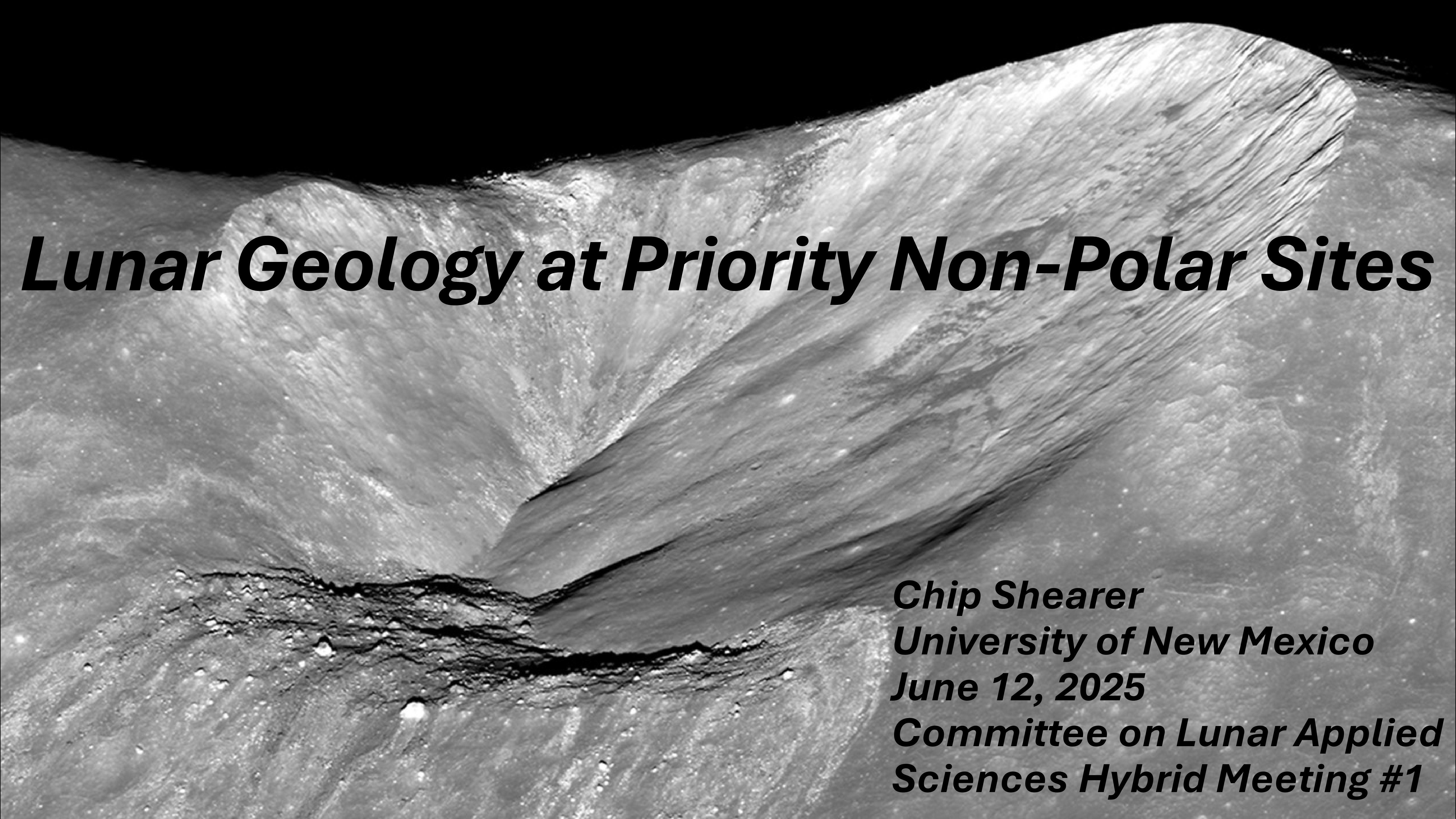


Lunar Geology at Priority Non-Polar Sites

Chip Shearer
University of New Mexico
June 12, 2025
Committee on Lunar Applied Sciences Hybrid Meeting #1

Previous Analyses

Jawin, E. R., Valencia, S. N., Watkins, R. N., Crowell, J. M., Neal, C. R., & Schmidt, G. (2018). Lunar science for landed missions workshop findings report. *Earth and Space Science*, *6*(1), 2-40.

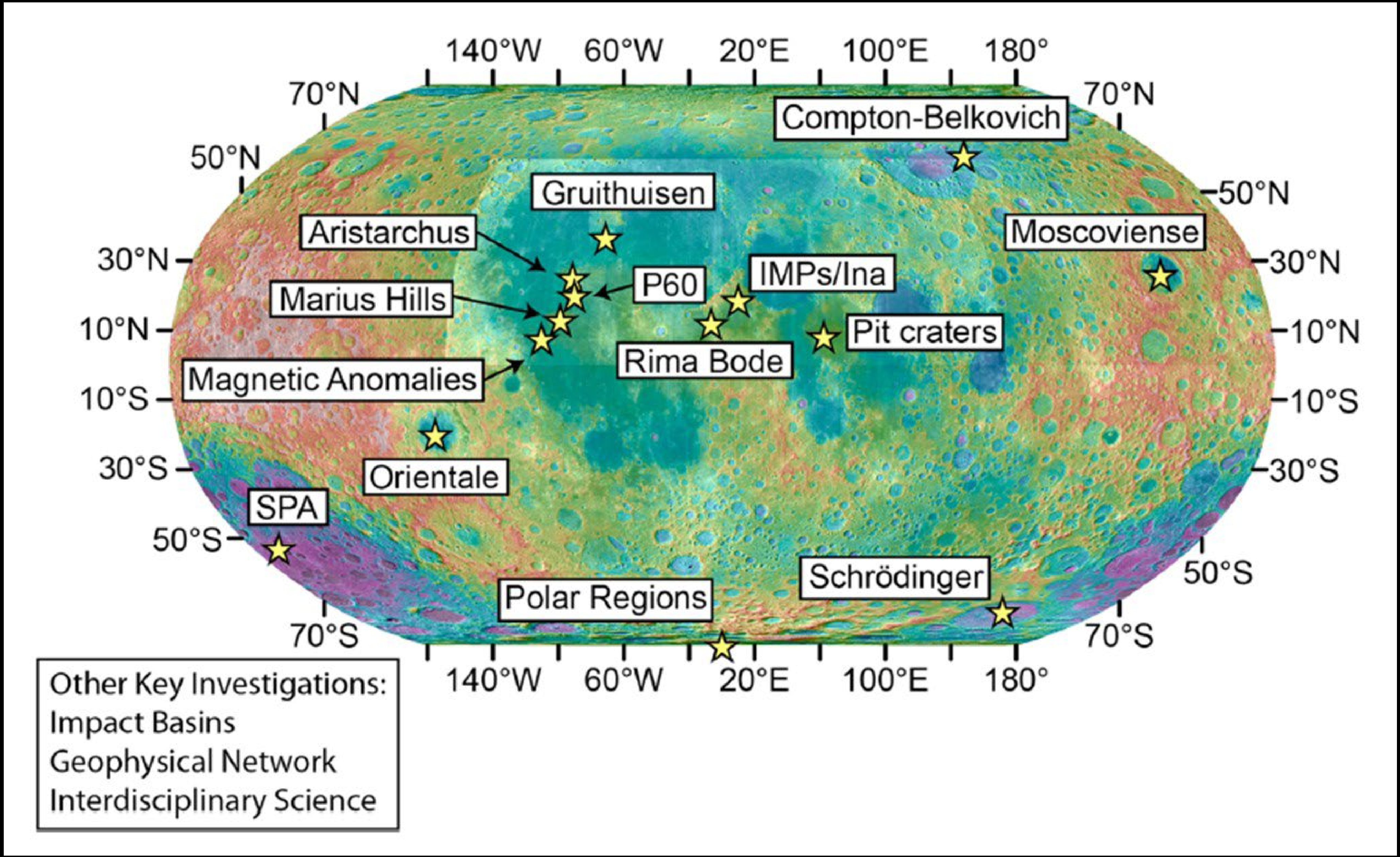
Ryder, G., Spudis, P. D., & Taylor, G. J. (1989). The case for planetary sample return missions: Origin and evolution of the Moon and its environment. *Eos, Transactions American Geophysical Union*, *70*(47), 1495-1509.

National Research Council, Division on Engineering, Physical Sciences, Space Studies Board, & Committee on the Scientific Context for Exploration of the Moon. (2007). *The scientific context for exploration of the Moon*. National Academies Press.

National Academies of Sciences, Engineering, and Medicine. 2023. Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032. Washington, DC: The National Academies Press. https://doi.org/10.17226/26522.National Academies of Sciences, Engineering, and Medicine. 2023. Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032. Washington, DC: The National Academies Press. https://doi.org/10.17226/26522.

Potential non-polar sites

Jawin et al. (2018)



Potential non-polar sites

Table 1
Summary of Science Themes Addressed at Each Landing Site

	SCEM overarching themes								ASM overarching themes			Enhancing technologies					
	S1: Bombardment	S2: Interior	S3: Crust	S4: Volatile Flux	S5: Volcanism	S6: Impacts	S7: Regolith	S8: Exosphere	A1: Water Cycle	A2: Origins	A3: Tectonics	Communications relay	Night survival	Cryogenic sampling	Automated hazard avoidance	Mobility	Dust mitigation
Aristarchus	×	×	×		×	×			×				×		×	×	×
Compton Belkovich		×	×		×				×			×	×		×	×	×
Gruithuisen domes		×	×		×				×				×		×	×	×
Ina/IMPs	×	×			×	×			×				×		×	×	×
Magnetic anomalies		×	×	×		×	×	×	×			×	×		×	×	×
Marius Hills	×				×				×				×		×	×	×
Moscoviense	×	×	×		×	×	×		×		×	×	×		×	×	×
Orientale	×	×	×		×	×	×		×		×	×	×		×	×	×
P60 basalt	×				×				×				×		×	×	×
Pit craters	×				×		×		×			×	×		×	×	
Polar regions				×					×			×	×	×	×	×	×
Rima bode		×			×				×				×		×	×	×
Schrödinger	×	×	×		×	×			×		×	×	×		×	×	×
SPA	×	×	×		×	×						×	×		×	×	×
Network of nodes - geophysics		×									×	×	×		×		×
Network of nodes - exosphere				×			×	×	×			×	×		×		×
Basin chronology	×					×						×	×		×	×	

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

Jawin et al. (2018)

Outline and Goals

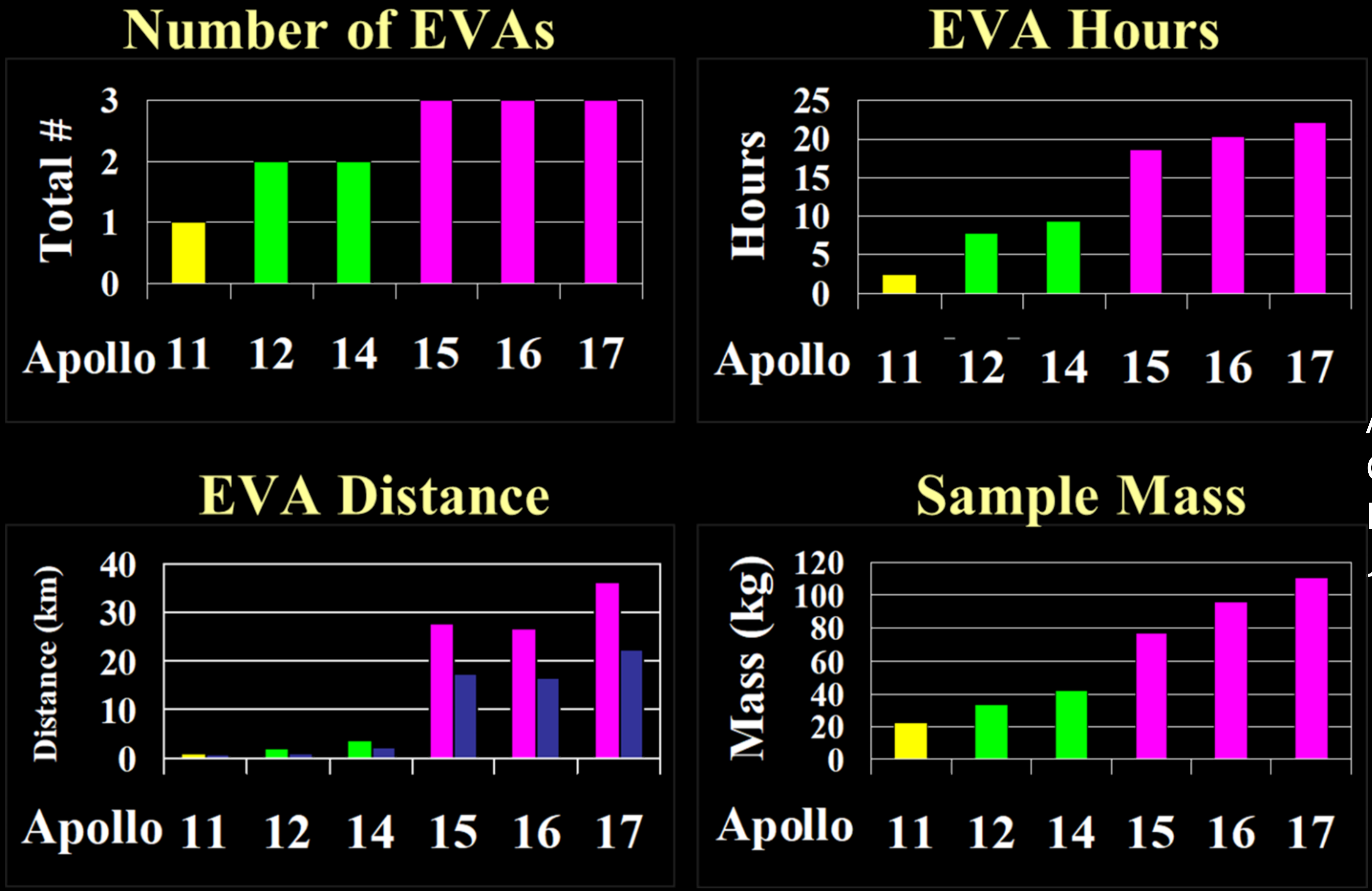
Examples of high-priority non-polar science locations
- Important science
- Why not at the South Pole
- Access needs fulfill science compared to Apollo
- G,H, J missions.

Role of samples
- Essential or secondary to completing science
- Sample types
- Sample mass

Role of human presence

Single missions versus exploration campaigns.

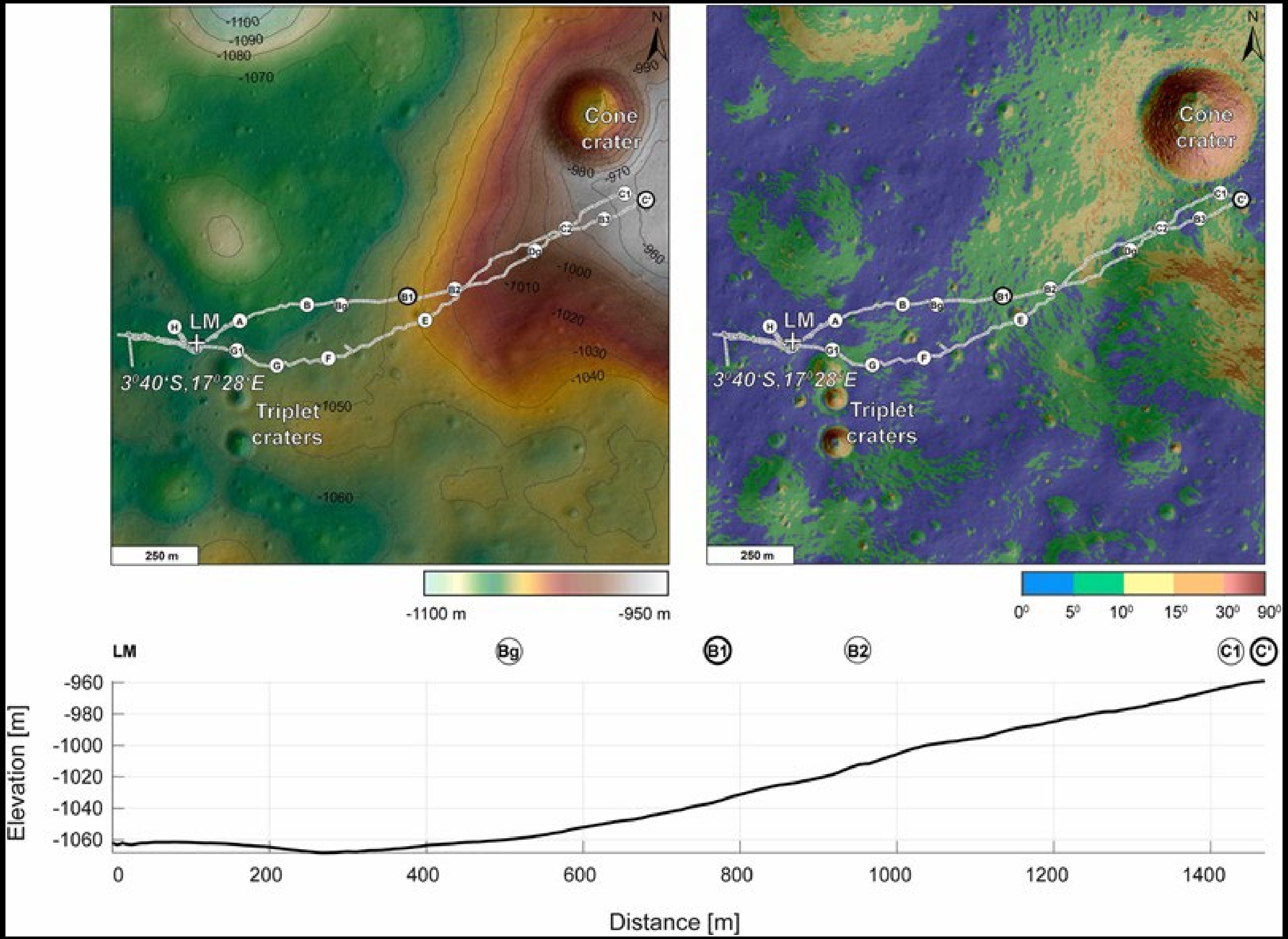
History of Apollo Program Capabilities



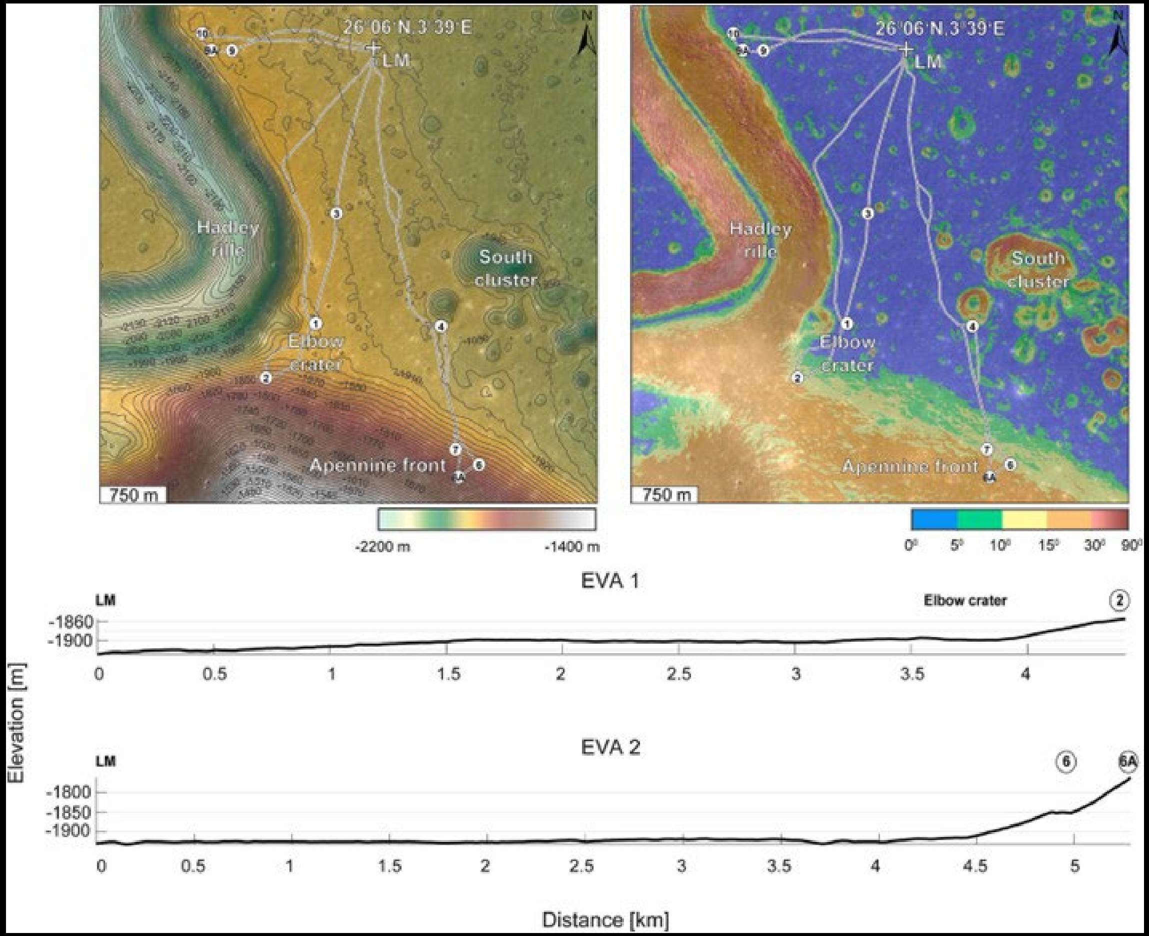
Apollo Missions
G missions: Apollo 11
H missions: Apollo 12, 13, 14
J missions: Apollo 15, 16, 17

History of Apollo Program Capabilities

Iqbal et al. (2024)

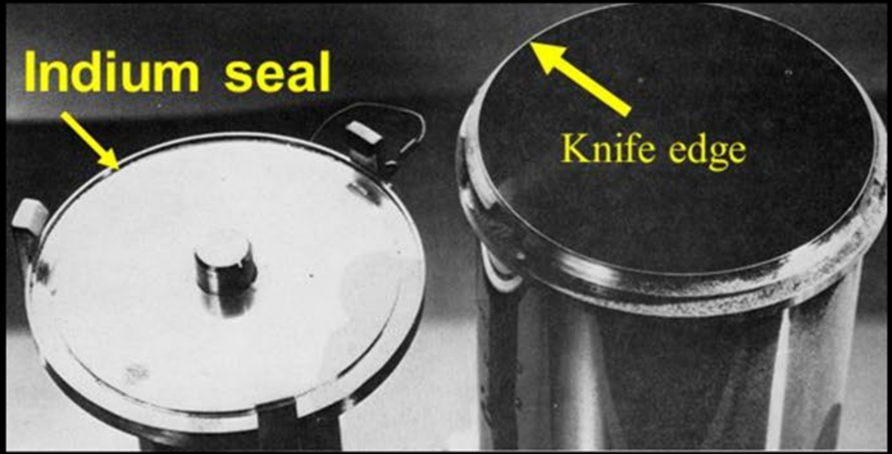


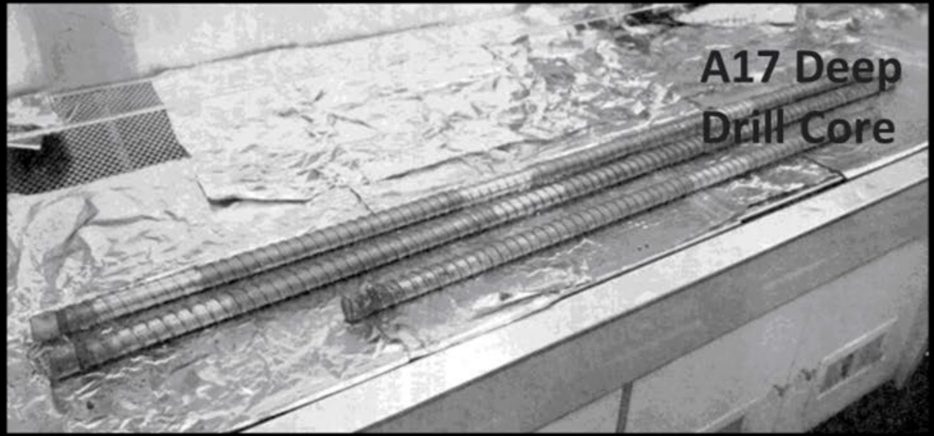
H mission, Apollo 14. During EVA 2, continuous slope of 5-10º to Cone crater. However, they could not reach Cone crater due to 30º slope.



J mission, Apollo 15
13º slope, estimated the rover could exceed 20. º

Examples of Apollo Program Sampling Capabilities





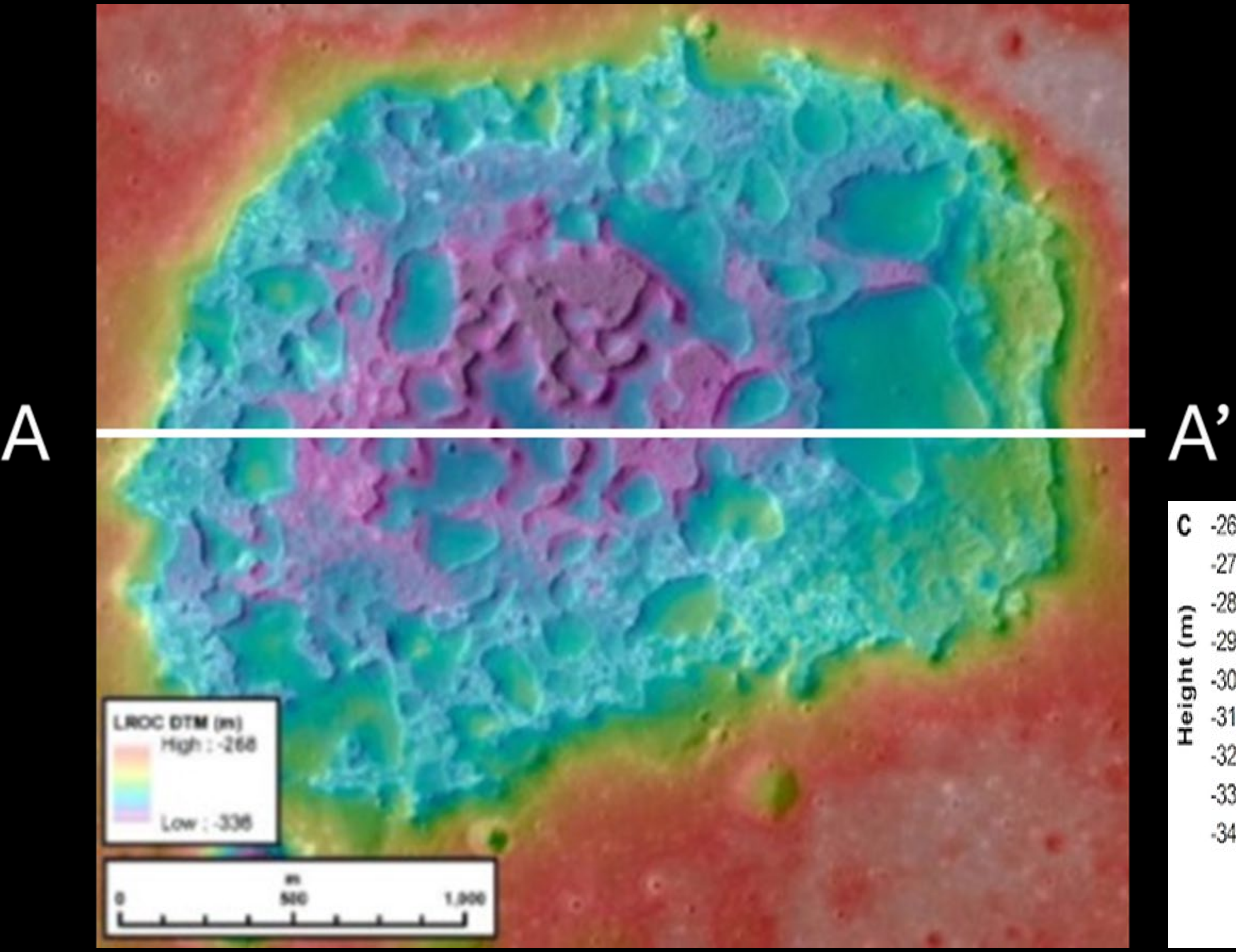
Potential Exploration sites examined here:

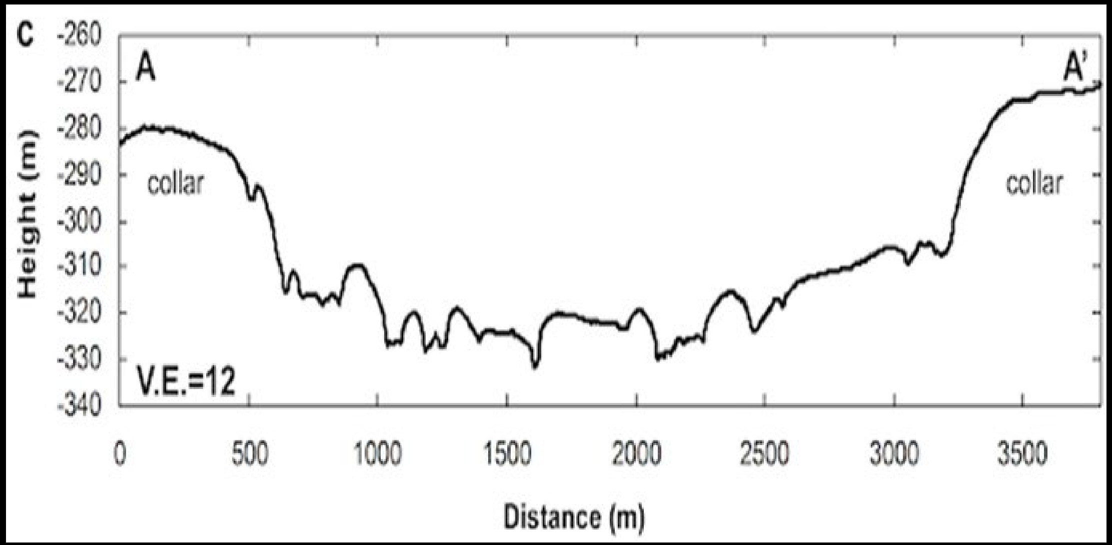
- Irregular Mare Patches (Ina Caldera)
- Silicic Domes (Gruithuisen Domes)
- Moscoviense Basin
- South Pole-Aitken Basin
- Single Target within the SPA Basin: Schrodinger Basin

H → J+

Single mission → Campaign of Missions

Irregular Mare Patches (Ina Caldera)





Irregular Mare Patches (Ina Caldera)

Important science:

- Resolve whether these deposits are very young (<100 Ma Branden et al., 2014) or old (3.5 Ga, Qiao et al., 2017) by determining absolute age of materials.

- If young provides information on the nature (chemistry, mineralogy, depth of melting) of some of the last LMO cumulates to melt. Further, would provide a temporal evaluation of the release of volatiles from the lunar interior.

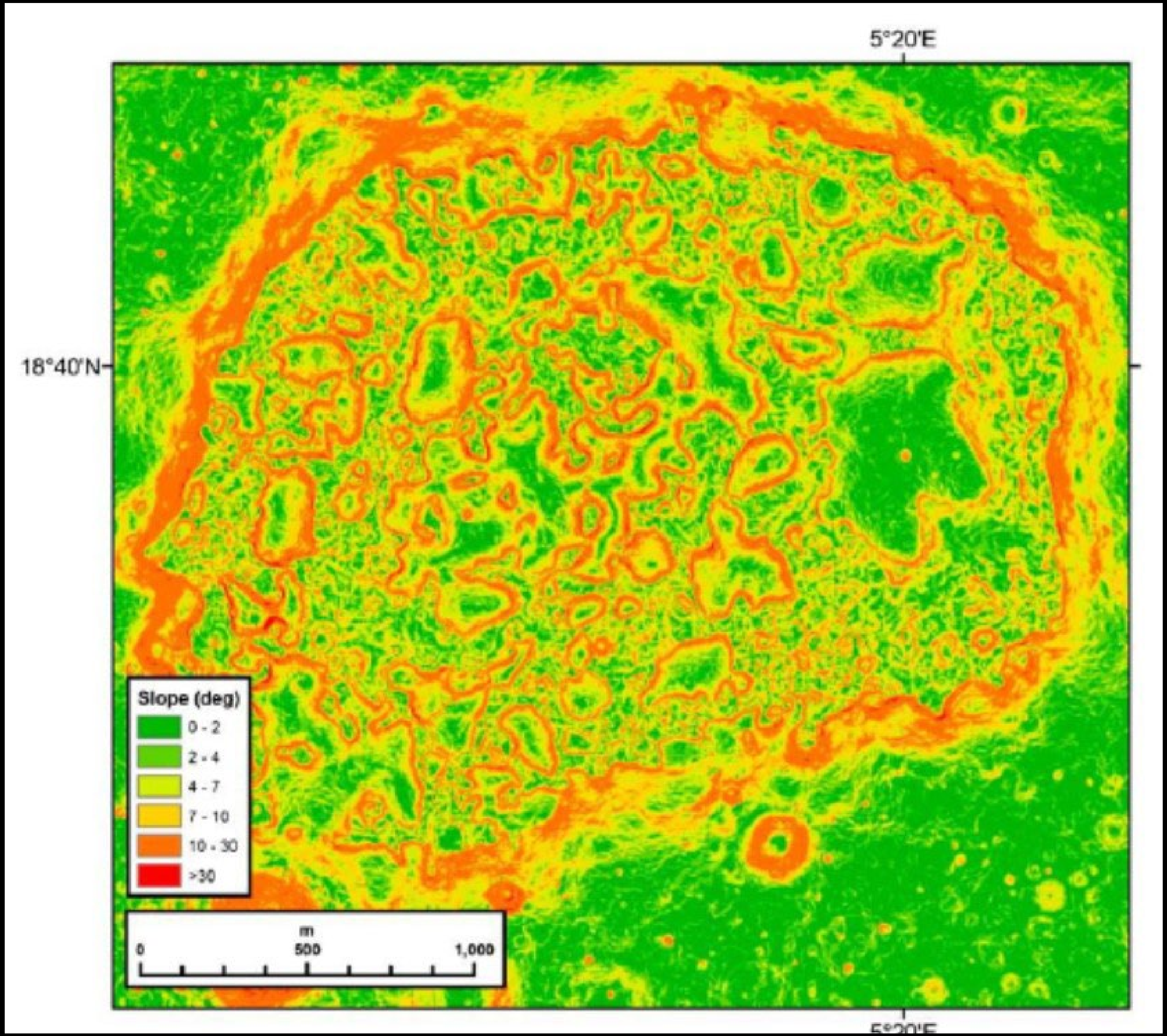
- If older, what chemical-volatile characteristics influence these unique morphologies and what does this say about mantle sources? These volcanics are proposed to be very porous, how does this characteristic influence response to impact and crater counting chronology.

- These are unique morphologies compared to other mare basalt terrains. What are the volcanic processes producing these features and are they similar to terrestrial analogs?

Irregular Mare Patches (Ina Caldera)

Why not at the South Pole. This type of material is absent at the South Pole region of the Moon.

Access needs fulfill science compared to Apollo G,H, J missions. Due to the small size of these features and access to important portions via slopes of 10-15º H mission capability would be appropriate.



Irregular Mare Patches (Ina Caldera)

Role of samples

Essential or secondary to completing science: Sampling is essential to fulfilling science goals. Chronology is important, but does not require large mass.

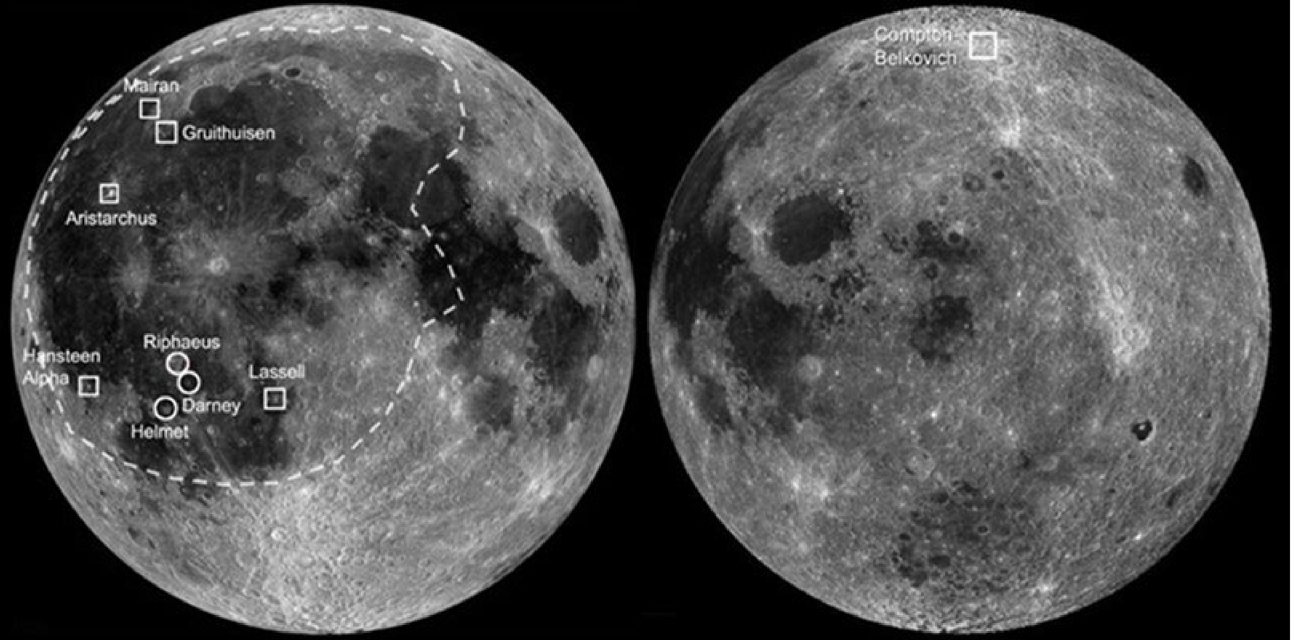
Sample types: Unique geological environment compared to the South Pole and Apollo landing sites. Individual hand samples of basalts. There could be volcanic or impact breccias consisting of mare basalts depending on age. Basalts with different degrees of porosity would be important to collect. Double drive tubes of regolith (70 cm) and rake samples.

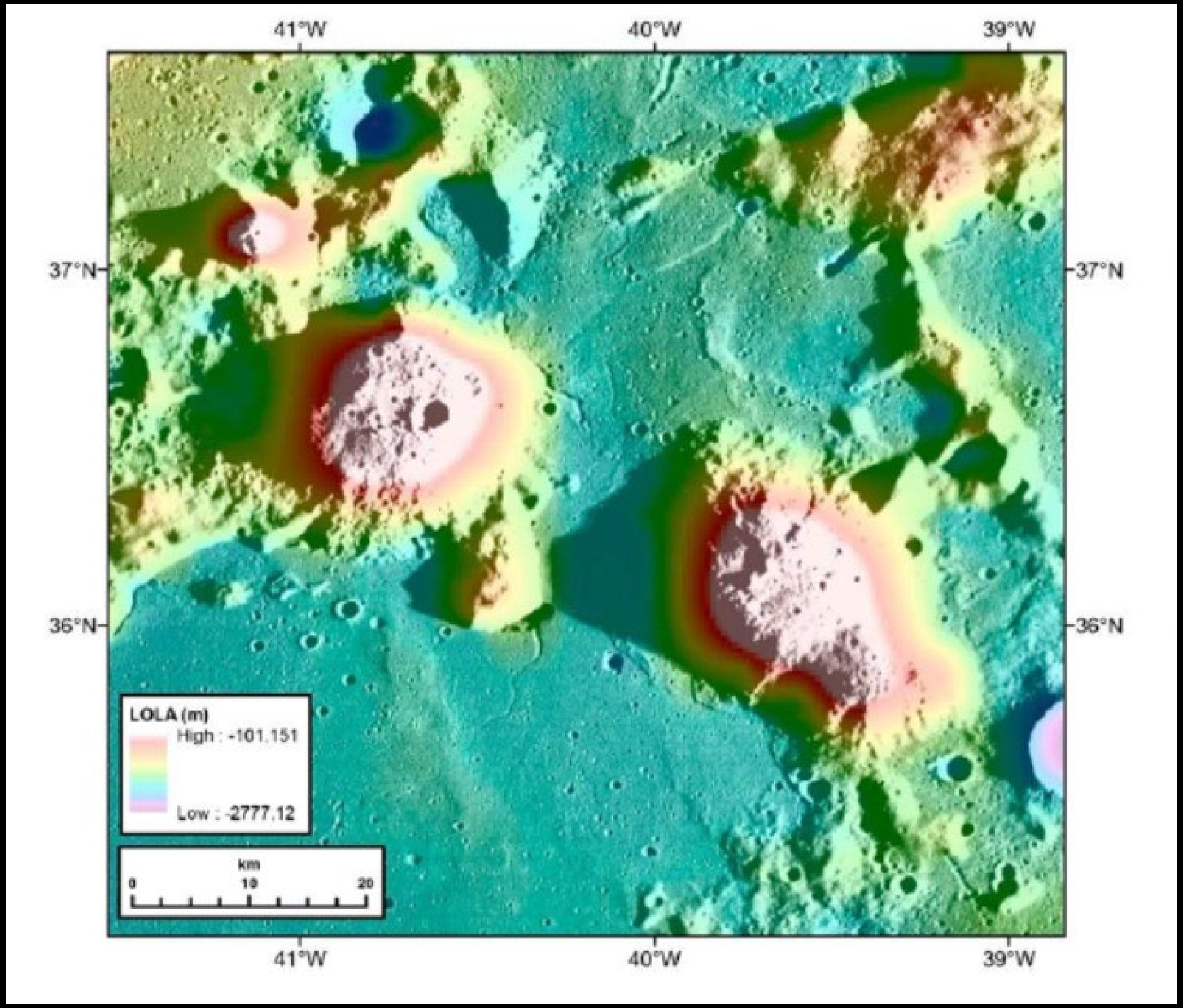
Sample mass: Representative samples need to be collected, but as these are basalts a large mass is not required to accomplish science. Total 50 kg

Role of human presence:

There will be steep slopes, but these can be avoided during human traverses. The geology may be fairly complex with different episodes of emplacement and degassing. Human geological context important. Boots on the ground examination of porosity and double drive tube collection. Local geophysical station (e.g., heat flow.

Silicic Domes (Gruithuisen Domes)

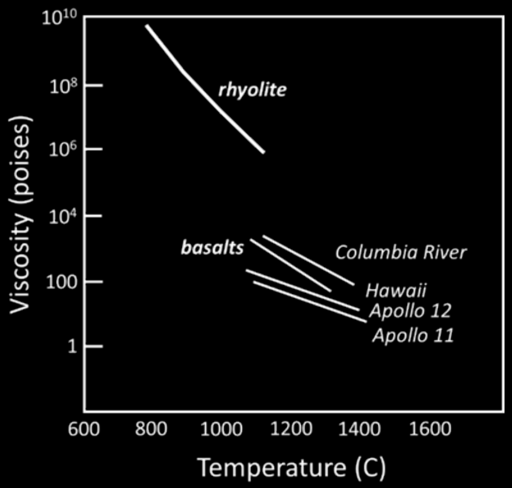




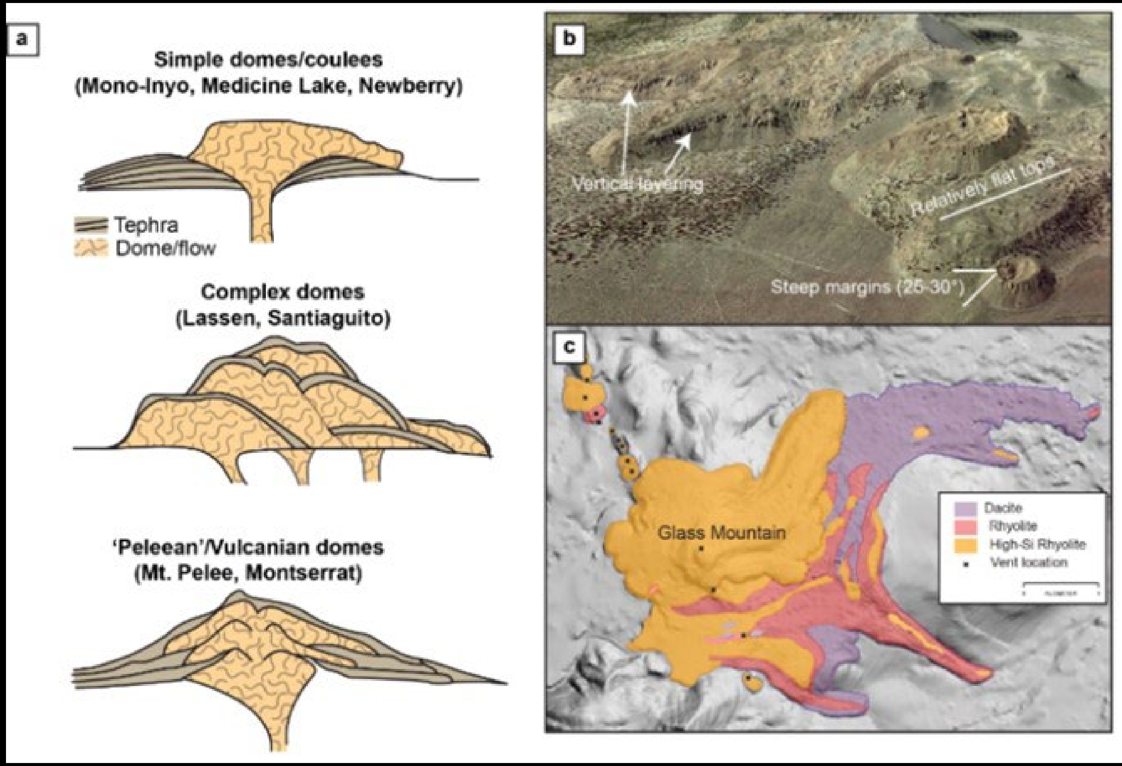
Silicic Domes (Gruithuisen Domes)

Important science

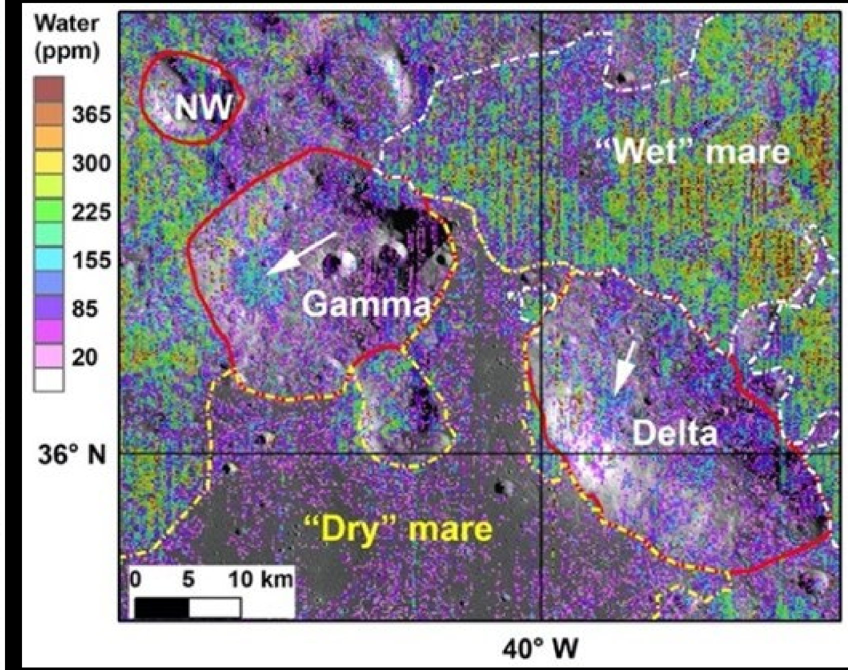
Origin of rhyolitic magmas in a basaltic planet. Petrogenetic relationship to rhyolitic material in Apollo samples.



Formation of rhyolitic domes on the Moon. Absolute chronology of rhyolitic magmatism



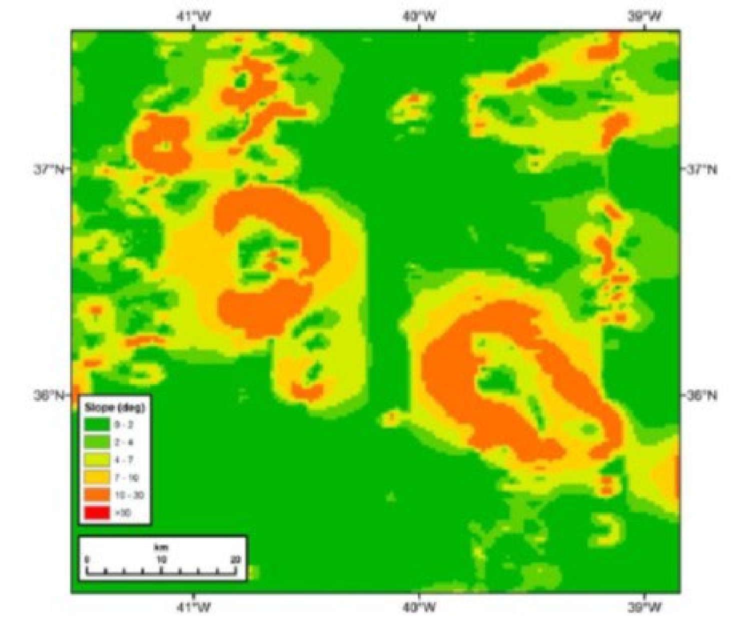
Volatiles in lunar rhyolitic and basaltic systems

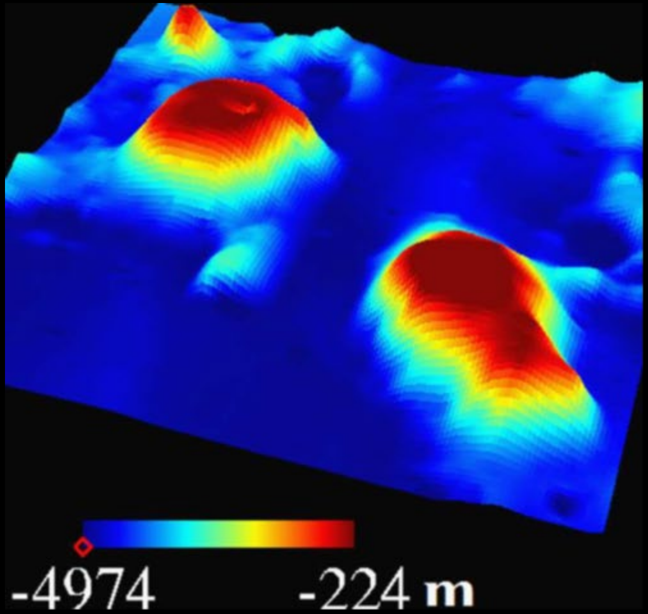


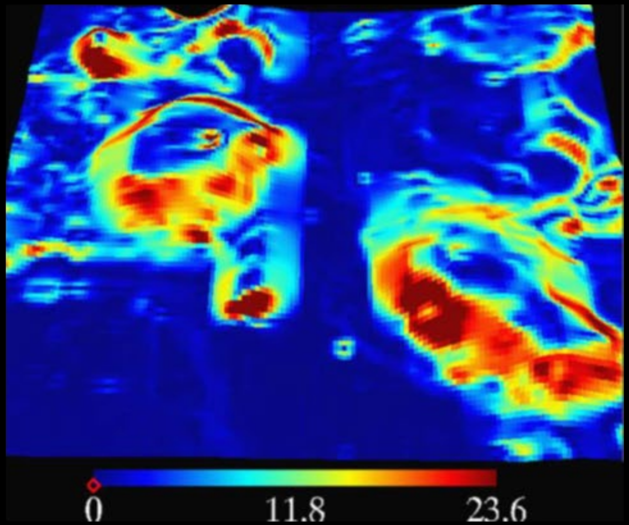
Silicic Domes (Gruithuisen Domes)

Why not at the South Pole. No known locations at the South Pole.

Access needs fulfill science compared to Apollo G,H, J missions. J mission capabilities required to examine these features.







LOLA Digital Elevation Model (DEM) Kusuma et al., (2012)

Silicic Domes (Gruithuisen Domes)

Role of samples

Essential or secondary to completing science: Sampling is ***e***ssential to fulfilling science goals. There is some additional highland science that may be accomplished.

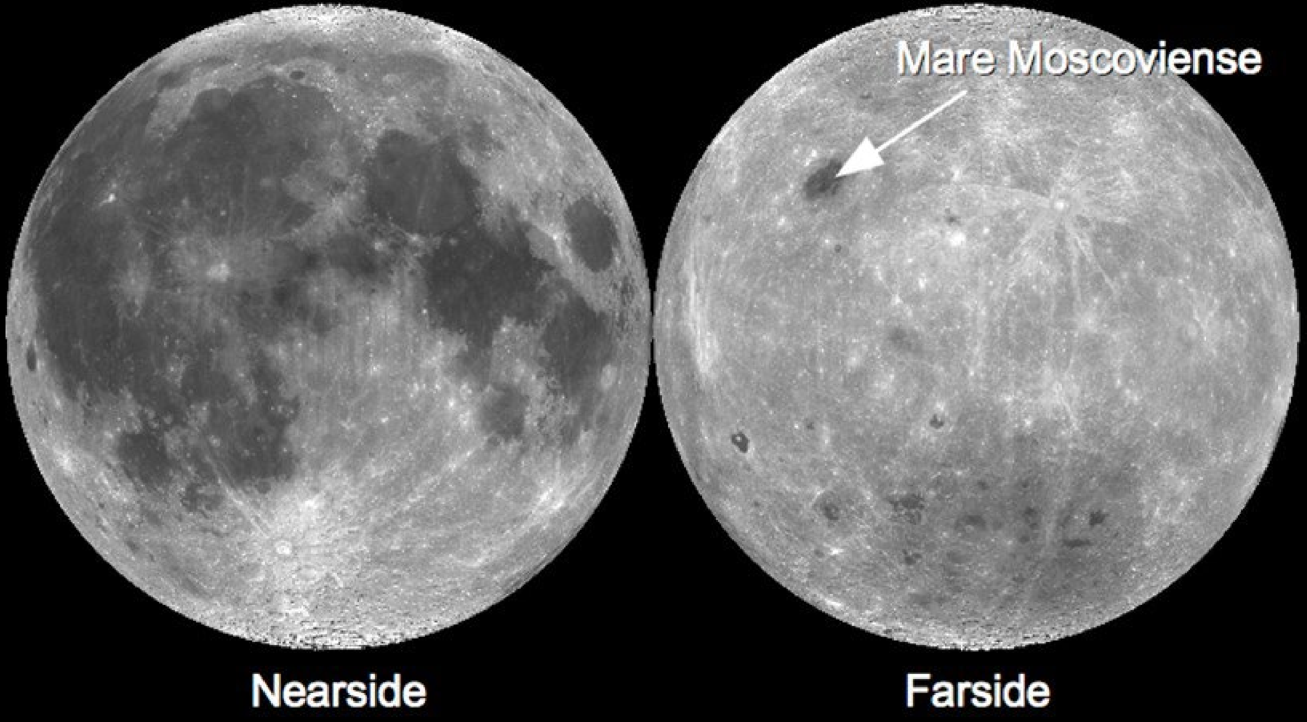
Sample types: Unique geological environment compared to the South Pole and Apollo landing sites. Individual hand samples of dome material and basalts. This may include volcanic brecias. Further, there are highland material at this site which would enable bonus science. Double drive tubes of regolith (70 cm) and rake samples similar to Apollo sample collection approaches.

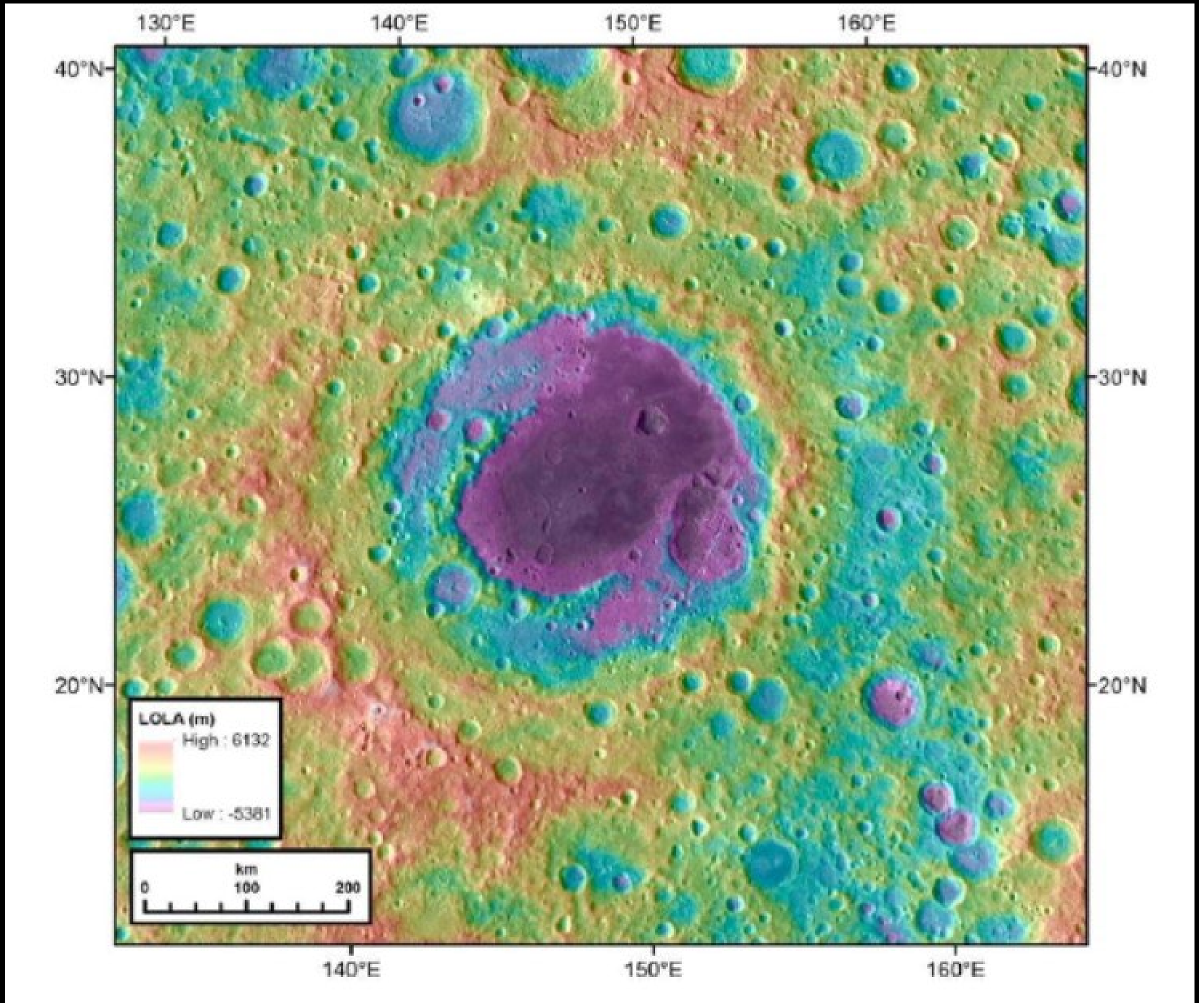
Sample mass: Total 100 kg

Role of human presence:

Domes may be fairly complex with different episodes of emplacement and degassing. Human geological context important. There will be steep slopes that will exceed safety standards. Utilization of rover with unique capabilities to aid human exploration endeavors. Local geophysical stations.

Moscoviense Basin

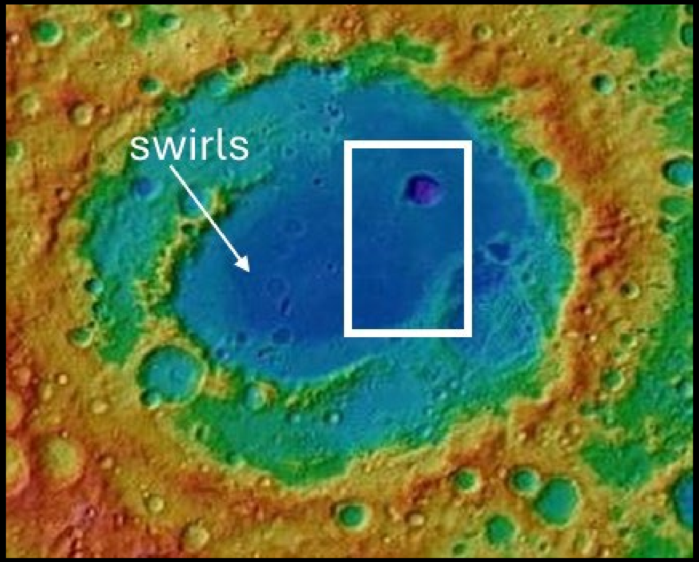


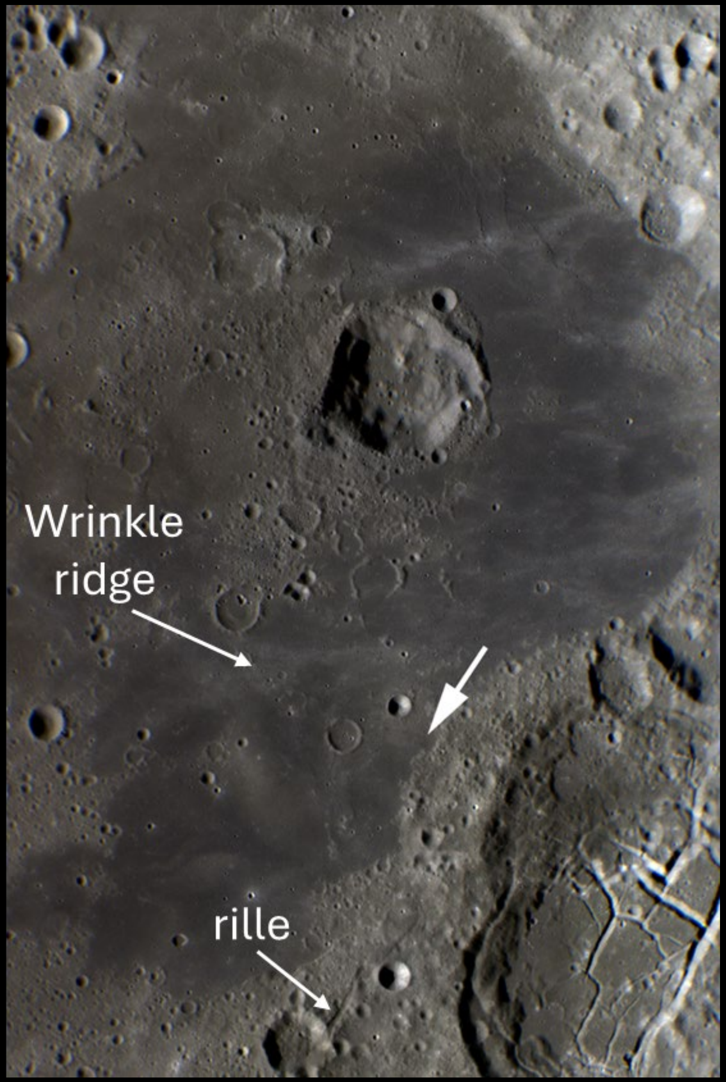


Moscoviense Basin

Important science:

- Determine the chronology, composition of far side basaltic magmas (low-Ti, and high-Ti, high-Al) provide important insights into the mantle sources on far side, existence of near-side, far-side mantle dichotomy, and origin of crustal dichotomy.



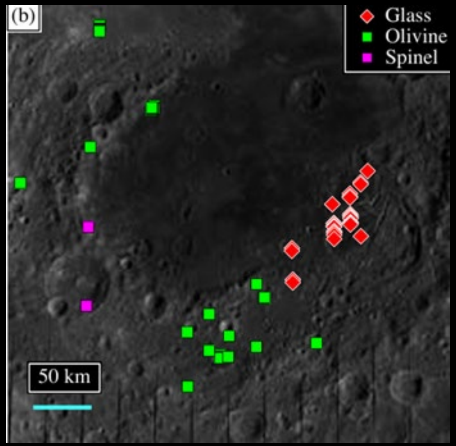


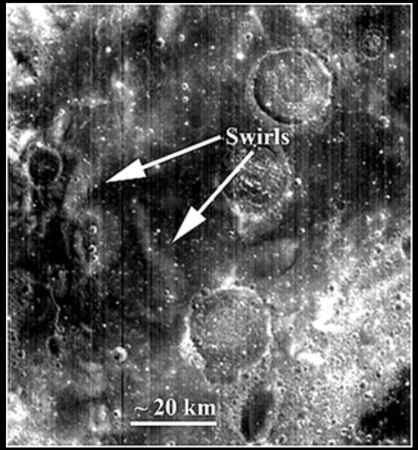
- Determine chronology and diversity of far-side crustal rocks from suite of highlands rocks in peak ring.
- Examination of pyroclastic deposits on far-side addresses volatiles distribution in the mantle.
- Regolith evolution and solar history from young, small impacts.
- Absolute chronology of impact event from impact melt sheet.
- Examination of wrinkle ridges help constrain internal structure and thermal history.
- Heat-flow measurements on thin crust on far-side constrain mantle component to lunar heat flow.
- Understand the dynamics of the lunar core and history/intensity of the Moon's magnetic field.

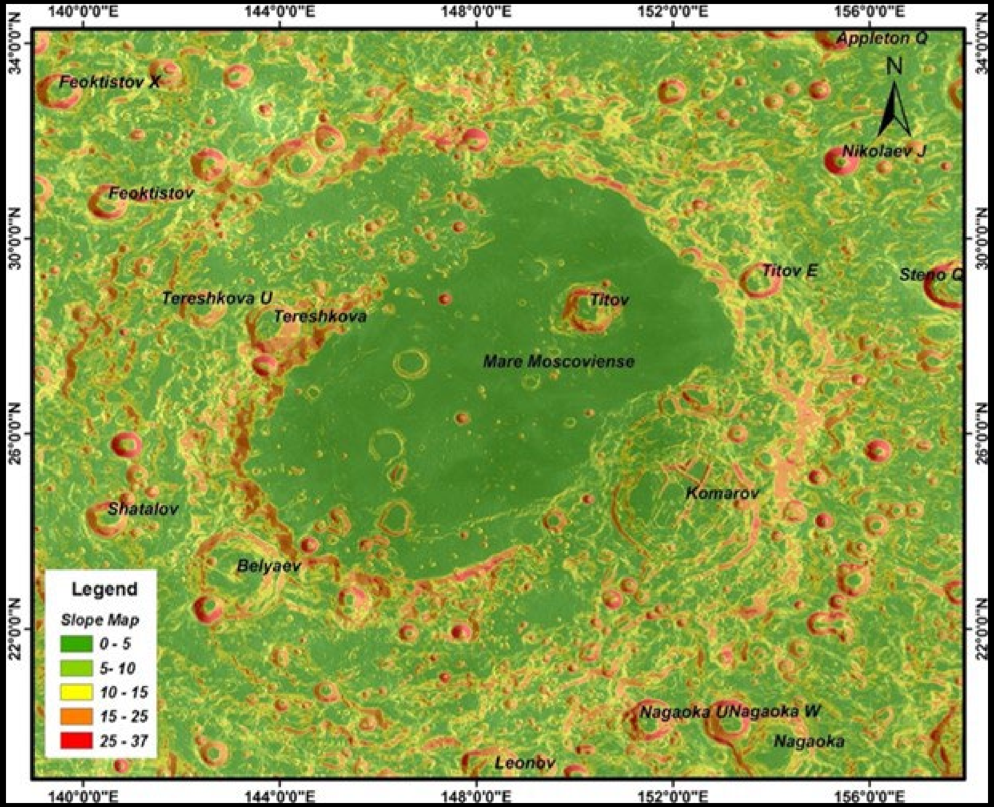
Moscoviense Basin

Why not at the South Pole. Geologic environment and potential materials distinct from the South Pole. Abundant far-side basalts, variety of ancient crystal rocks, relatively thin crust adjacent to thick far-side crust, swirls, tectonic features.

Access needs fulfill science compared to Apollo G,H, J missions. J style mission capabilities is required to explore a limited region of the basin.







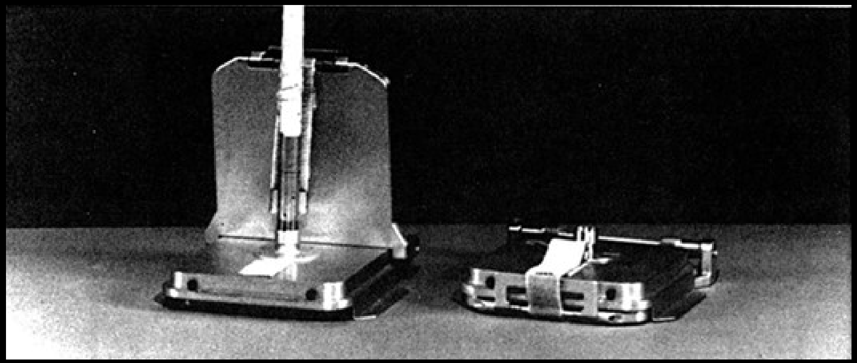
Moscoviense Basin

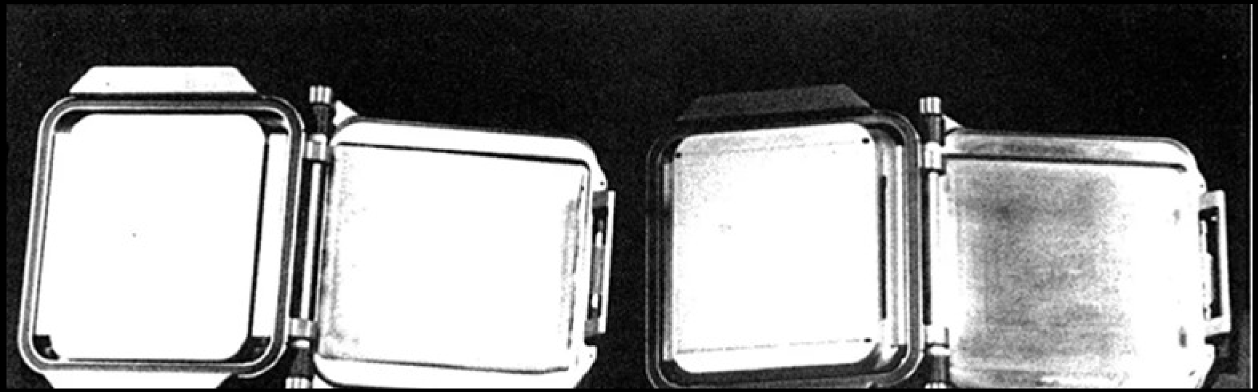
Role of samples

Essential or secondary to completing science: Sampling is essential to fulfilling science goals.

Sample types: Unique geological environment compared to the South Pole and Apollo landing sites. Individual hand samples of various types of basalts and highland samples, impact melt rocks, and potential breccias. Pyroclastic samples and regolith collected by double drive tubes (70 cm). Potential ancient regolith collected at new impacts. Rake samples could collect adjacent FAN terrain. Collection of swirl material requires modification of Apollo approaches (e.g. contact soil sampling device, trenching).

Sample mass: Total 100+ kg





Moscoviense Basin

Role of human presence:

Human’s provide geologic context.

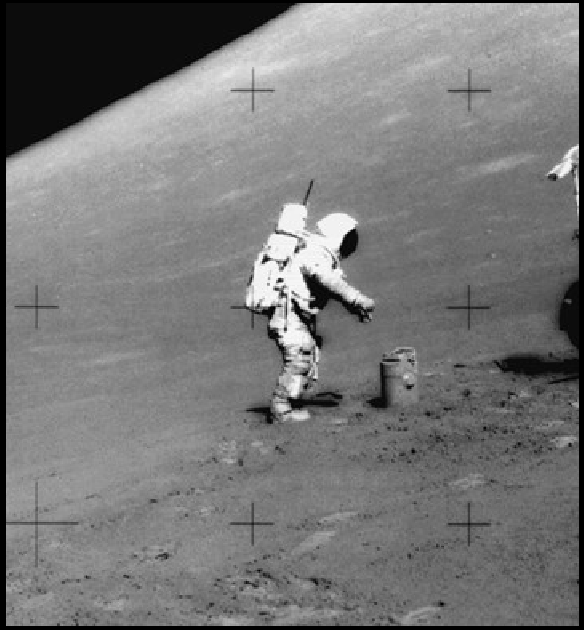
Sample collection will involve trenching, double drive tube collection, raking, Sealed samples (GAC, SEC,CSVC) and perhaps contact soil sampling.

Large highland samples (20 pounds) consisting of breccias may be required.

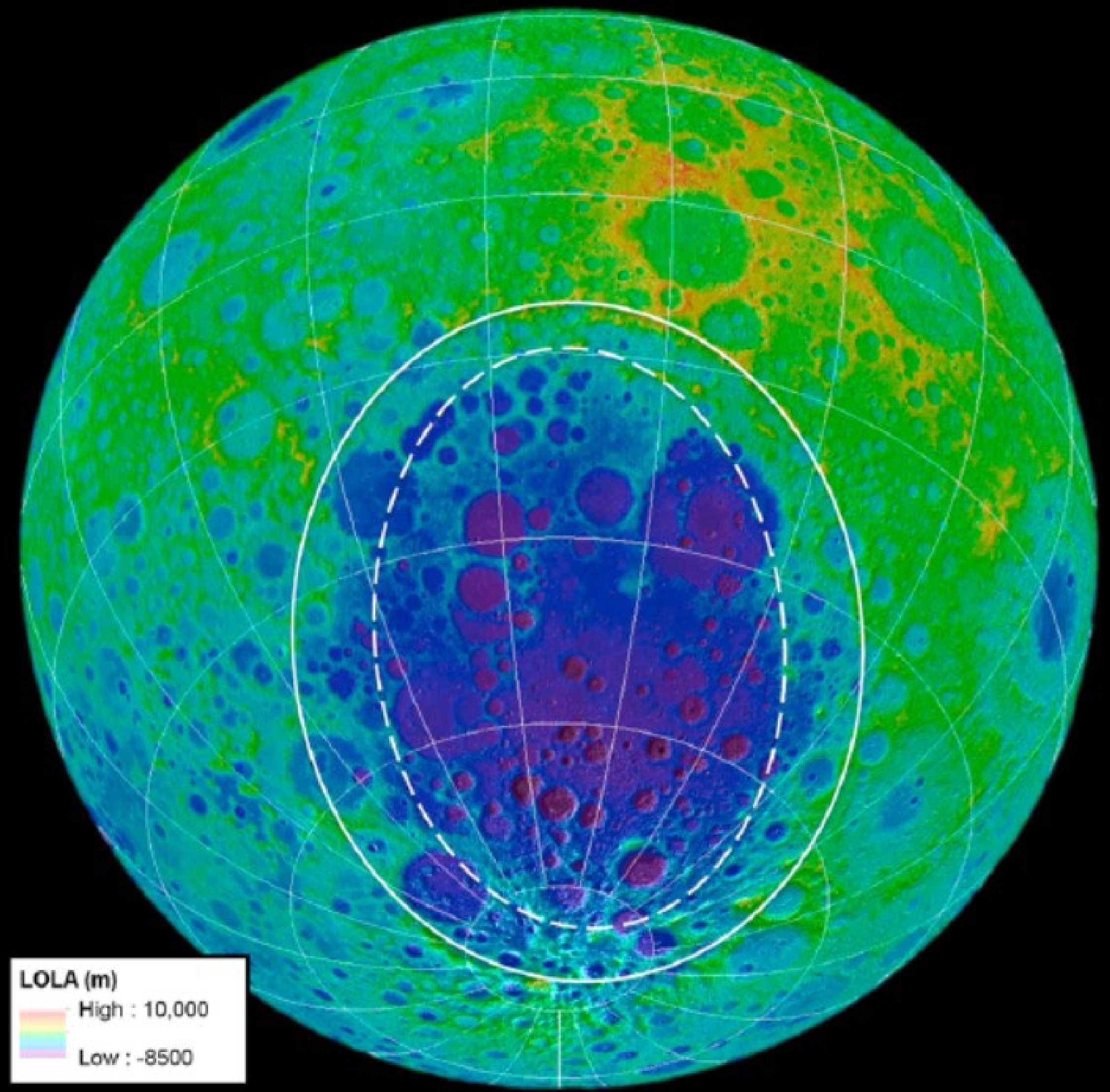
Identification of highland samples with high probability of yielding chronology.

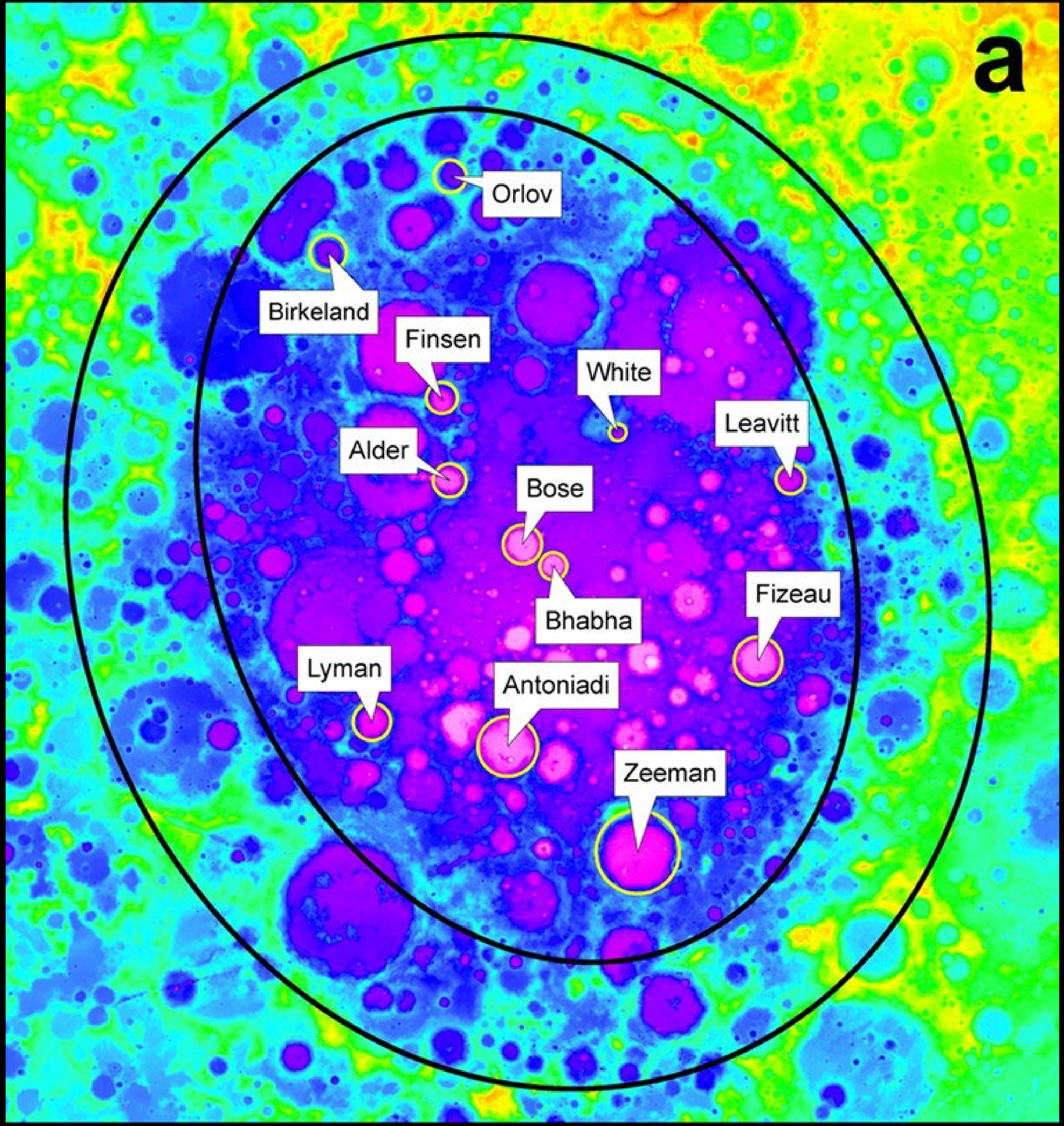
Deployment of static geophysical stations.

Geophysical measuremts during EVAs that include gravity and magnetics.



South Pole-Aitken Basin





Vaughan and Head (2014)

South Pole-Aitken Basin

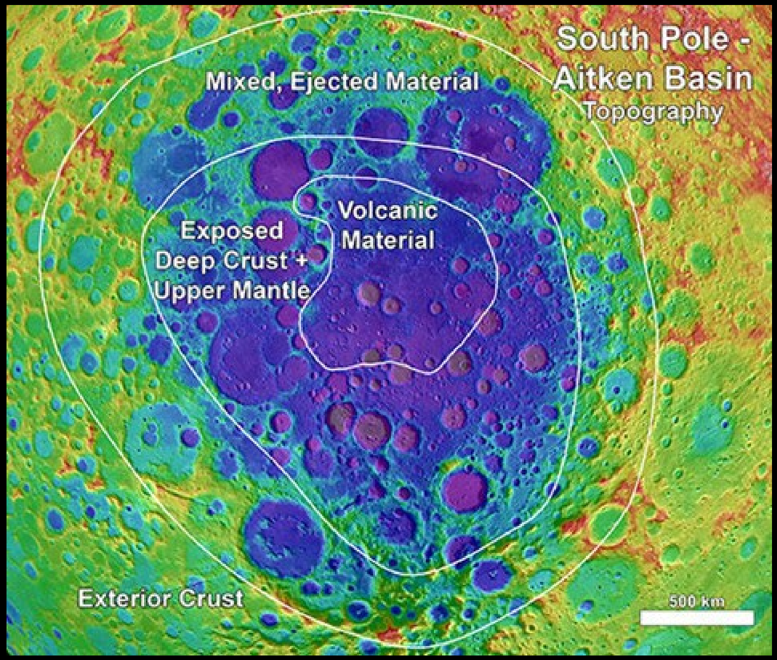
Important science:

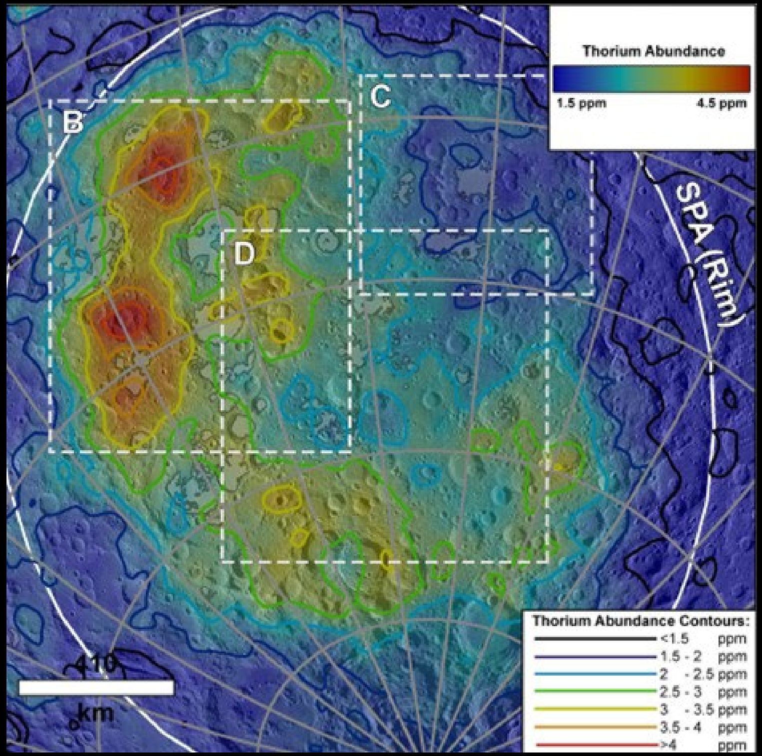
- Determine the age of the SPA impact event.
- Determine the chronology of impact events post-SPA.
- Reconstruct the dynamics and evolution of large impact basins.
- Explore the lunar mantle, the thermal history of the Moon, and lunar differentiation.

  Mantle at the lunar surface

  Basalts derived from the lunar mantle (Crypto-mare, mare basalts, pyroclastic deposits

  Crater floor fractures
- Determine the nature and distribution of lunar volatiles in the lunar mantle.
- Understand the dynamics of the lunar core and history/intensity of the Moon’s magnetic field (impact melts, mare basalts, crypto mare).

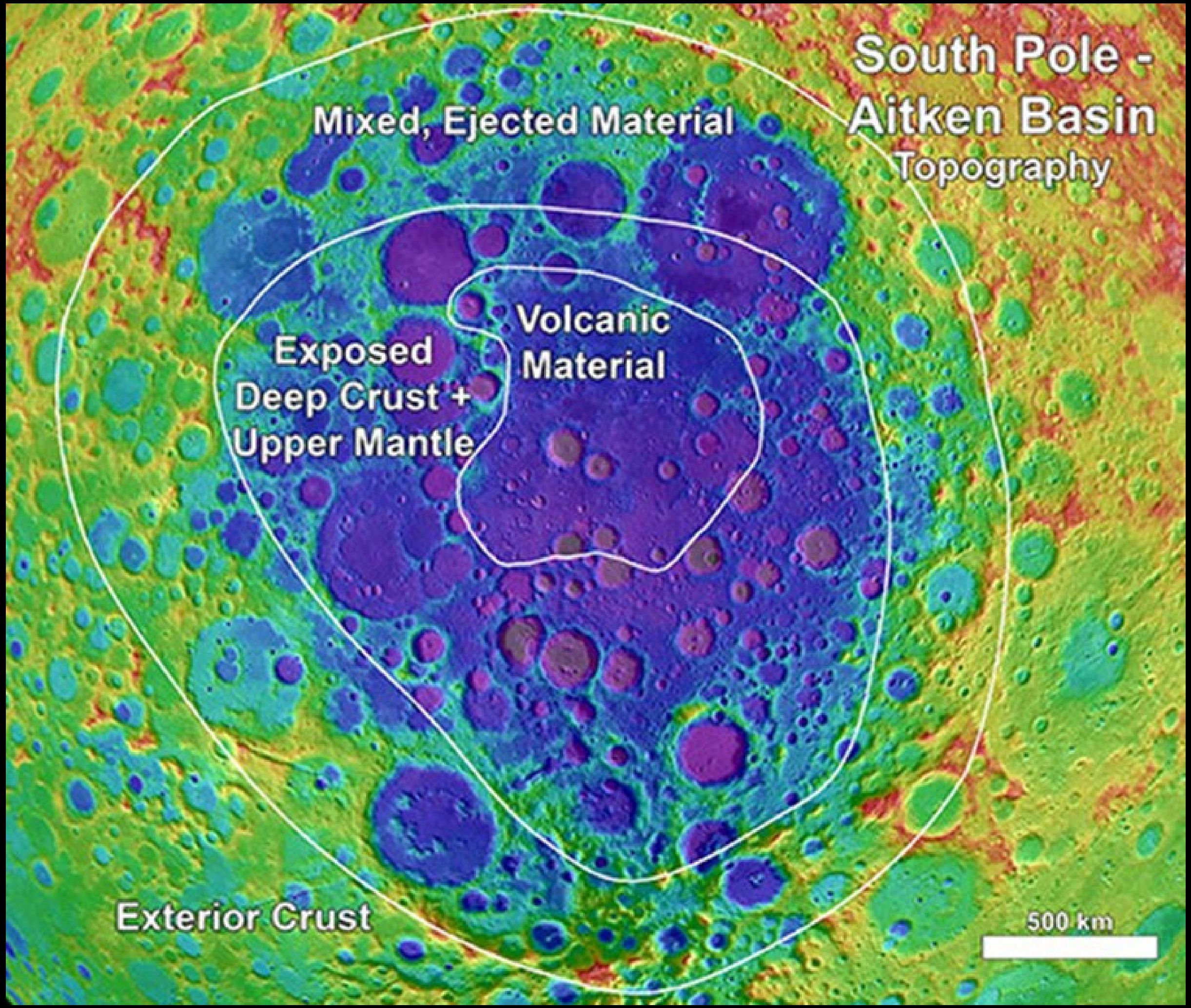




South Pole-Aitken Basin

Why not at the South Pole. There should be SPA material ejected into the south pole region. However, there is an issue with geologic context.

Access needs fulfill science compared to Apollo G,H, J missions. J+ mission capabilities is required to carry out SPA missions. But there are multiple important sites that could be 100 kms away from each other in distance.



Moriarty et al (2013, 2018, 2021)

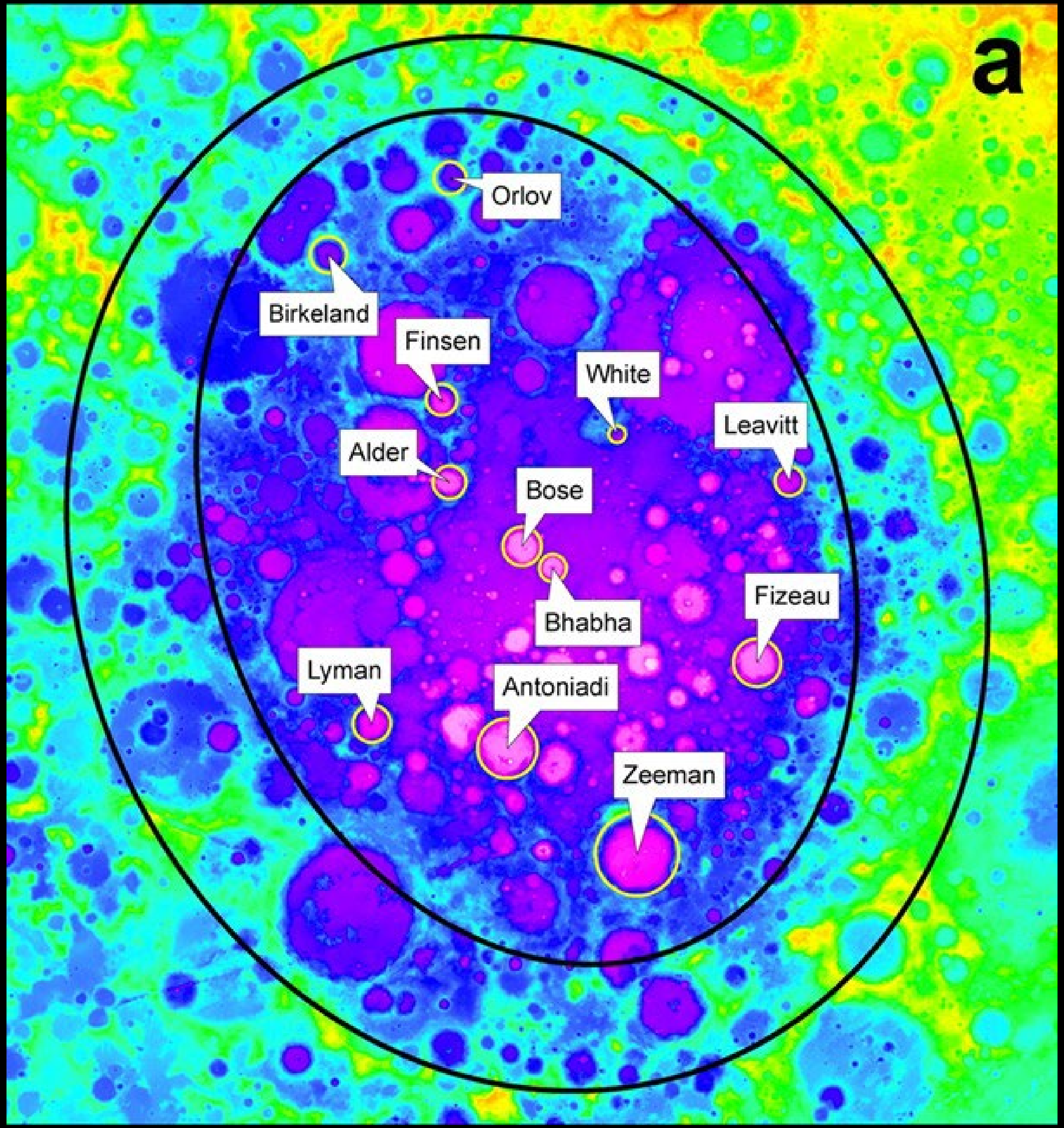
South Pole-Aitken Basin

Role of samples

Essential or secondary to completing science: Sampling is ***e***ssential to fulfilling science goals.

Sample types: Individual hand samples of various types of basalts (mare and crypto-mare) and highland samples, impact melt rocks, and potential breccias. Collection of impact melts from various impact features will not only establish chronology of events, but also provide insights into interpretation of SPA event. Pyroclastic samples and regolith collected by double drive tubes (70 cm). Different levels of SPA impact melt sheet may be collected at different craters/basins. Rake samples could collect a variety of unique materials.

Sample mass: Total 100+ kg



South Pole-Aitken Basin

Role of human presence:

Human’s provide geologic context.

Sample collection will involve trenching, double drive tube collection, raking, and sealed samples (GAC, SEC,CSVC) and perhaps contact soil sampling.

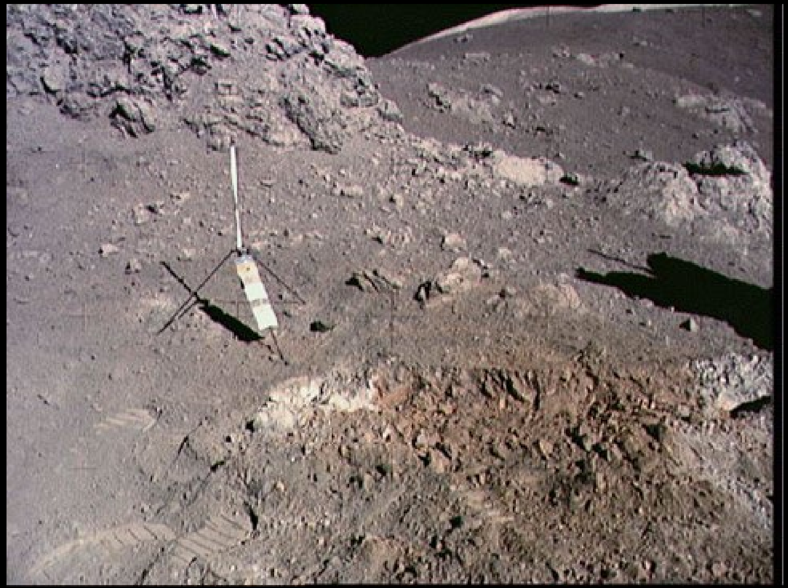
Large highland samples (20 pounds) consisting of breccias may be required.

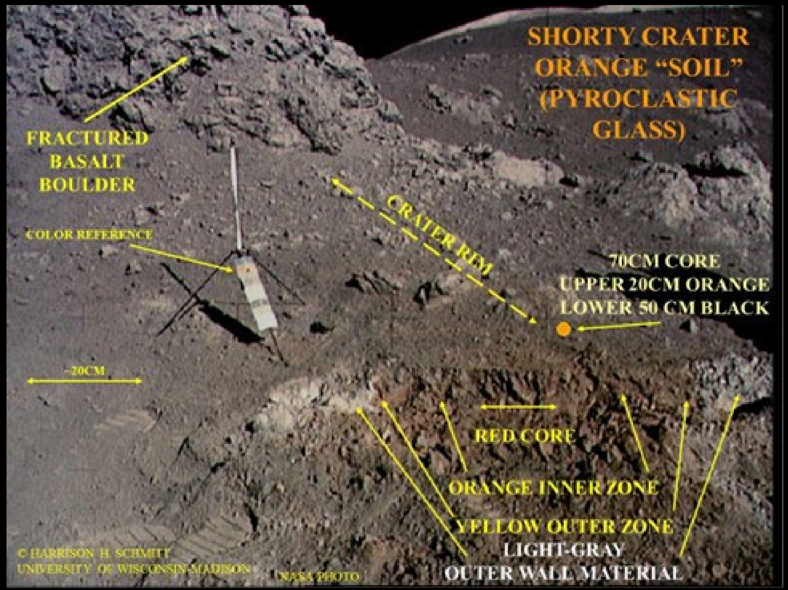
Identification of samples with high probability of yielding chronology.

Deployment of static geophysical stations.

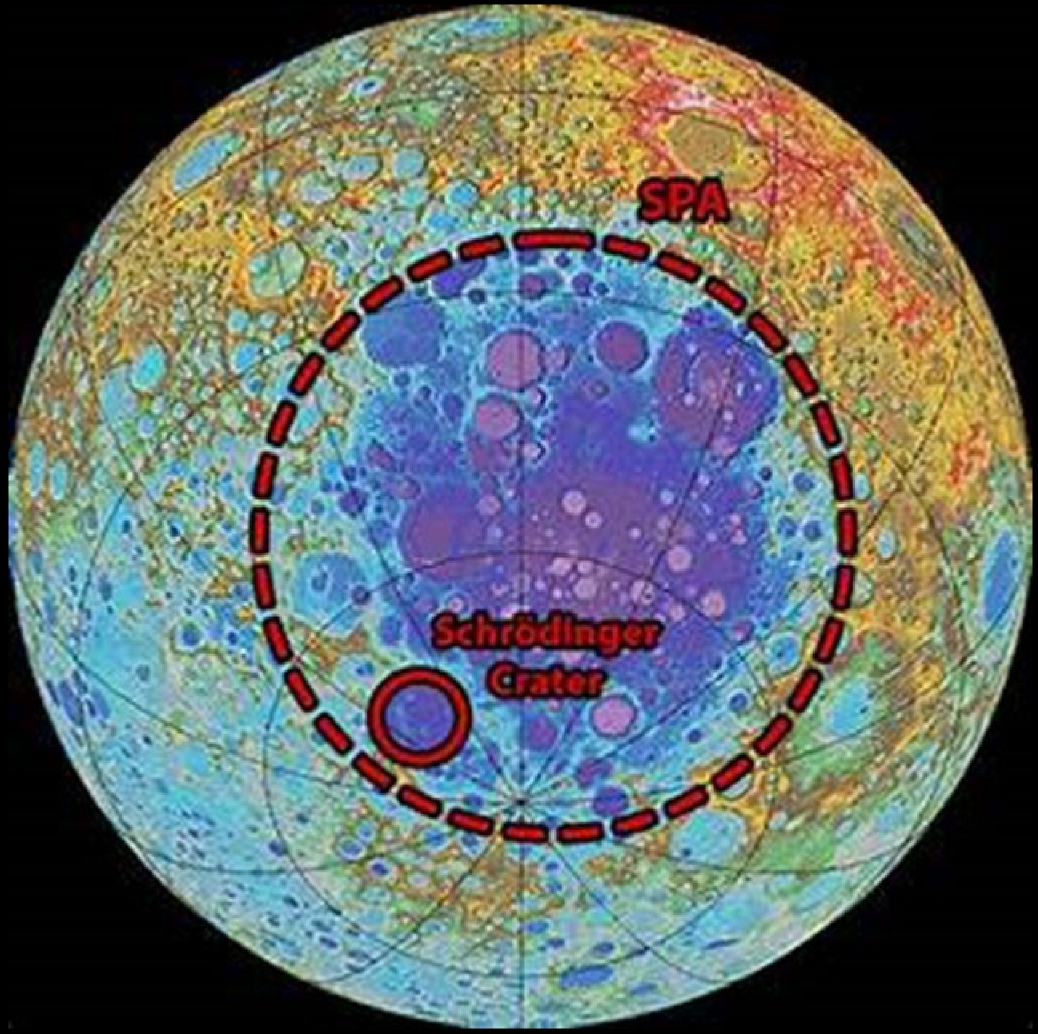
Geophysical measurements during EVAs that include gravity and magnetics.

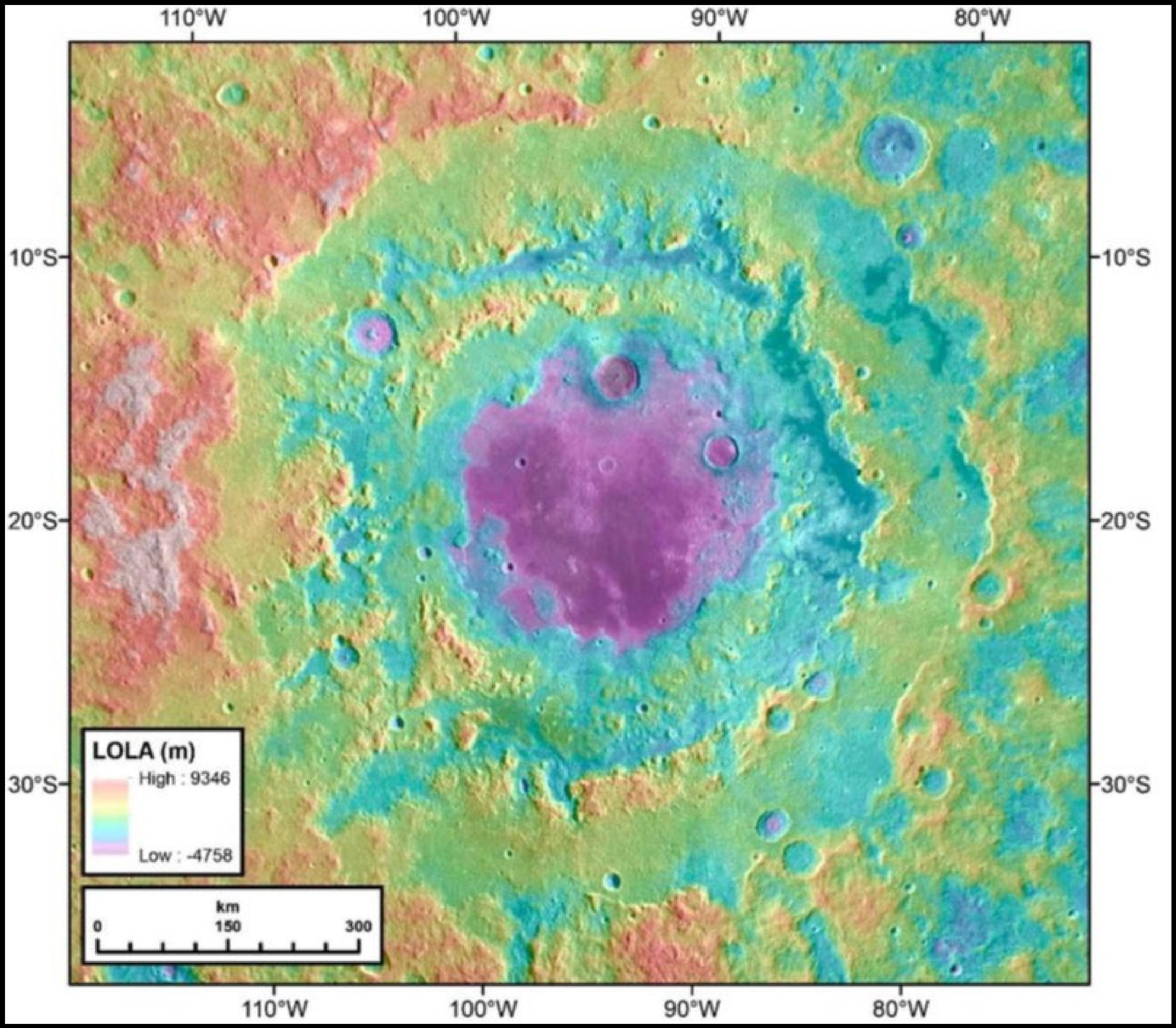
Still, this is best suited for a single site in a campaign, long term rover mission, or a rover mission that links human missions.





Single Target within the SPA Basin: Schrodinger Basin

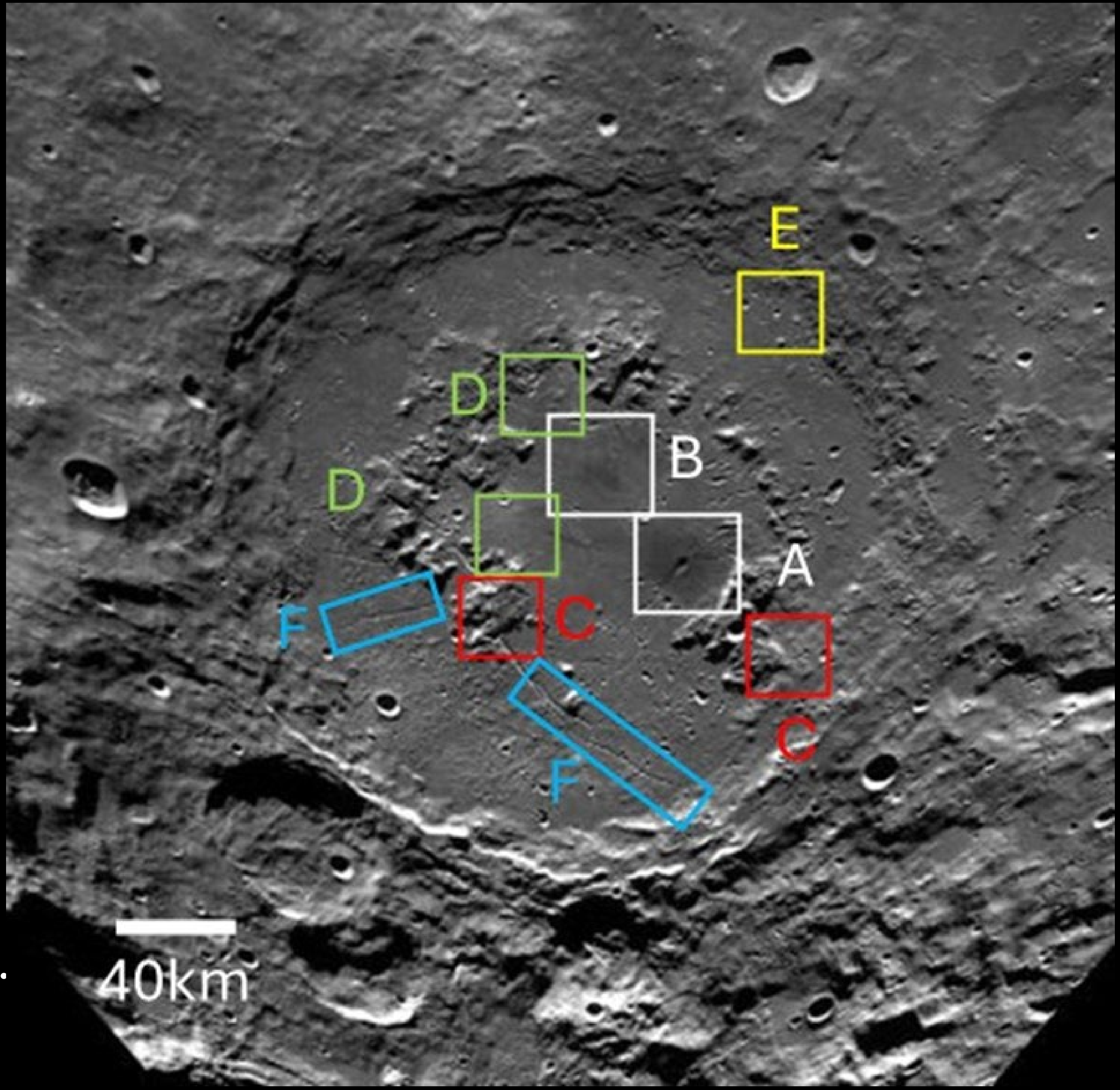




Single Target within the SPA Basin: Schrodinger Basin

Important science:

- Determine the distribution of volatiles in the lunar mantle (A). Perhaps best pyroclastic deposit to sample.
- Determine the sources of far-side mare magmatism (A,B).
- Determine the lateral heterogeneity of LMO cumulates (A,B).
- Determine the diversity and chronology of the ancient lunar crust. Determine the origin for the diversity and chronology (C).
- Determine the chronology of impact events in the SPA (D,E).
- Determine the age of the SPA event (E).
- Determine the thermal evolution of the Moon (A,B,F).
- Understand the dynamics of the lunar core and history/intensity of the Moon's magnetic field (A,B,D,E).

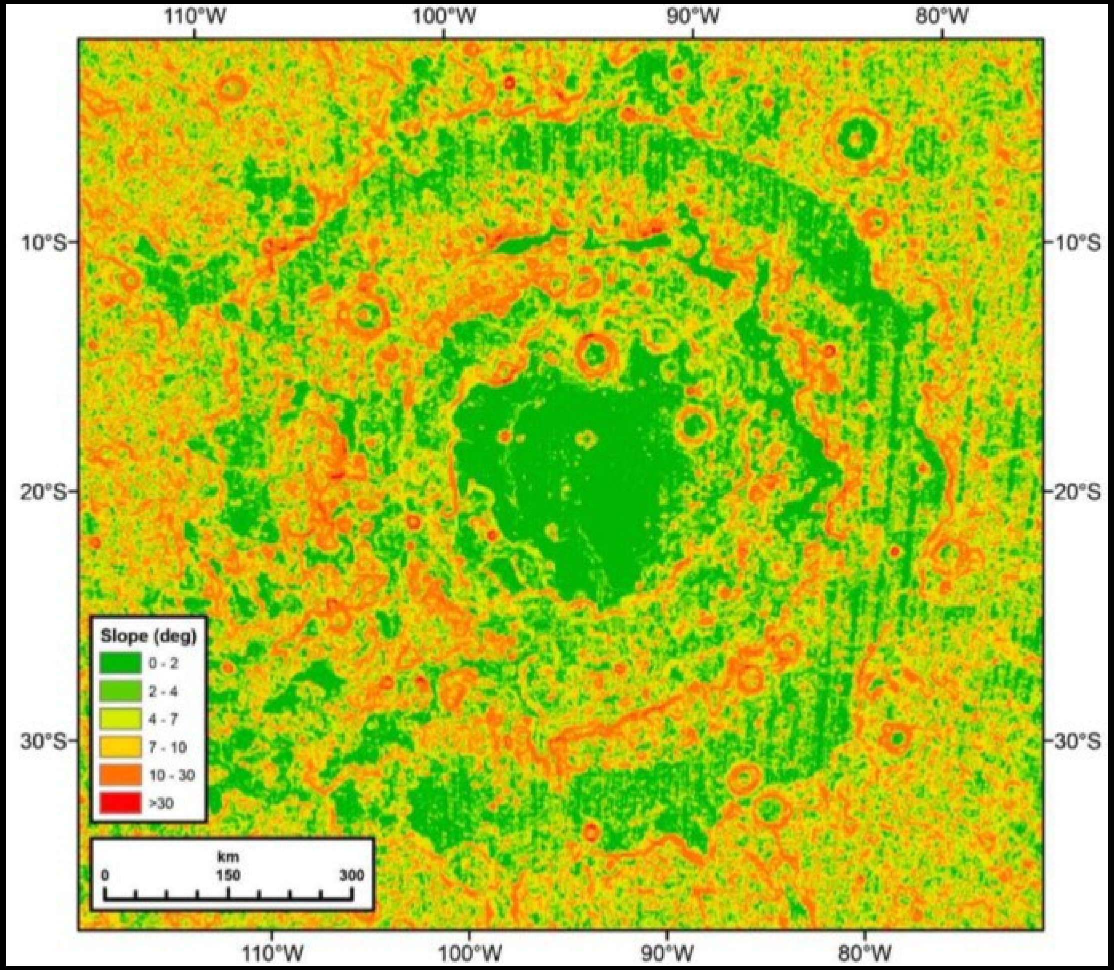


Modified after D. Kring and colleagues

Single Target within the SPA Basin: Schrodinger Basin

Why not at the South Pole. There should be SPA material ejected into the south pole region. However, there is an issue with geologic context.

Access needs fulfill science compared to Apollo G,H, J missions. J mission capabilities is required to carry out SPA missions. But there are multiple important sites that could be 100 kms away from each other in distance.



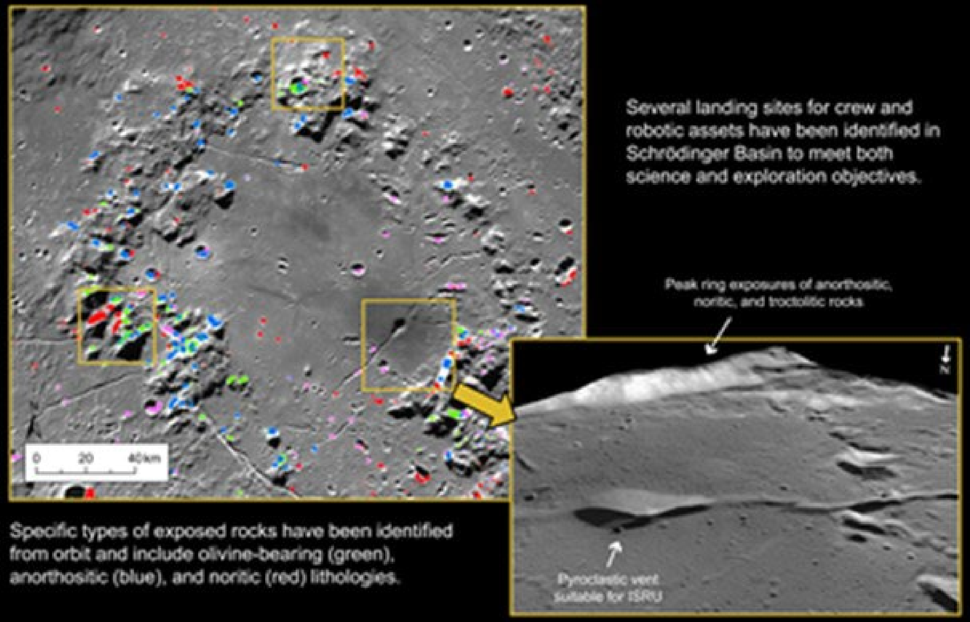
Single Target within the SPA Basin: Schrodinger Basin

Role of samples

Essential or secondary to completing science: Sampling is essential to fulfilling science goals.

Sample types: Individual hand samples of various types of basalts and highland samples, impact melt rocks (including SPA), and potential breccias. Pyroclastic samples and regolith collected by double drive tubes (70 cm) and trench samples. Rake samples could collect a variety of local materials.

Sample mass: Total 100+ kg



From D. Kring and colleagues.

Single Target within the SPA Basin: Schrodinger Basin

Role of human presence:

Human's provide geologic context. This is especially true with exploring pyroclastic deposit.

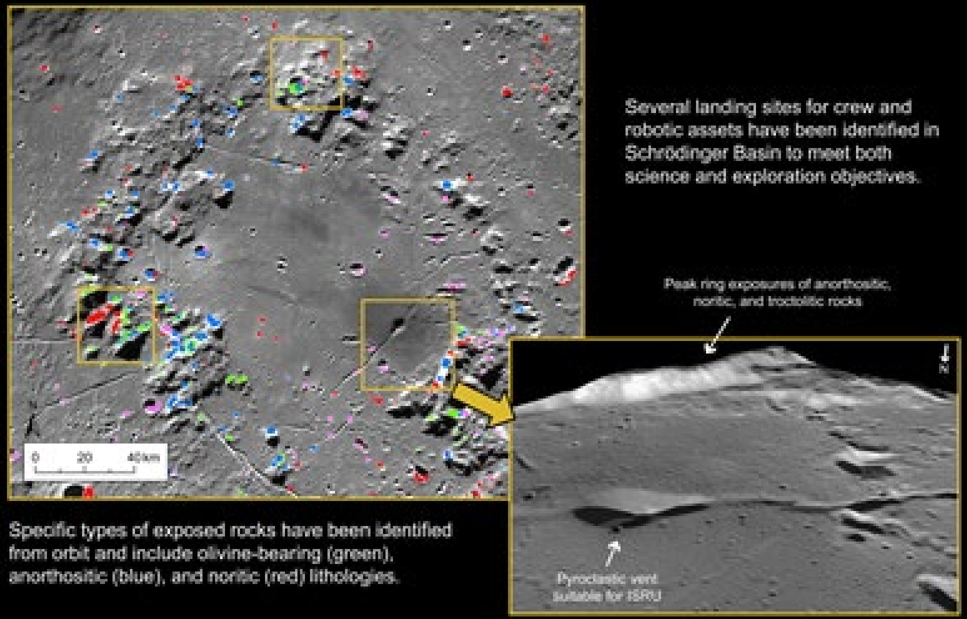
Sample collection will involve trenching, double drive tube collection, raking, and sealed samples (GAC, SEC,CSVC) .

Large highland samples (20 pounds) consisting of breccias may be required.

Identification of samples with high probability of yielding chronology.

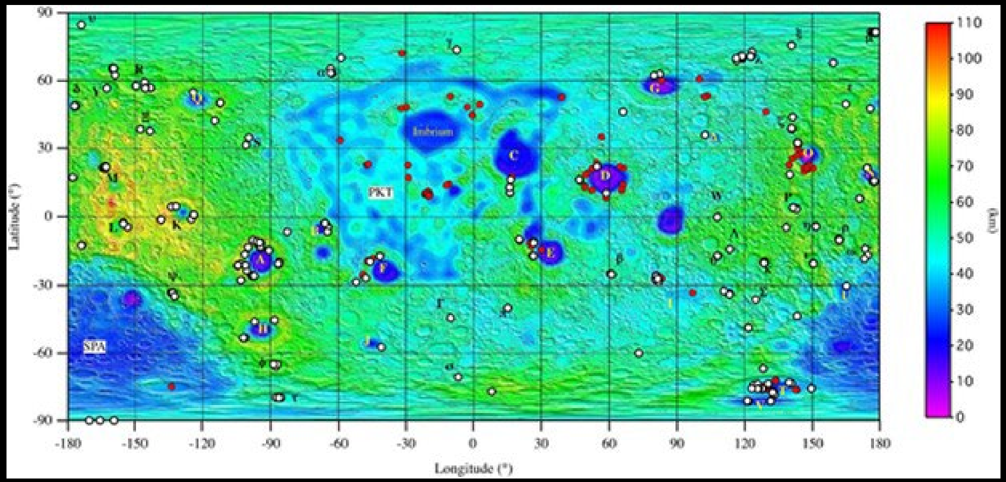
Deployment of static geophysical stations.

Geophysical measurements during EVAs that include gravity and magnetics.

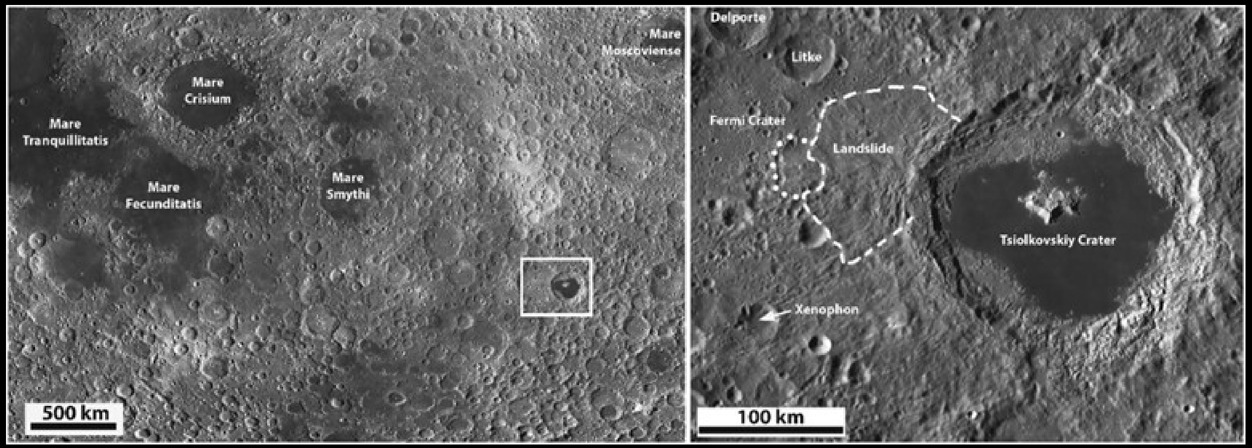


From D. Kring and colleagues.

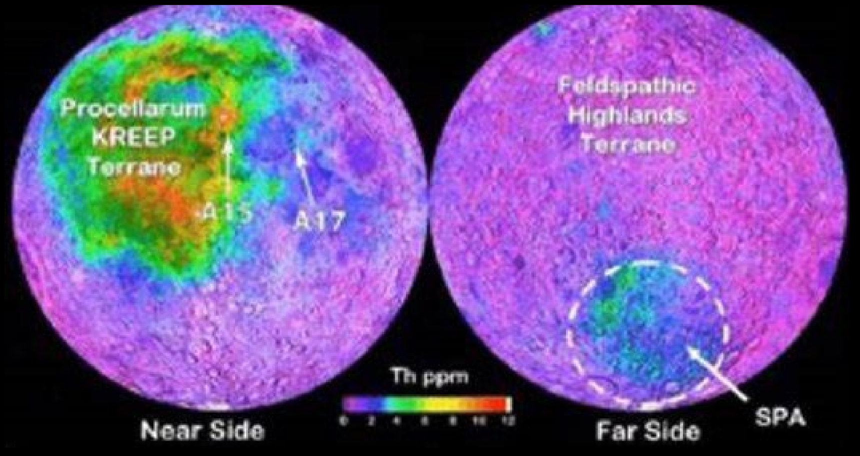
So many other important science targets



Primordial Crust



Tsiolkovskiy basin



KREEP basalts of various ages

Important science questions

- What occurs during the transition between formation of the Moon and first lunar crust?
- What is the origin and timing of the transition between the first lunar crust (FAN) and first period of magmatism (Mg-suite)?
- What is the origin and timing of the transition between Mg-suite magmatism and mare magmatism?
- What is the role of KREEP in lunar magmatism? Does it change with time?

Conclusions

- Many important science targets
- The Jawin et al (2018) report summarizes only a few of the potential sites.
- Many more should be considered for carrying out important lunar science.
- Target science may be achieved with a simple mission (H) to a campaign of multiple missions with J+ mission capabilities.
- Teaming robotic capabilities with humans may be an important component of regional campaigns.