Community-Driven Priorities for Lunar Landed Science

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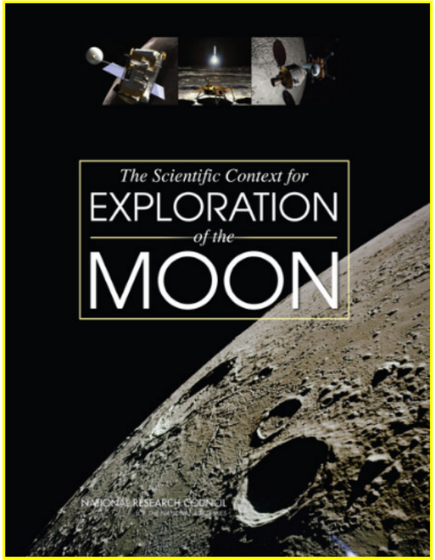
NAC Science Committee
August 28, 2018

Community Input

- Scientific Context for the Exploration of the Moon (SCEM) report – 2007, NRC report
- LEAG SATs (reports on LEAG website: https://www.lpi.usra.edu/leag/reports.shtml)
  - Advancing Science of the Moon (ASM-SAT)
  - Next Steps on the Moon (NEXT-SAT)
- Lunar Science for Landed Missions Workshop
  - Talks and report archived here:
    https://lunar-landing.arc.nasa.gov/
- Survive and Operate Through the Night Workshop
  - Fall 2018, prior to LEAG meeting



ASM-SAT – Advancing Science of the Moon Specific Action Team

- Numerous lunar missions from the U.S. and other countries (LRO, LADEE, GRAIL, ARTEMIS, Chang'e-1/2/3, Kaguya, Chandrayaan-1) have been flown since the publication of the 2007 SCEM report.
- 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 decade of intensive lunar science research has led to substantial progress in many areas, but the concepts, goals, and priorities of the 2007 NRC Report remain relevant today and provide important context and a prioritized framework for advancing lunar and Solar System science.

SCEM Concepts

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 that 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

ASM-SAT – Concept 3 progress

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

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

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

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

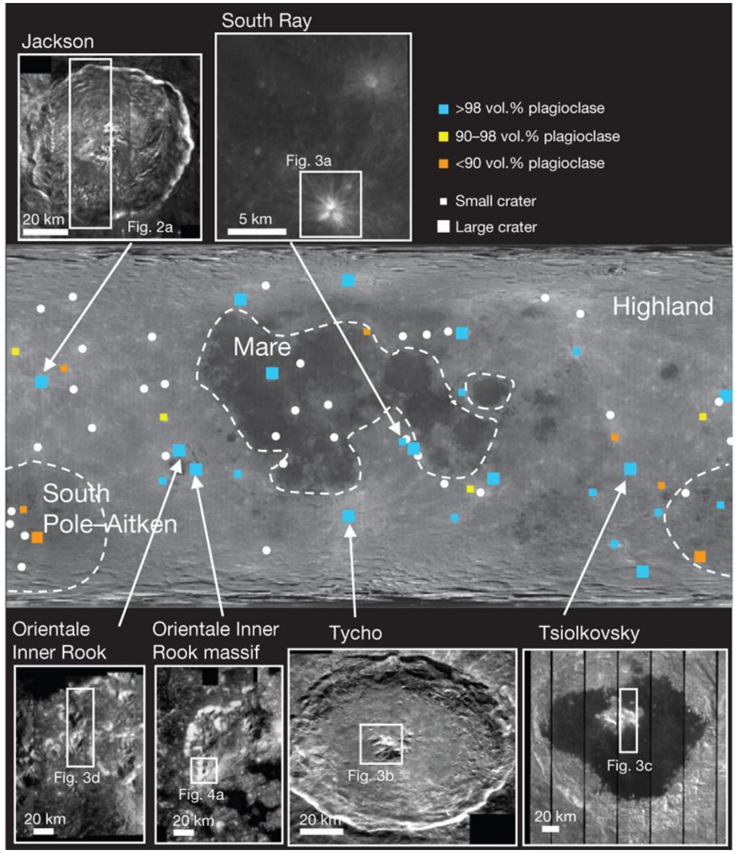
Goal 3d. Quantify the local and regional complexity of the current lunar crust.

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

ASM-SAT – Concept 3 progress

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

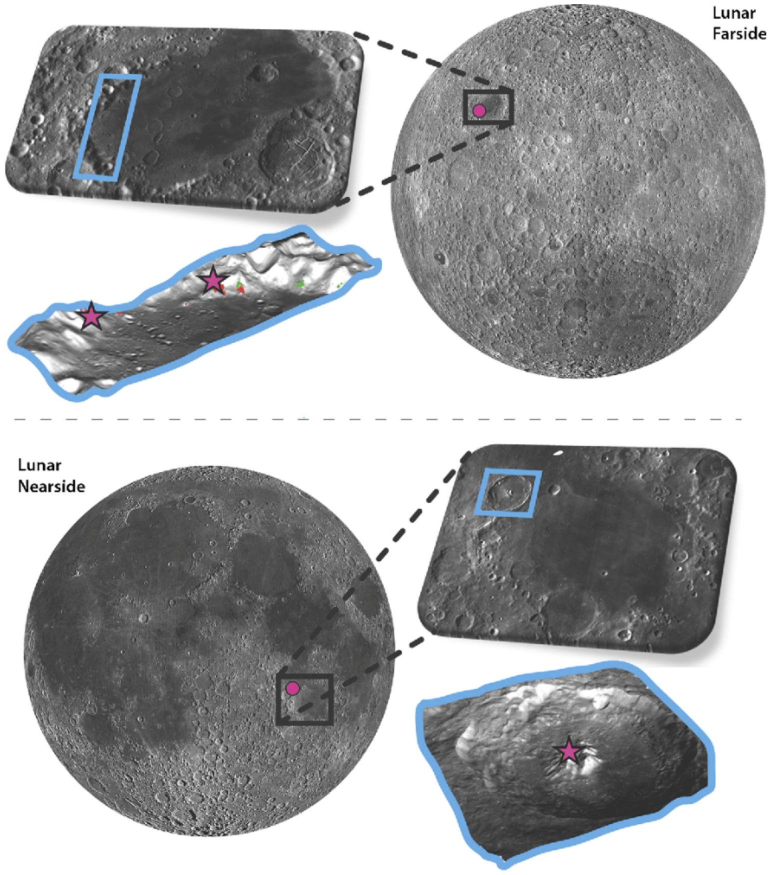
- Extensive deposits of pure crystalline anorthosite (PAN) have been identified and mapped across the exposed inner ring of basins and elsewhere with spectroscopic data from Chandrayaan-1 (M3) and SELENE (MI and SP) (e.g., Ohtake et al., 2009; Pieters et al., 2009; Cheek et al., 2013; Donaldson Hanna 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 the lunar Potassium, Rare-Earth-Element, and Phosphorus (KREEP) component, an enigmatic geochemical component of lunar materials.
- 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, 2016).



ASM-SAT – Concept 3 progress

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

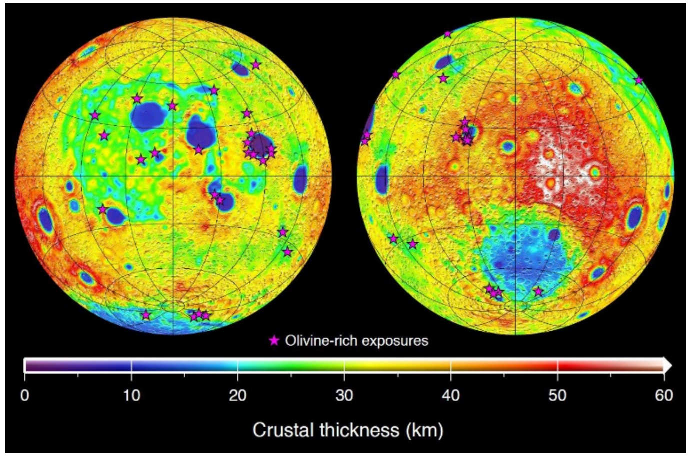
- Orbital instruments: Chandrayaan-1 (M3), SELENE (MI and SP) and LRO (DIVINER, LROC WAC) have led to significant advances.
- In addition to primary rock types of the crust (Greenhagen et al., 2010; Taylor, 2009; Dhingra et al., 2015), the orbital data have identified new rock types (not represented in the sample collections) 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 formation sequence during the early lunar history and the sequence of events post-differentiation remains a future goal.

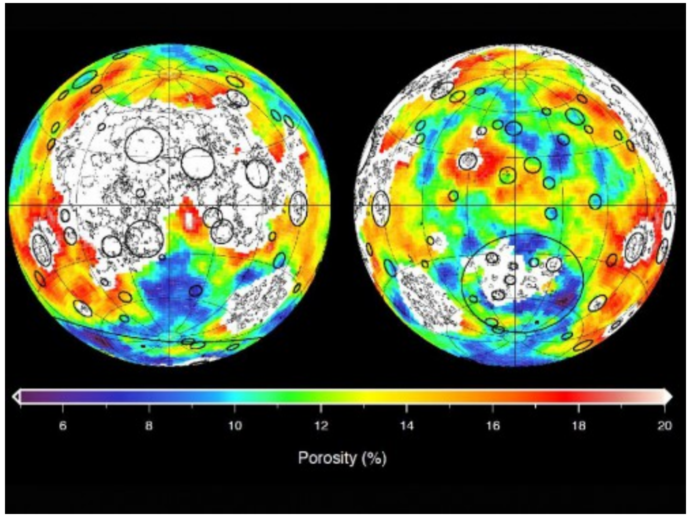


ASM-SAT – Concept 3 progress

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 analyses of data from orbit 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; 2016). The breccia composition of the megaregolith is also largely 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 calculations include the composition of the lower mantle and temperature; heat flow measurements would provide critical new constraints.

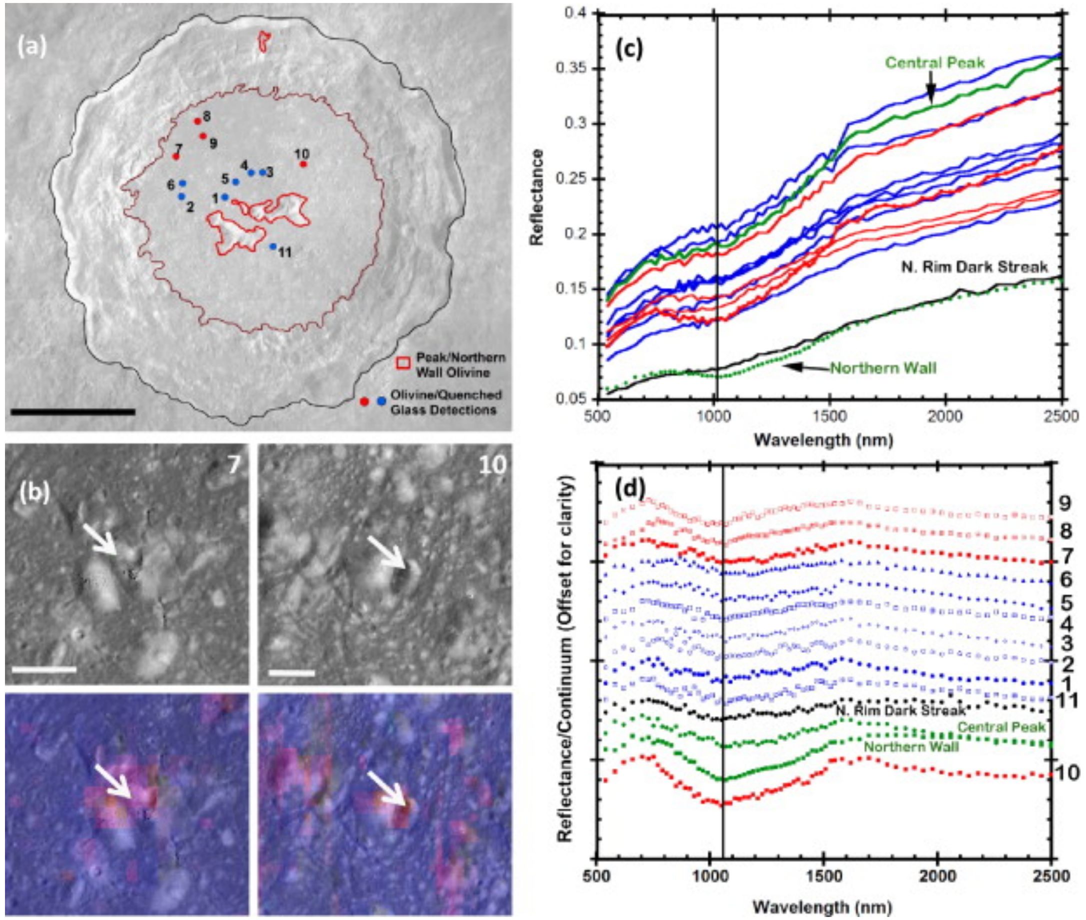




ASM-SAT – Concept 3 progress

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

- Aspects of the complexity of the lunar crust have 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).

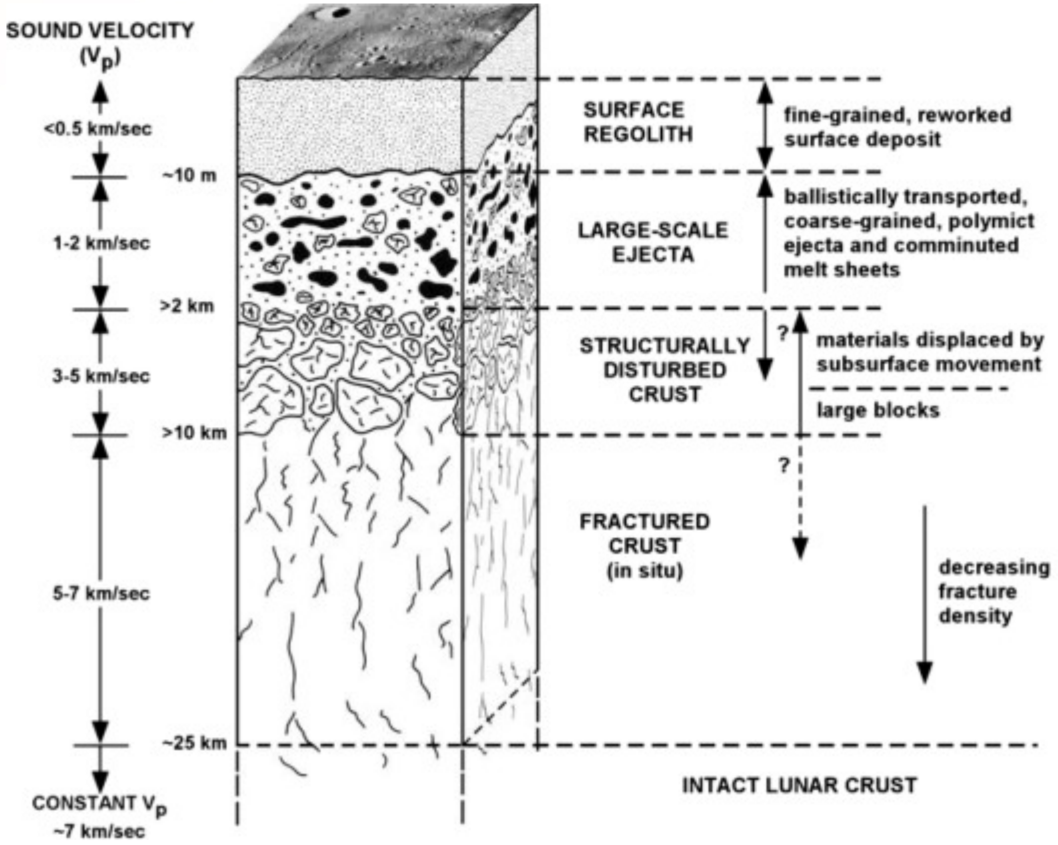


Dhingra et al., 2015

ASM-SAT – Concept 3 progress

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

- No significant new understanding of their composition
- Geophysical models of GRAIL data have shown that the initial porosity of the megaregolith is 10–20%, which decrease to zero at a depth of 10–20 km (Han et al., 2014).



ASM-SAT – Concept 3 progress

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 2007 NRC report.

- The recommendations for implementation from the 2007 NRC 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.

ASM-SAT (SCEM update)

- Nearly all goals had at least some progress; none were “done”
- No effort was made to reprioritize
- Identified concepts and goals not called out in SCEM
  - Lunar ‘water’ cycle
  - Origin of the Moon
  - Lunar tectonism and seismicity
- Progress made in the last decade really helps us ask better questions and refines our concepts of where to go to get the answers

ASM-SAT (SCEM update)

“We are now in a much stronger position to take advantage of landed missions and identify ideal landing sites to address the SCEM goals.”

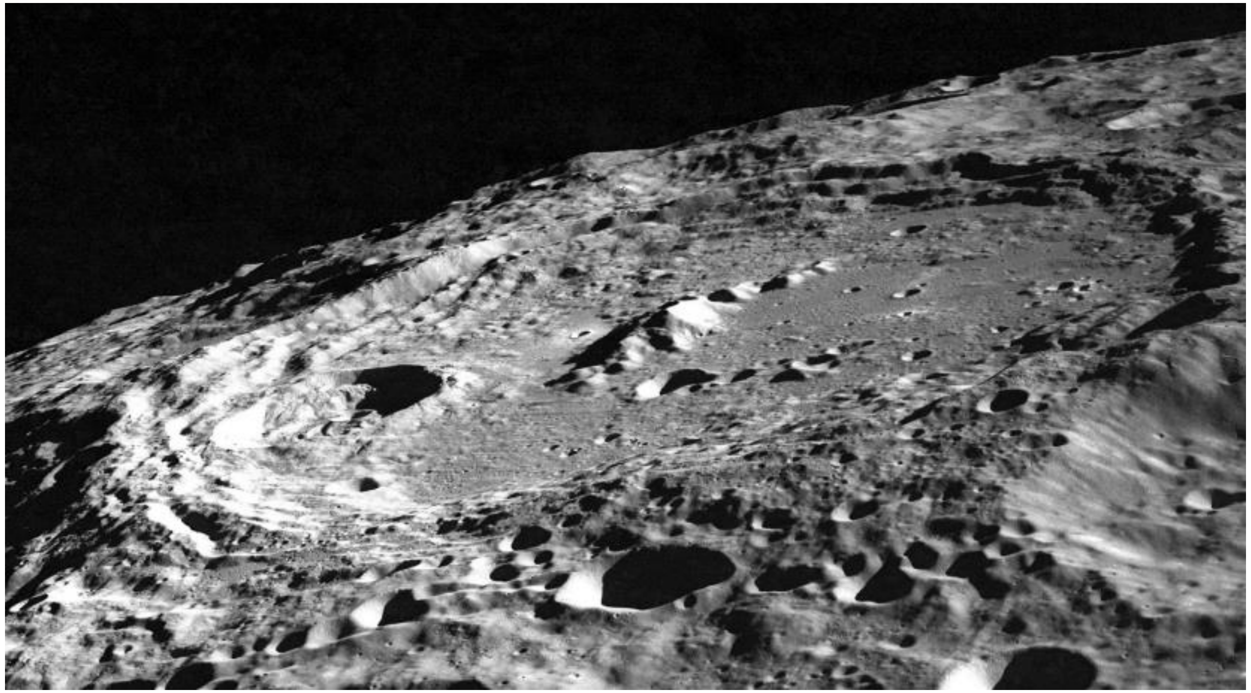
“While there is still real progress to be made from orbital missions, the advancement of many of these goals requires landed missions.”

NEXT-SAT – Next Steps on the Moon Special Action Team

- **FINDING:** Lunar science presently has a well-developed slate of compelling science questions that are profoundly impactful for understanding the entire Solar System. **There are numerous options for lunar missions to address these questions that would provide openings to make dramatic, paradigm-shifting advances in planetary science.**
- FINDING: NEXT-SAT references the Finding 3 arising from the 2017 LEAG Commercial Advisory Board meeting. **Commercial entities should be employed to the fullest practical extent to increase competition, decrease costs, and increase the flight rate.**
- FINDING: There are <u>numerous</u> potential opportunities for commercial services, with NASA as a customer, to play a role in lunar surface exploration.
- FINDING: LRO observations of the Chang'e-3 mission activities on the surface pointed to the kinds of science and operational support that LRO data can enable and support for future missions. Future mission teams should leverage active targeting from LRO instruments to ensure that data for site selection certification is readily available, and interface with the LRO project team to enable comprehensive mission support and new science.

NEXT-SAT – Investigations Addressing Key Science Questions

- Orbital Missions
  - Global compositional information
  - Next-generation hyperspectral imaging system with higher spatial resolution than Kaguya, Chandrayaan-1, and LRO instruments
  - Global Major-minor element maps
  - XRF Spectrometer
  - Polar hydrogen/volatile maps
  - Bi-static radar
  - Laser frost-finder
- Impactors
  - Reveal details about subsurface
  - More LCROSS-style missions
- Relay satellites/navigational aids
- CubeSat/Smallsat
  - Characteristics of magnetic anomalies
  - Orbital mapping of polar volatile deposits

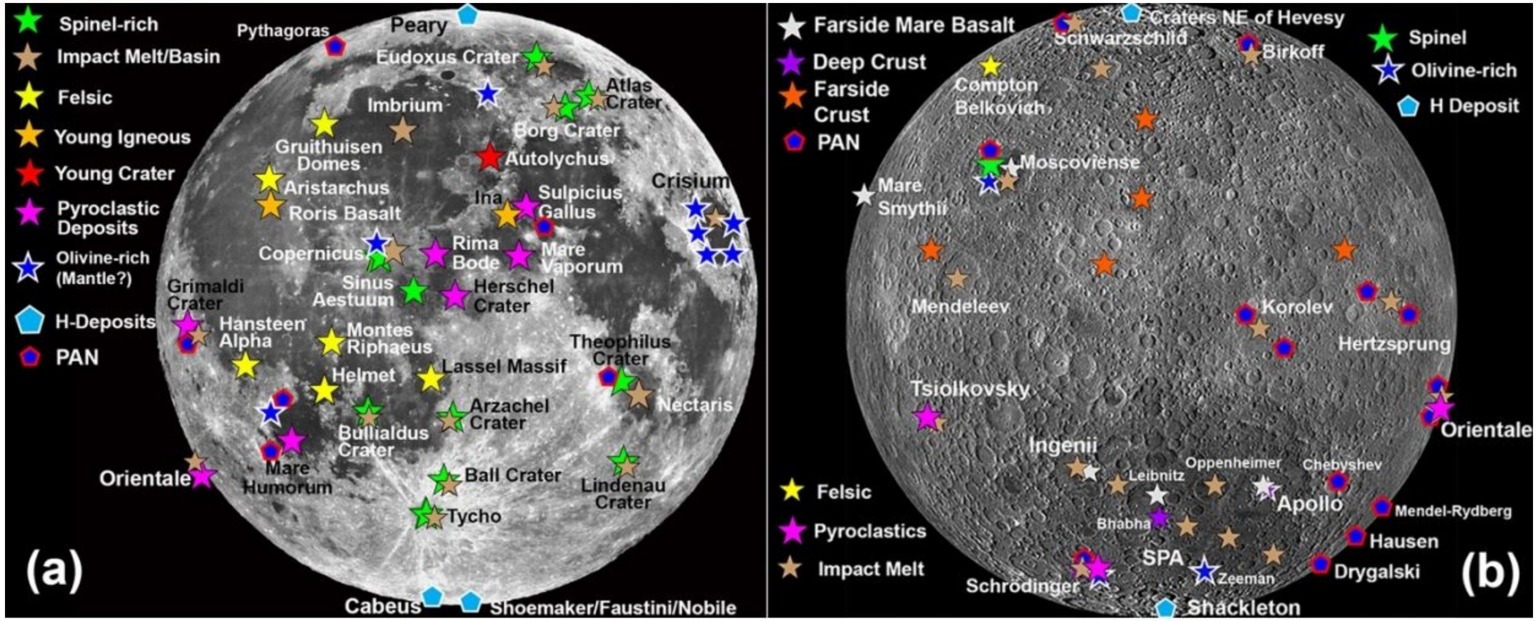


NEXT-SAT – Investigations Addressing Key Science Questions

- Fixed, Stationary Landers
  - Polar region landed mission - understand plasma and electrical environment of lunar poles
  - Lunar Geophysical Network - understand the lunar interior at 3+ locations across lunar surface
- Mobility-desired Missions (rovers, hoppers)
  - Understand origin of magnetic anomalies – rover traverse across a lunar magnetic anomaly
  - Understand volcanic processes – rover traverse through complex terrain (Marius Hills volcanic complex, Hadley Rille), absolute ages and geochemistry of silicic volcanoes (Lassell Massif, Gruithuisen Domes)
  - Understand resource potential of lunar poles – rover traverse through several permanently shadowed regions
  - Understand the resource potential and geology of lunar pyroclastic deposits – bulk chemistry, geochemistry, and depth
  - Understand history of lunar volcanism – absolute ages of proposed young basalt units
  - Understand lunar tectonic processes – rover traverse over a local thrust fault
  - Understand geology of lunar lava tubes – land and explore sublunarean voids
  - Understand the time-stratigraphy of lunar basin formation – determine absolute ages of key impact melt deposits

NEXT-SAT – Investigations Addressing Key Science Questions

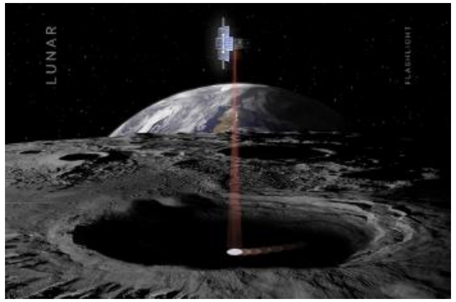
- Sample Return Missions - Numerous proposed targets for sample return missions across the entire lunar surface, e.g.
  - Silicic volcanic materials (lunar differentiation)
  - Erastoshenian and Copernican mare basalts (lunar volcanism)
  - Ancient Buried Mare Basalts (lunar volcanism)
  - Polar volatile deposits
  - Regional Pyroclastic deposits
  - ….and dozens more!

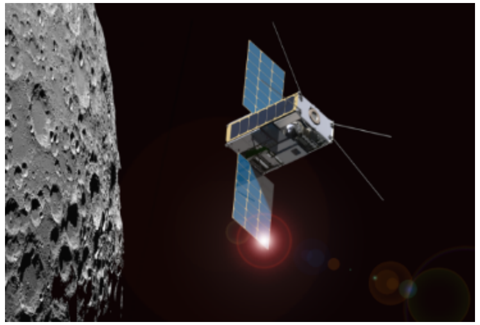


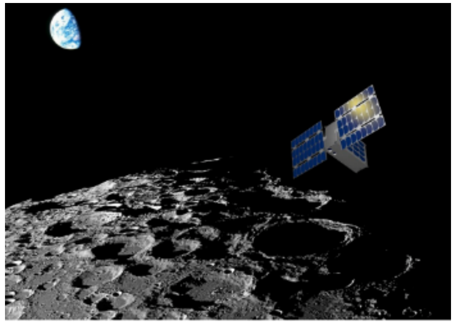
NEXT-SAT – Example Missions

Polar Volatiles: Composition, Physical State, Form, Distribution, and Context

- Orbiters: Surface mineralogy/ice mapping (Lunar Flashlight, Lunar IceCube, KPLO ShadowCam), improved resolution hydrogen mapping (LunaH-Map). High resolution SAR.
- Up to 40 kg payload to the lunar surface, no mobility, no night survival: Image surface within PSR, identify surficial ice composition, obtain subsurface sample and determine volatile abundance, chemistry, isotopics. Stratigraphy if possible. (Many landing sites needed for lateral coverage.)
- >40-500 kg payload lander, mobility, night and out-of-comm survival: Chemical & isotopic composition, physical state, lateral/vertical distribution via subsurface sample analysis from at least 1 meter depth at multiple stations. Measure subsurface H concentration continuously.
- Sample Return: Return of volatile-bearing materials in pristine condition from multiple polar locations.
- Desired Technology Investments: Precision landing and hazard avoidance. Cryogenic sample materials handling, lossless storage. Rover development, including thermal management in cryogenic environment.







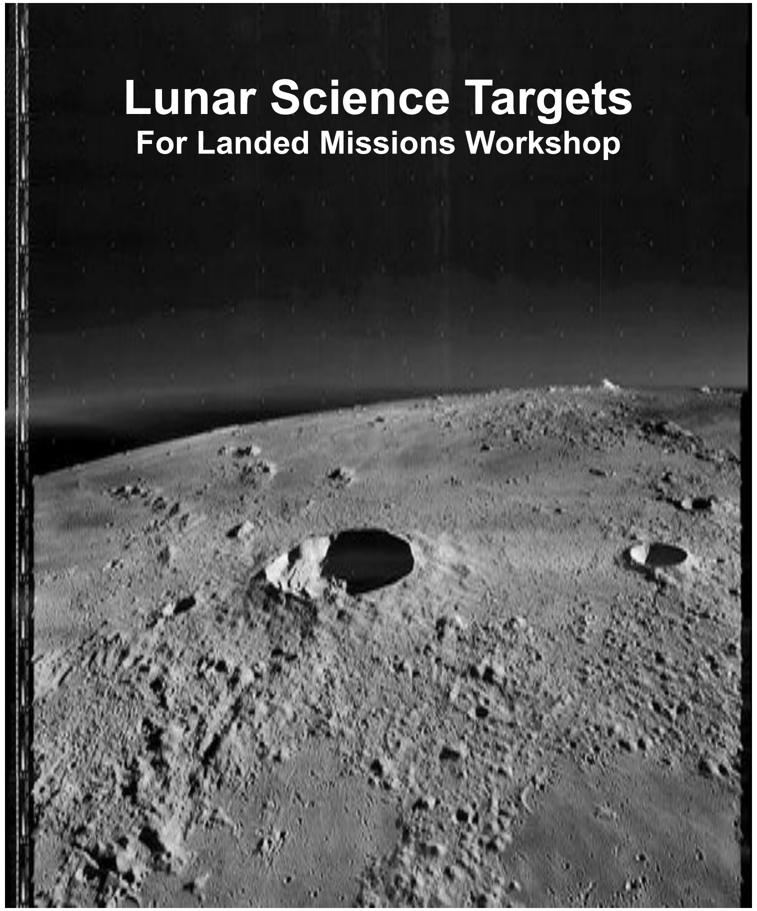
NEXT-SAT – Example Missions

Lunar Magnetic Anomalies

- Orbiters: Low passes with magnetometer-equipped spacecraft. Obtain contours and lateral topology of magnetic fields near, but not at, the surface.
- Up to 40 kg payload to the lunar surface, no night survival: In-situ measurements of surface magnetic fields; measurement of radiation environment of swirls to understand solar wind interactions with surface.
- >40-500 kg payload lander, mobility, night survival: Traverse around a swirl, measure the magnetic field intensity and interactions with surface and implications for radiation environment.
- Sample Return: Return regolith samples from a swirl in order to measure the composition, absolute ages, magnetic properties, and physical characteristics of the regolith within that swirl.
- Desired technology investments: Precision landing and hazard avoidance; rover development; sample handling.

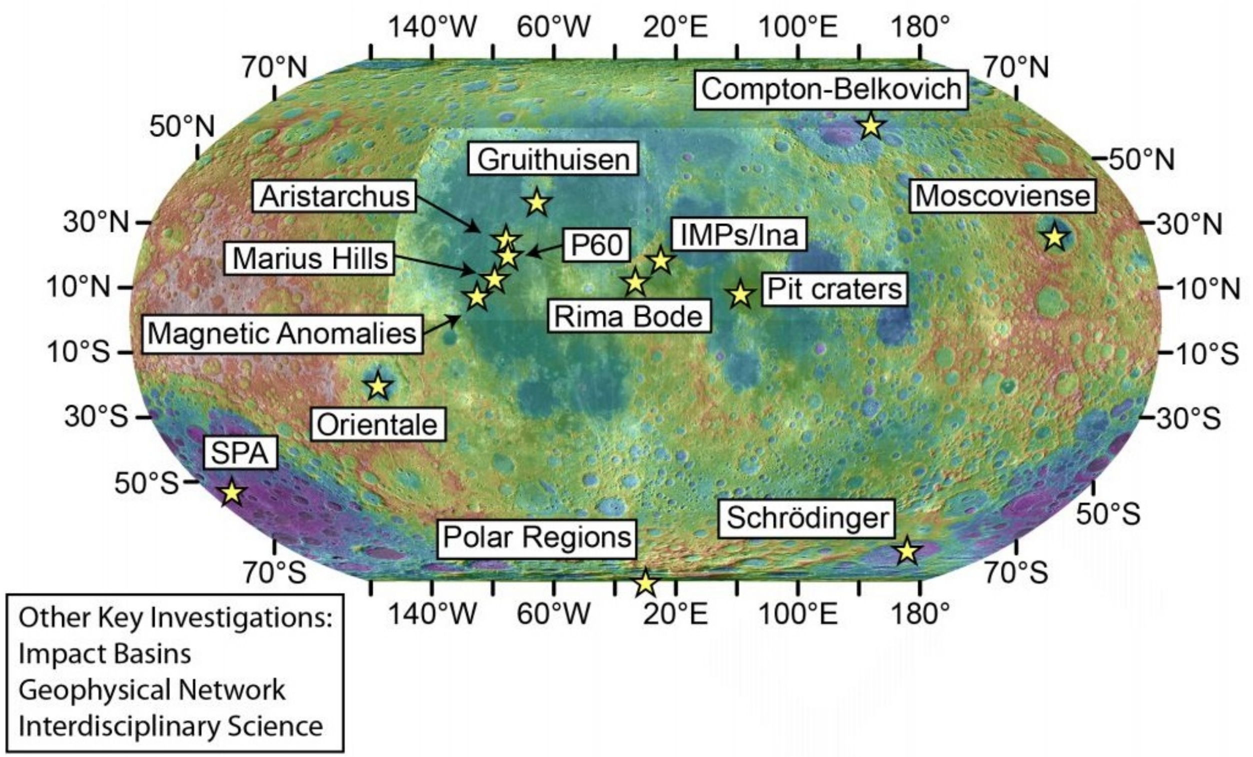
Lunar Science for Landed Missions

- Workshop held at Ames on January 10-12, co-chaired by SSERVI and LEAG.
- Targets in contributed talks were evaluated for both science and human exploration interests, aligned in sessions topically:
  - Lunar Volatiles
  - Lunar Magmatism and Volcanic Deposits (pyroclastics, pits and lava tubes, unusual volcanism)
  - Age Dating and Impact Processes (Solar System chronology, basins and impact processes)
  - Lunar Crust and Dust
  - Geophysics and Astrophysics
  - Magnetism and Swirls
- Eight lunar commerce companies participated in 2 panel sessions; additional international session included with Japanese, European contribution
- Talks and report archived here: https://lunar-landing.arc.nasa.gov/



Lunar Science for Landed Missions

- Aristarchus (50°W, 25°N)
- Compton-Belkovich Volcanic Deposit (99.5°E, 61.1°N)
- Gruithuisen Domes (40.5°W, 36.6°N)
- Irregular Mare Patches (5.3°E, 18.66°N, Ina)
- Magnetic Anomalies (e.g., 59°W, 7.5°N, Reiner Gamma)
- Marius Hills (53°W, 13°N)
- Moscoviense (147°E, 26°N)
- Orientale (95°W, 20°S)
- P60 Basaltic Unit (49°W, 20°N)
- Pit craters (e.g., 33.22°E, 8.336°N, Mare Tranquillitatis)
- Polar Regions (e.g., 0.0°E, 89.9°S, Shackleton Crater)
- Rima Bode (3.5°W, 12°N)
- Schrodinger (135°W, 75°S)
- South-Pole Aitken Basin (170°W, 53°S)
- Global network of nodes - Geophysical
- Global network of nodes – Exosphere
- Dating Large Impact Basins to Anchor Lunar Chronology
- Interdisciplinary science



There is excellent science to be done at every step while preparing for human exploration

- Small stationary lander/1-day operations
- CubeSats/SmallSats
- Long-lived landers
- Small rovers
- Large rovers
- Sample return