lunar surface.

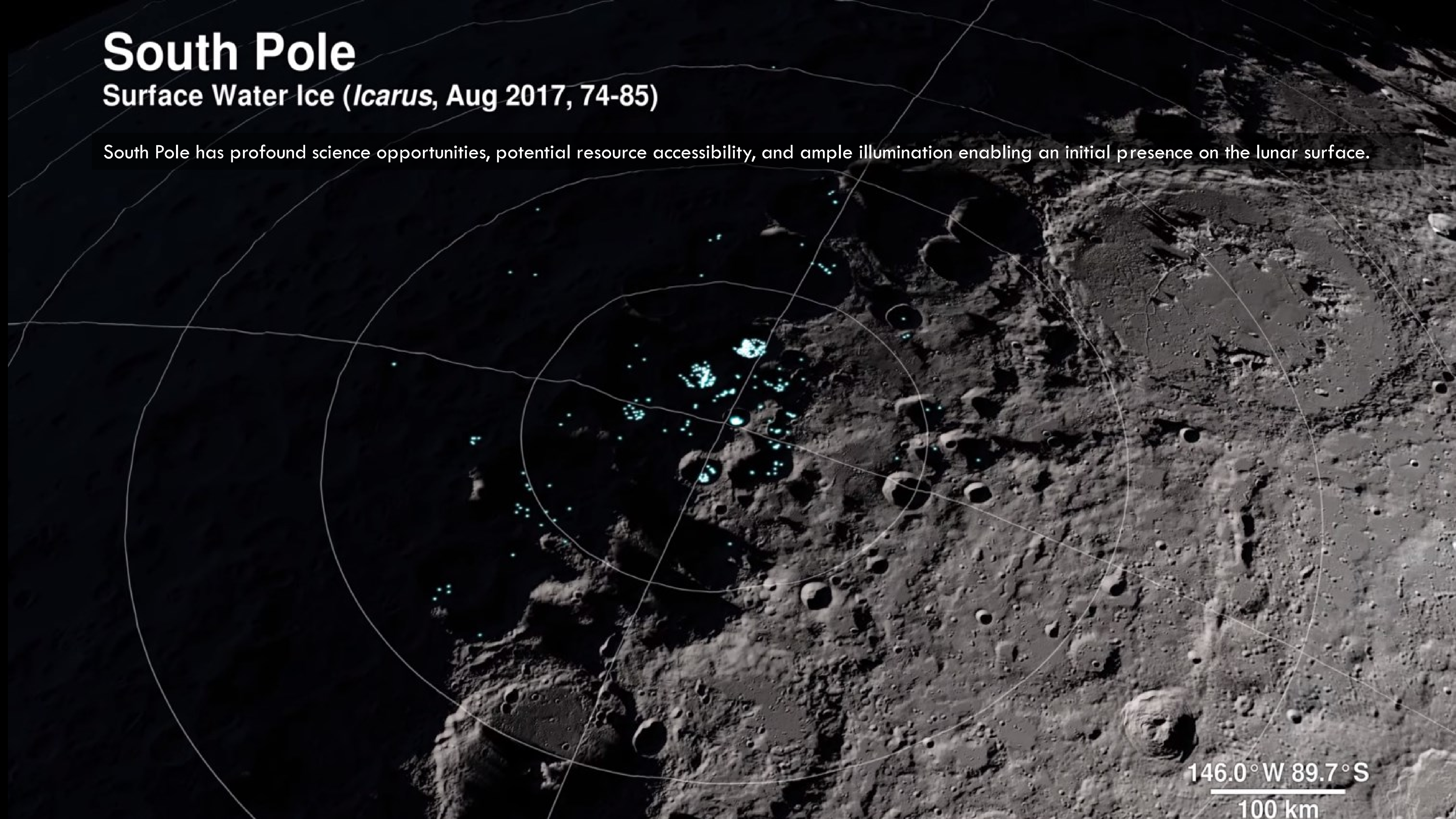
When they land, Artemis astronauts will step foot where no human has ever been before: the Moon's South Pole.

With the horizon goal of sending humans to Mars, Artemis begins the next era of exploration.

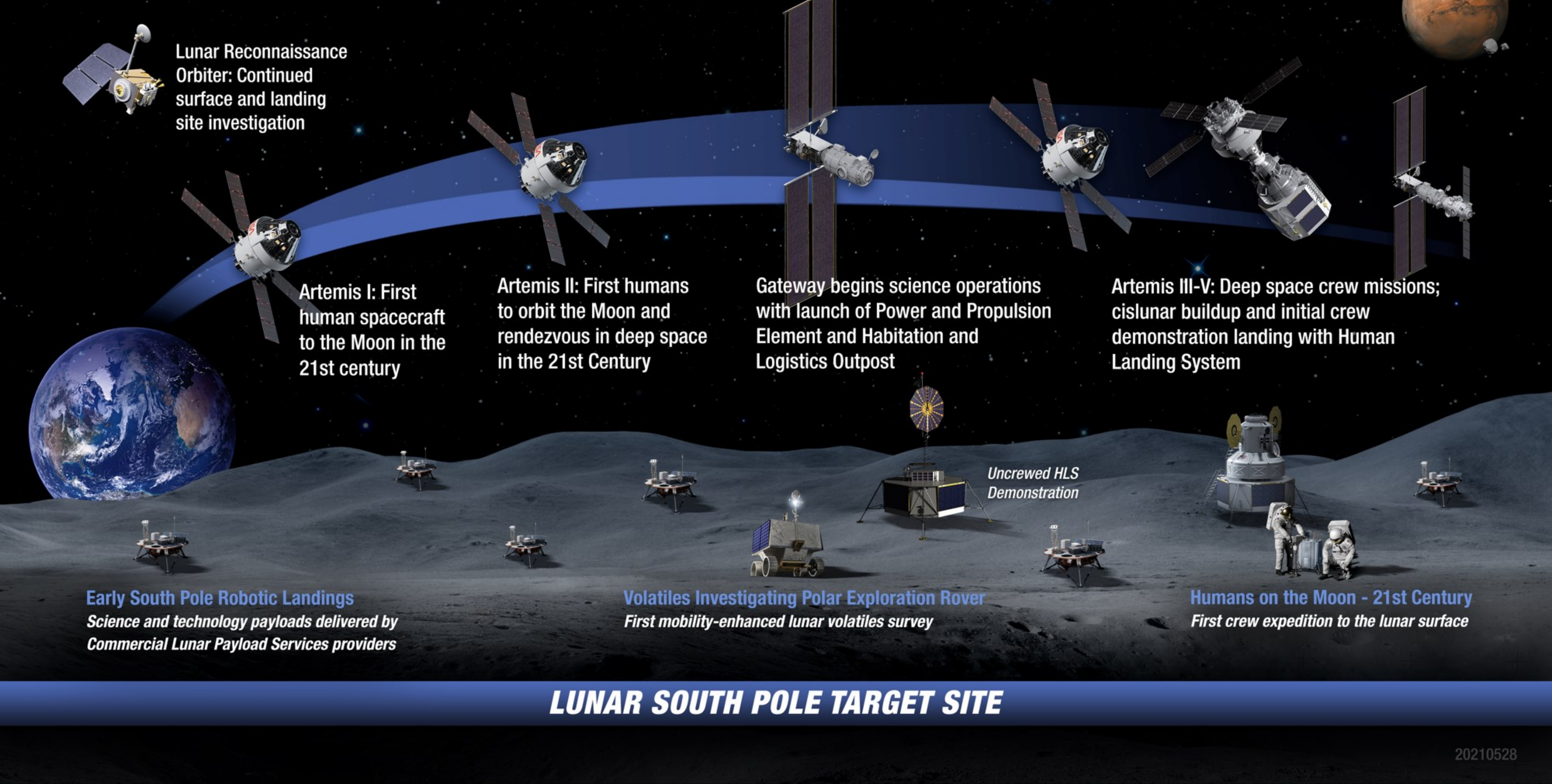
South Pole

Surface Water Ice (*Icarus*, Aug 2017, 74-85)

South Pole has profound science opportunities, potential resource accessibility, and ample illumination enabling an initial presence on the lunar surface.



Artemis: Landing Humans On the Moon



A Bold New Era of Scientific Discovery: The Artemis III Science Definition Team

The Artemis III SDT was chartered by Thomas Zurbuchen for NASA SMD. The Committee was charged to:

- Define compelling and executable science objectives for the Artemis III mission, the first human mission to the surface of the Moon in the 21st century.
- Assess objectives for the mission to achieve the science goals articulated by NASA including investigation approaches, key surface science activities, and potential inputs into the concept of operations.
- Submit a final report to the Planetary Science Division that contains prioritized science objectives for all aspects of the Artemis III mission, including sampling strategies and science goals and priorities of deployable instrument packages.

Schedule

- White Papers due September 8
- First meeting September 10
- Town Hall #1 September 14 (LEAG meeting)
- Draft report released October 14
- Town Hall #2 October 22
- Public comments deadline October 26
- Final report submitted November 13

Artemis III SDT Membership

Co-chairs
- Renee Weber, NASA MSFC
- Barbara Cohen, NASA GSFC
- Samuel Lawrence, NASA JSC

Community consultants
- Amy Fagan, LEAG Chair
- Carlé Pieters, SSERVI Chief Scientist
- Juliane Gross, CAPTEM Lunar Sample Subcommittee Chair

Executive Secretary
- Amanda Nahm, SMD PSD

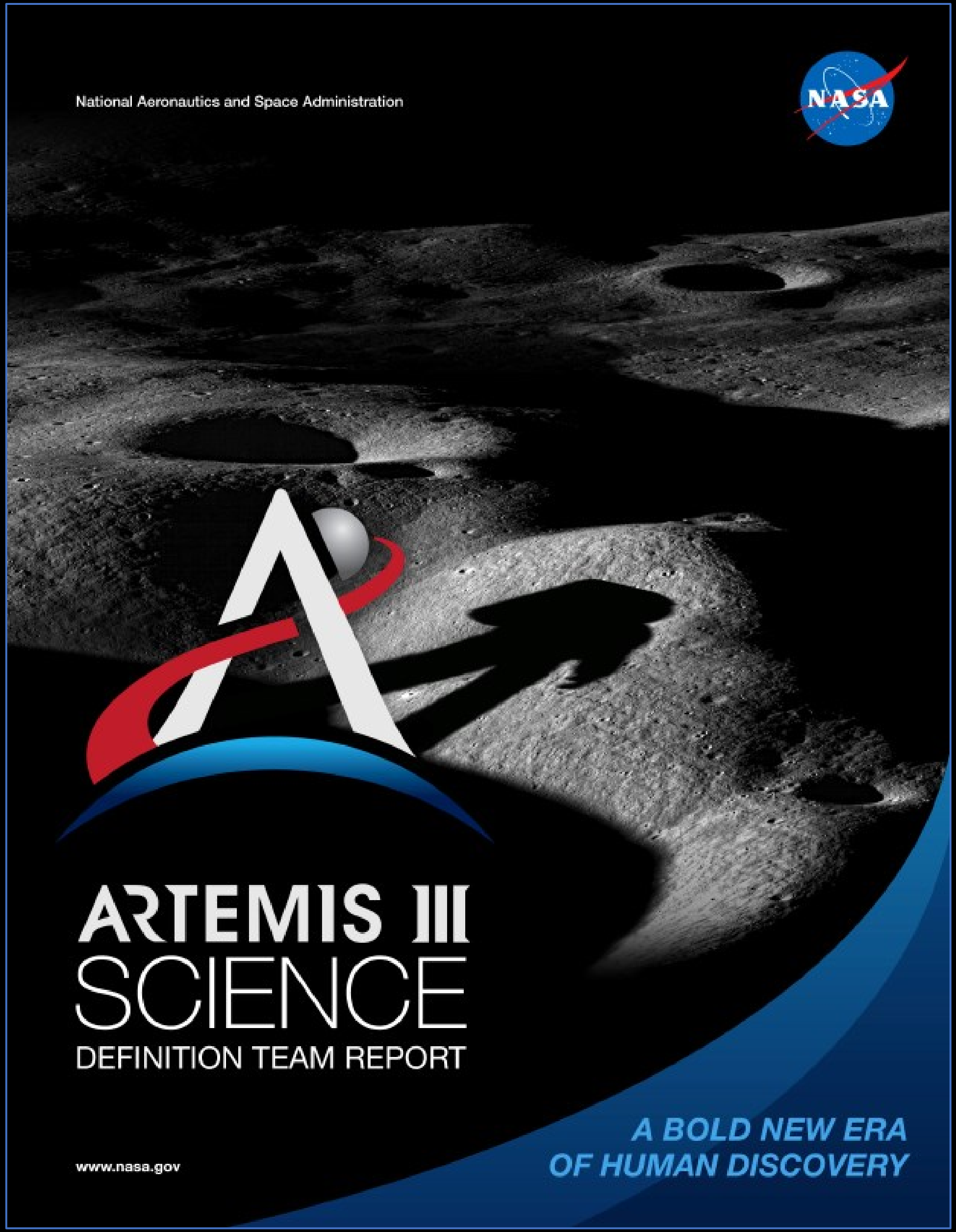
Civil Servant Members
- Jeremy Boyce, NASA JSC
- Michael Collier, NASA GSFC
- Caleb Fassett, NASA MSFC
- Lisa Gaddis, USGS Astrogeology (now at LPI)
- John Gruener, NASA JSC
- Jennifer Heldmann, NASA ARC
- Noah Petro, NASA GSFC
- Kelsey Young, NASA GSFC

- ***Ex officio observers:*** Sarah Noble (PSD), Debra Needham (ESSIO), James Spann (HPD), Kevin Sato (BPS), Jake Bleacher (HEOMD), Julie Mitchell/Francis McCubbin (JSC curation), David Draper (OCS)

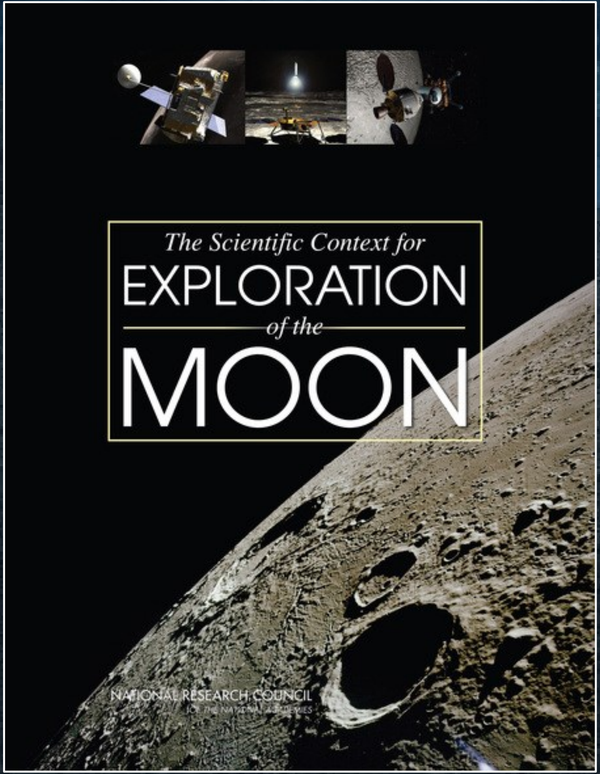
Artemis III Science Definition Team Report

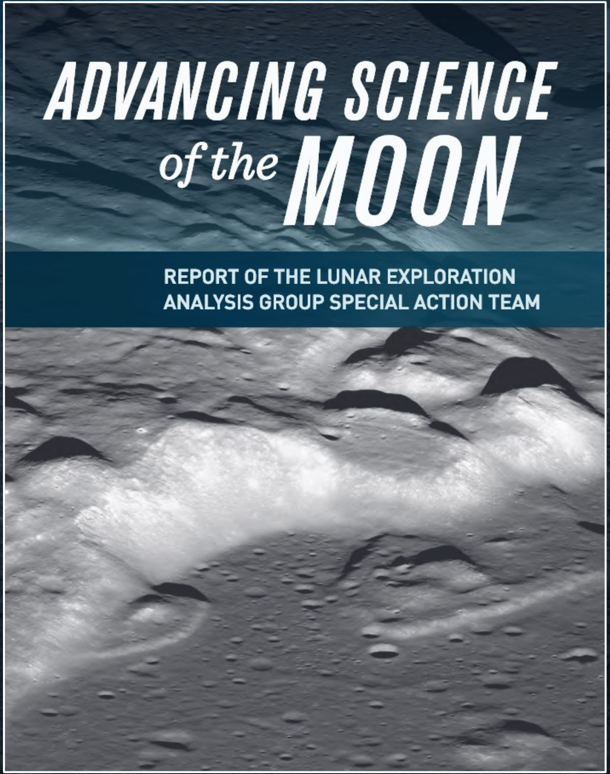
(available at www.nasa.gov/reports)

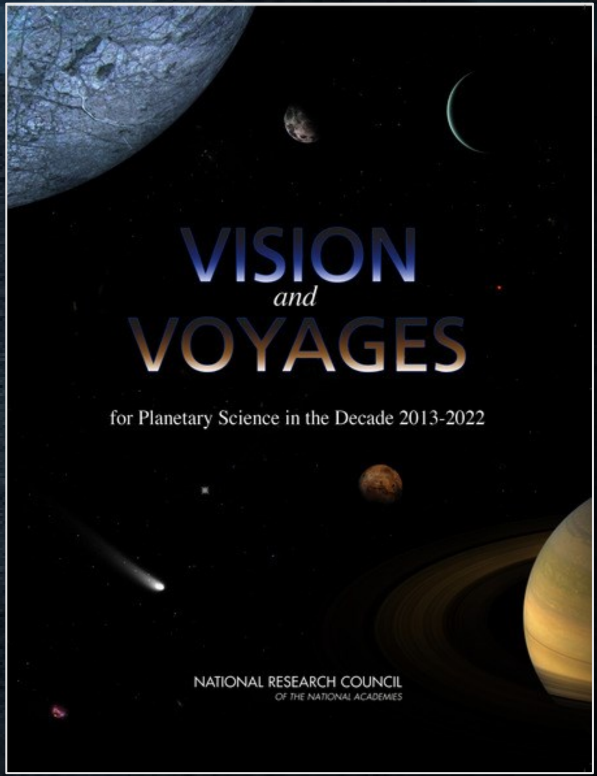
Table of Contents



Guiding Community Documents







… as well as community-submitted white papers and draft report comments

Artemis Science Objectives and Traceability to Science Priorities

NASA HQ’s Artemis Plan laid out seven Science Objectives:

- Objective 1: Understanding Planetary Processes
- Objective 2: Understanding the Character and Origin of Lunar Volatiles
- Objective 3: Interpreting the Impact History of the Earth-Moon system
- Objective 4: Revealing the Record of the Ancient Sun and Our Astronomical Environment
- Objective 5: Observing the Universe and the Local Space Environment from a Unique Location
- Objective 6: Conducting Experimental Science in the Lunar Environment
- Objective 7: Investigating and Mitigating Exploration Risks

The SDT was charged with expanding upon science these Objectives. We chose to map science Goals (areas of research) down to Investigations (specific activities undertaken to address Goals).

Traceability and Prioritization

- Both traceability and prioritization drew on community-submitted white papers and our guiding documents.
- Each investigation was ranked on two independent criteria:
  - Compelling science (e.g., how fundamental is the investigation to making a significant scientific advancement
  - Whether Artemis III presents an enabling opportunity given the architectural constraints

Artemis Science Objective	Science Goal	Science Investigation	Traceability	Science Priority	Enabled by Artemis III
1. Understanding Planetary Processes	1c. Volcanism: Partial melting, eruptions, flow sequence and compositions	Determine the compositional range and physical characteristics of pyroclastic deposits and vents.	LER Investigation-Sci-A-5B	H	N
2. Understanding the Character and Origin of Lunar Polar Volatiles	2a. Determine the compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and with depth) of the volatile component in lunar polar regions.	**2a-7. Determine distribution of micro cold traps across lunar surface within illuminated regions**	SCEM 4a, 8d; VVM-SAT; ASM-4a, 4c; LER Investigation-Sci-A-3A; LER Investigation-Sci-A-3B	H	Y
3. Interpreting the Impact History of the Earth-Moon System	3b. Understand changes to the Earth-Moon bombardment rate	Determine the composition and source of impactors with time	LER Investigation-Sci-B-1C	M	Y

Candidate Program

- We constructed a notional program that would capture the highest-priority science for Artemis III and provide the greatest feed-forward to follow-on missions and the build-up to the Artemis Base Camp
- A cohesive program contains a mix of activities including
  - Sample collection and return
  - *In situ* and field science
  - Deployed experiments
- This candidate set of activities, taken collectively, would address the highest investigation priorities as well as a multitude of additional Investigations.
- A more detailed mission operations plan will need to be developed by NASA when HLS system capabilities, a landing site, and other architectural details come into sharper focus

Candidate Program: Samples

- Samples for Earth return would address a wide range of investigations – not just those that were highly ranked
- Committee recommends “traditional” sample collection (like rake samples) and advanced techniques like hermetically sealed and cryogenically maintained regolith core samples to preserve volatiles in soils
- Continued investment in terrestrial laboratory facilities, analysis techniques, and workforce are also needed to make the best use of the returned samples.

Sample	**Type**	**$Mass_i$ (kg)**	**N**	**Mass (kg)**	**N_{min}**	**$Mass_{min}$ (kg)**	**Investigations**
Contingency	bulk	1	2	2	1	1	
Small clast	rake	1	4	4	1	1	1a-1, 1a-2, 1a-3, 1b-1 ,1b-2, 1b-3
Large clast	hand	1	15	15	4	4	1a-1, 1a-2, 1a-3, 1b-1 ,1b-2, 1b-3
Sealed core	drill	4.5	8	36	4	18	1f-1, 2a-6, 2b-1, 2c-1, 2c-3
Sealed surface	bulk	1.2	20	24	0	0	2b-1, 2c-1
Regolith surface	CSSD	0.5	4	2	2	1	1f-1, 2b-1, 2c-1
				Total 83		**Total 25**	

Candidate Program: *In situ* and Deployed Science

- The HLS down-mass allocation for science & utilization (60-70 kg) must be first reserved for sample collection tools (rakes, core tubes, etc.) and sample return containers
- Therefore, there may be little mass available for *in situ* tools (handheld instruments) or crew-deployed experiments left on the surface
- Measurement techniques are preferred that maximize science return by addressing multiple Investigations and have the ancillary benefit of increasing crew safety and/or reducing risk for future missions.

Measurement Technique	Primary Investigation(s)	Synergistic Investigations
1. *In Situ* Volatile Monitoring	2a-1, 2a-2, 2a-3, 2a-4, 2a-5, 2a-6, 2a-7, 2b-1, 2c-1, 2c-3, 2d-1, 2f-1	1a-1
2. Deployed Environmental Monitoring	7m-1, 7m-2, 7k-1, 7k-2, 7l-1, 7l-2, 5b-1	2a-3, 2a-7, 2c-3, 2f-1
3. Deployed Geophysics Instruments	1a-3, 1b-2, 2c-2	3b-1, 5b-1, 7m-1, 7m-2, 7k-1, 7k-2, 7l-1, 7l-2
4. *In Situ* Geochemistry/Mineralogy	1a-1, 1a-2, 1b-1, 1b-2, 1b-3, 1f-1	3a-1, 3b-1, 3c-1
5. *In Situ* Geotechnical Properties	1f-1	2c-2, 3c-1
6. *In Situ* Geophysics (Traverse Instrumentation)	1a-3, 1b-2	

Report recommendations: Landing site considerations

The scientific return of the Artemis III mission will be intrinsically linked to the Artemis III landing site.

The SDT suggested the following factors be considered in the Artemis III site selection process in order to fully inform the ultimate selection of the Artemis III landing site, in addition to other physiographic parameters such as block abundance, crater frequency, and slope:

- Sufficient illumination for long-duration solar power stations to enable long-lived surface experiments (if solar power is used);
- Availability of a range of sizes of craters for radial traverses and sampling, which will inform our understanding of the impact process;
- Comprehensive sampling which will inform our understanding of the complex geology of the landing site and its link to both surface and internal processes;
- Accessibility of larger blocks to enable sampling of large crater ejecta;
- Proximity and accessibility of mostly or permanently shadowed regions to understand volatile processes;
- Proximity to multiple geologic units of differing time-stratigraphic age;
- Proximity to geologic units that enable specific, high-priority investigations (SPA and PSRs)

"WITH ITS TREMENDOUS BOUNTY OF
ACCESSIBLE RESOURCES,
STUNNINGLY
BEAUTIFUL VISTAS,
AND
COMPELLING SCIENTIFIC QUESTIONS,
THE MOON
CONTINUES TO BECKON US TOWARDS THE NEXT HORIZON AS THE
GATEWAY TO THE REST OF THE SOLAR SYSTEM."

-FROM THE INTRODUCTION TO THE REPORT