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Lunar South Pole Geology: Preparing for a Seventh Landing & Lunar Surface Science Operations

David A. Kring

With input from the Exploration Science interns
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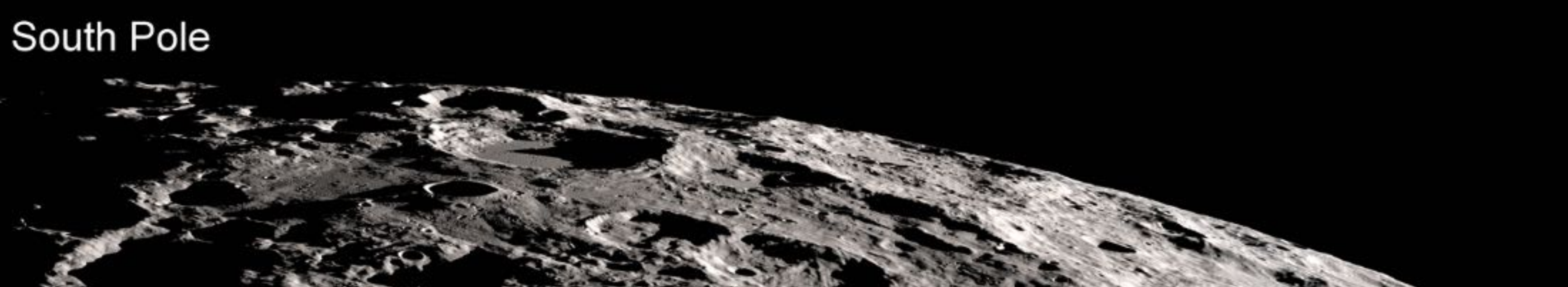
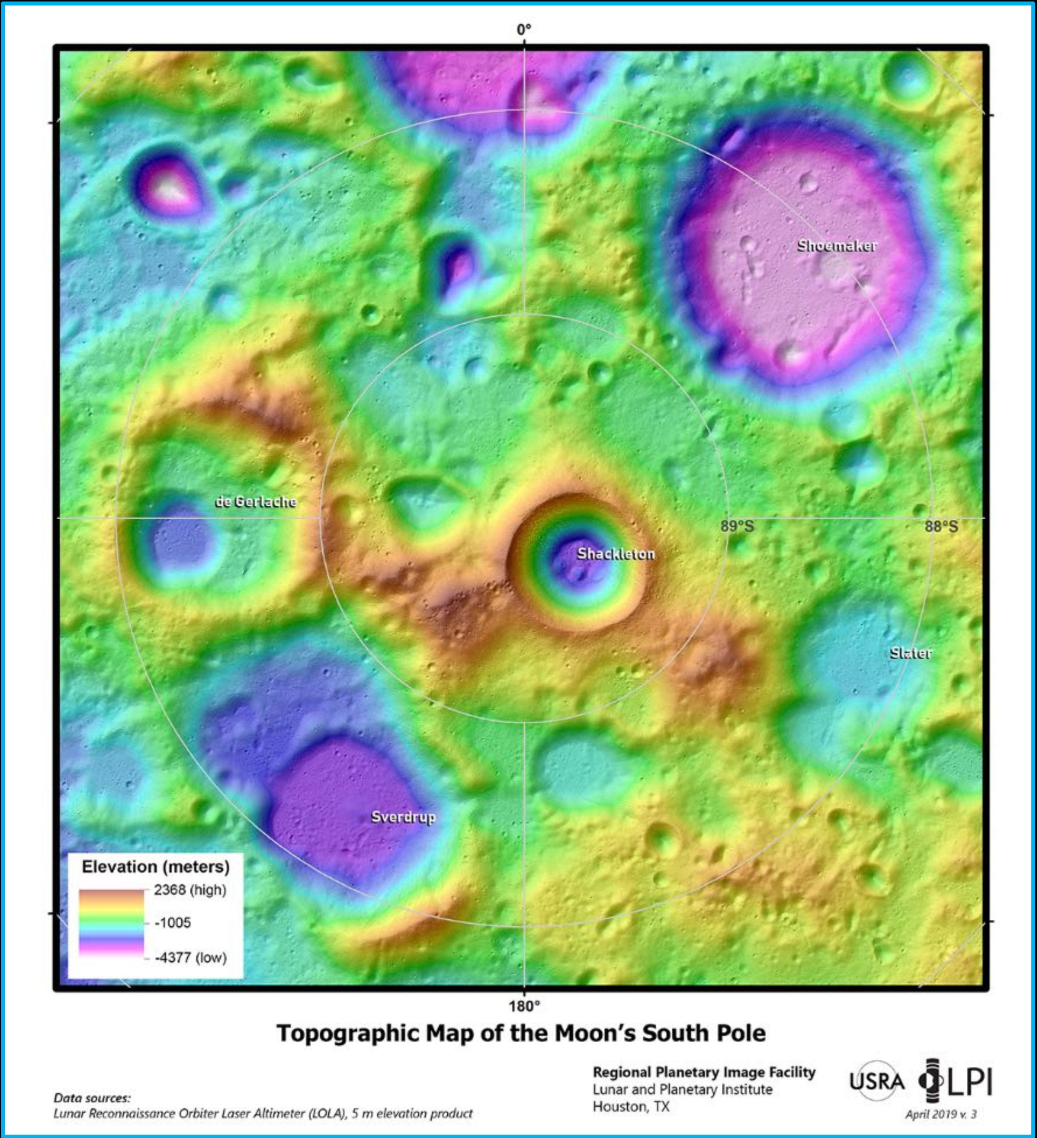


Geography of the Lunar South Pole



Location

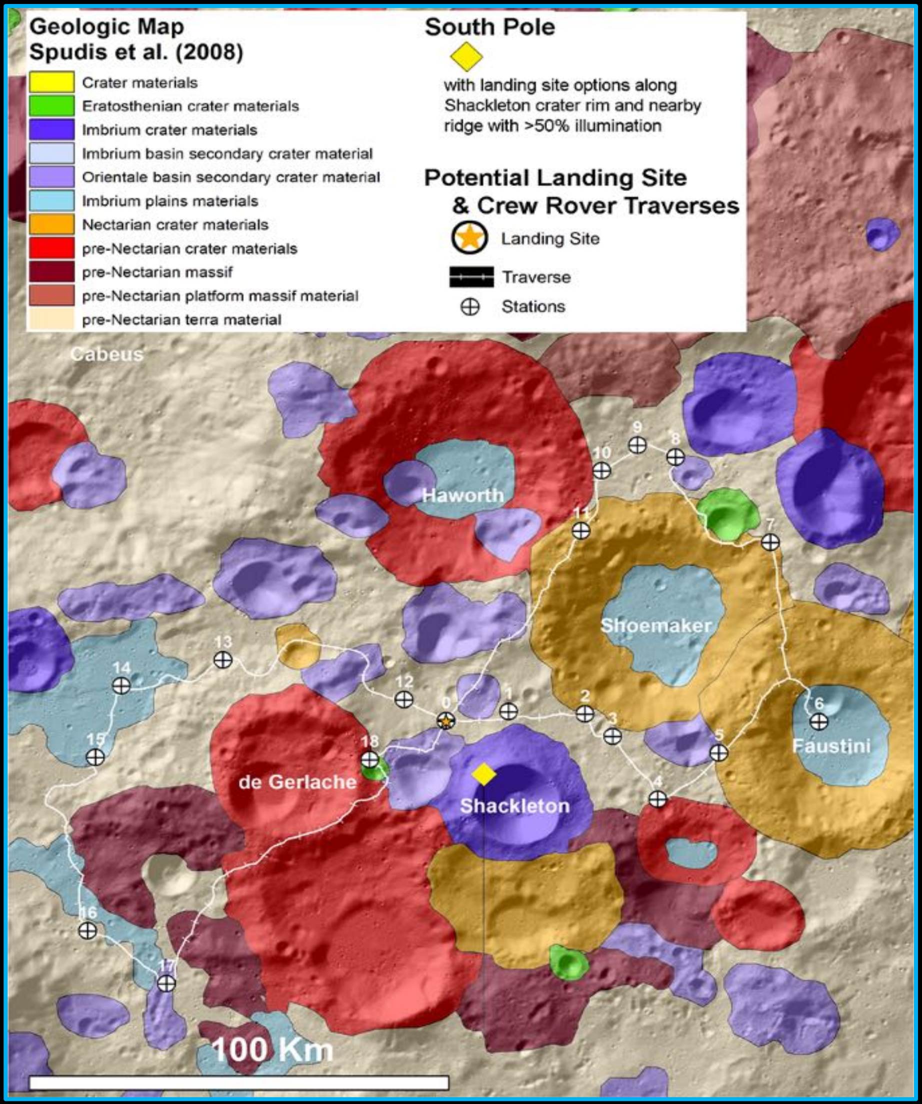
The lunar south pole is located on the rim of Shackleton crater.

In this map perspective, the nearside is in the top half of the image. Due to topography, not all nearside locations have direct line-of-sight to Earth, so an orbital relay is necessary.

Shackleton crater has a diameter of 21 km and depth of 4.2 km.

It is a simple crater, much like Meteor Crater, Arizona, which we use to train astronauts.

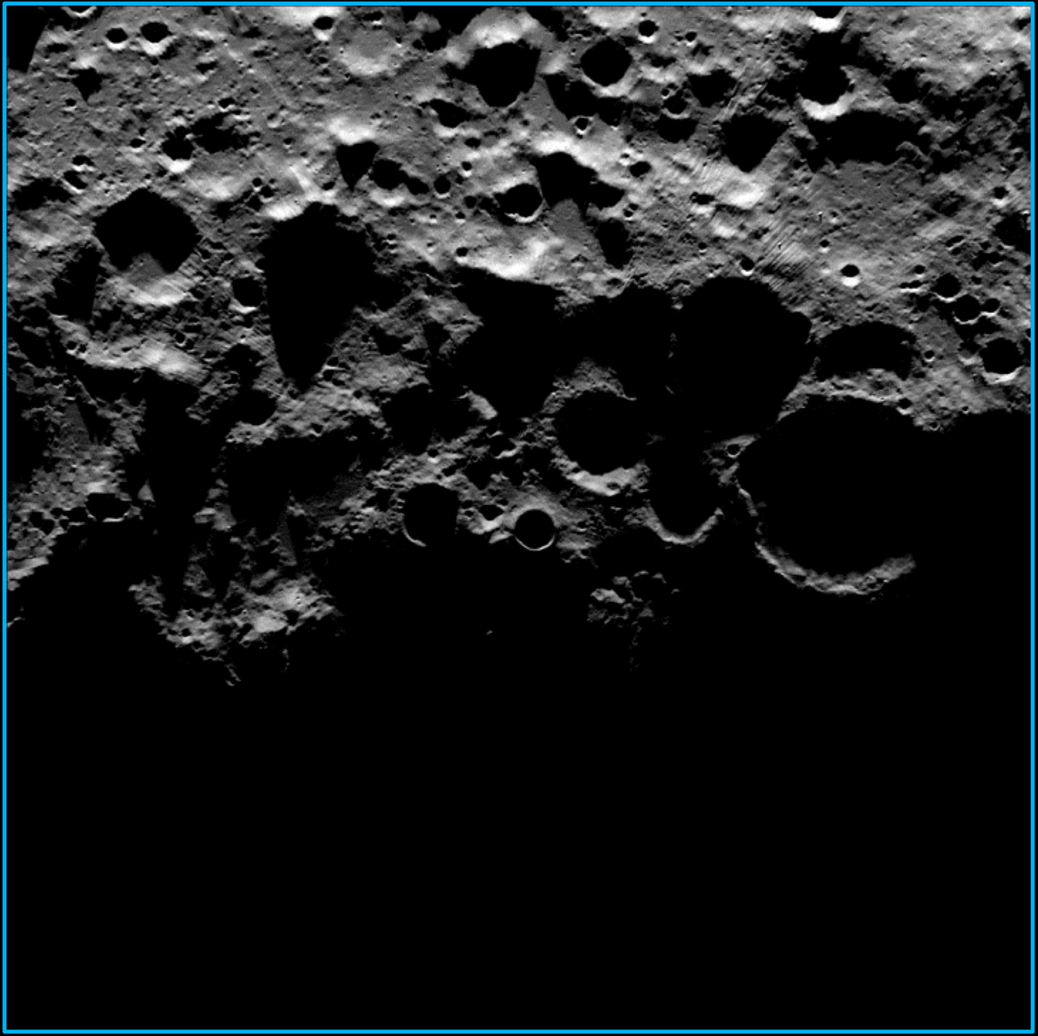
Geology of the South Polar Region



After Spudis et al. (2008) and Allender et al. (2019)

- The south polar region is a heavily cratered highland region.
- It was shaped by bombardment during the first billion years and by subsequent impact events.
- It sits on the margin of the oldest basin, the South Pole-Aitken basin.
- It was affected by ejecta from the final two basin-forming impacts: Orientale and Schrödinger.
- De Gerlach and Haworth are among the oldest craters; Shoemaker and Faustini may be younger.
- Shackleton was produced after the basin-forming epoch.

South Pole Illumination & Permanently Shadowed Regions (PSRs)



South pole – Ops issues

Dramatic topography

Long shadows

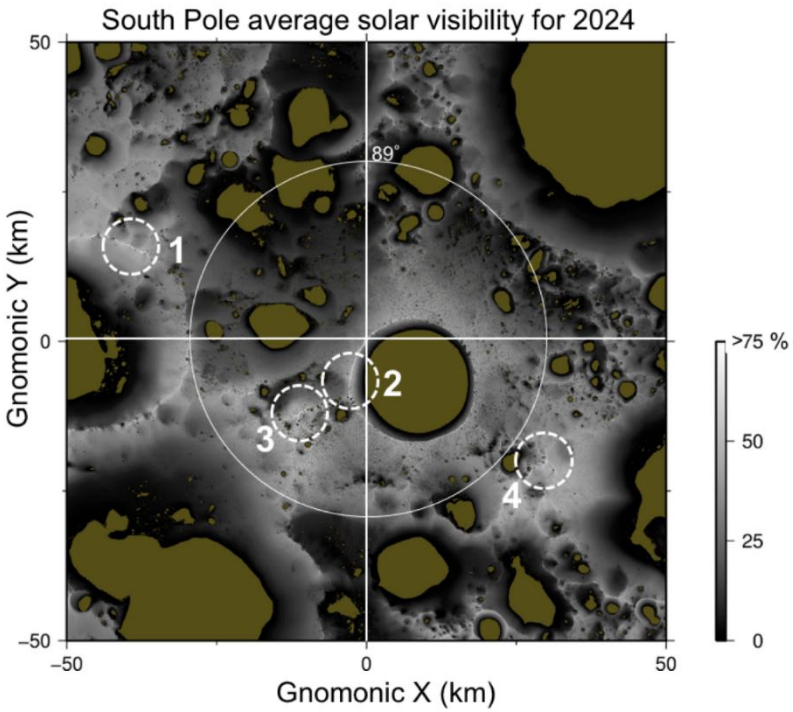
Deep shadows (including PSRs)

And, in stark contrast,

A few, small, near-constantly illuminated areas

Note: Previous simulations have shown that shadows may affect communication comprehension between crew and mission control staff.

South Pole Illumination & Permanently Shadowed Regions (PSRs)



Four highly illuminated areas shown above:

1. De Gerlache Rim,
2. Shackleton Rim
3. Shackleton – De Gerlache Ridge
4. Plateau near Shackleton

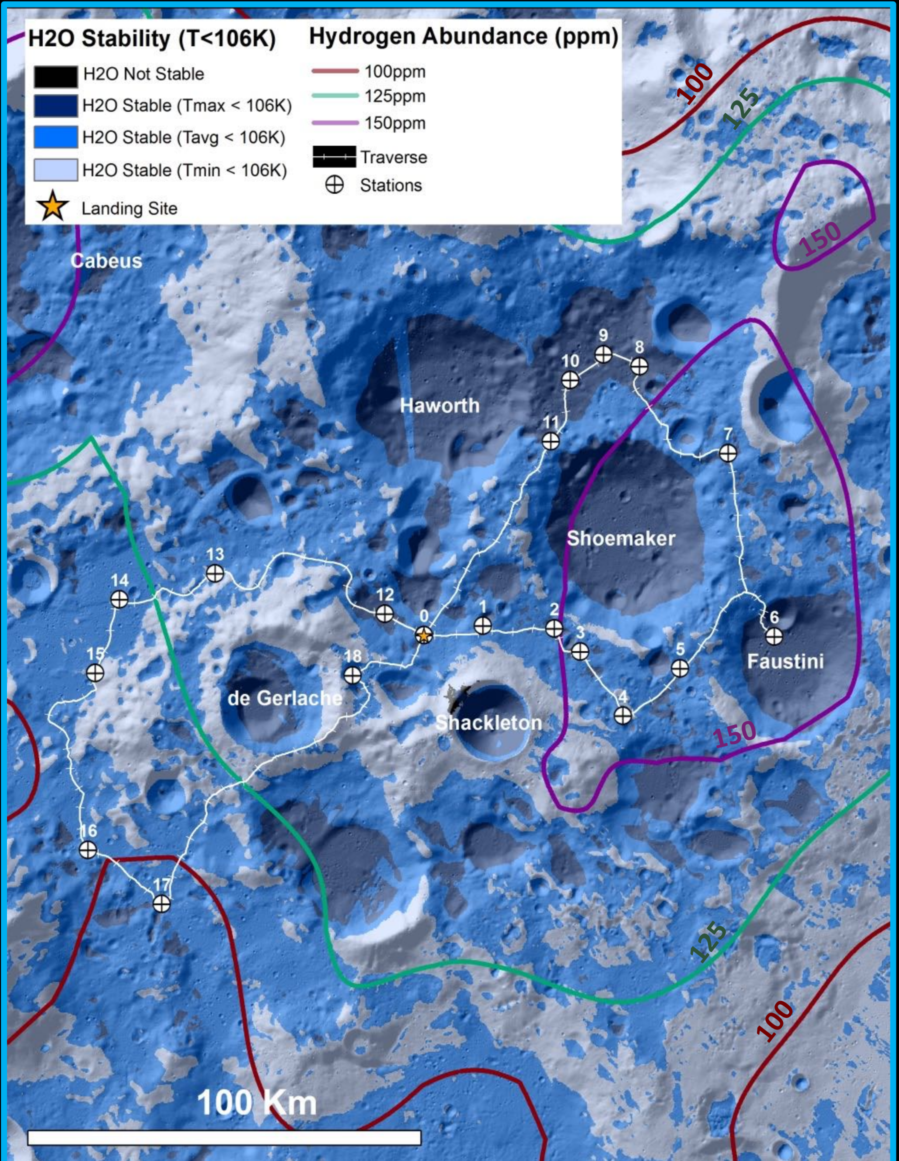
Source: https://www.nasa.gov/sites/default/files/atoms/files/20190528-nac-heoc-smith-v5b.pdf

South pole

Here are some of those small, near-constantly illuminated areas

Adjacent to them are PSRs

- These areas can trap volatiles.
- Providing a scientifically-rich library of the delivery and evolution of internal and externally delivered volatiles throughout Solar System history.
- While also providing potential *in situ* resources for crew consumables and propellant.



Calculated Diviner Temperature 240 m/px
Lunar Prospector Neutron Detector 15 km/px

South Polar Region

- H_2O stability map where temperature is lower than 106 K (Zhang and Paige, 2010)
- Dark blue shows the highest probability of finding H_2O ice since the max temperature in those regions are below sublimation point
- Contour lines indicate 100, 125 and 150 ppm hydrogen levels derived from the Lunar Prospector Neutron Detector

Allender et al. (2019)

Volatile Sources – Thinking in Terms of Geologic Evolution

LPI/David A. Kring

Volatile sources

Understanding volatile sources is important, because:

- That constrains when and, thus, where volatiles were deposited.
- That constrains the chemistry of any ices, which will greatly affect the ops associated with the *in situ* study and recovery of volatiles.

For example, volcanic and potentially impact-sourced volatiles may contain S and halogens, which may produce corrosives during ISRU ops.

Volatile Sources – Thinking in Terms of Geologic Evolution

LPI/David A. Kring

Volatile sources

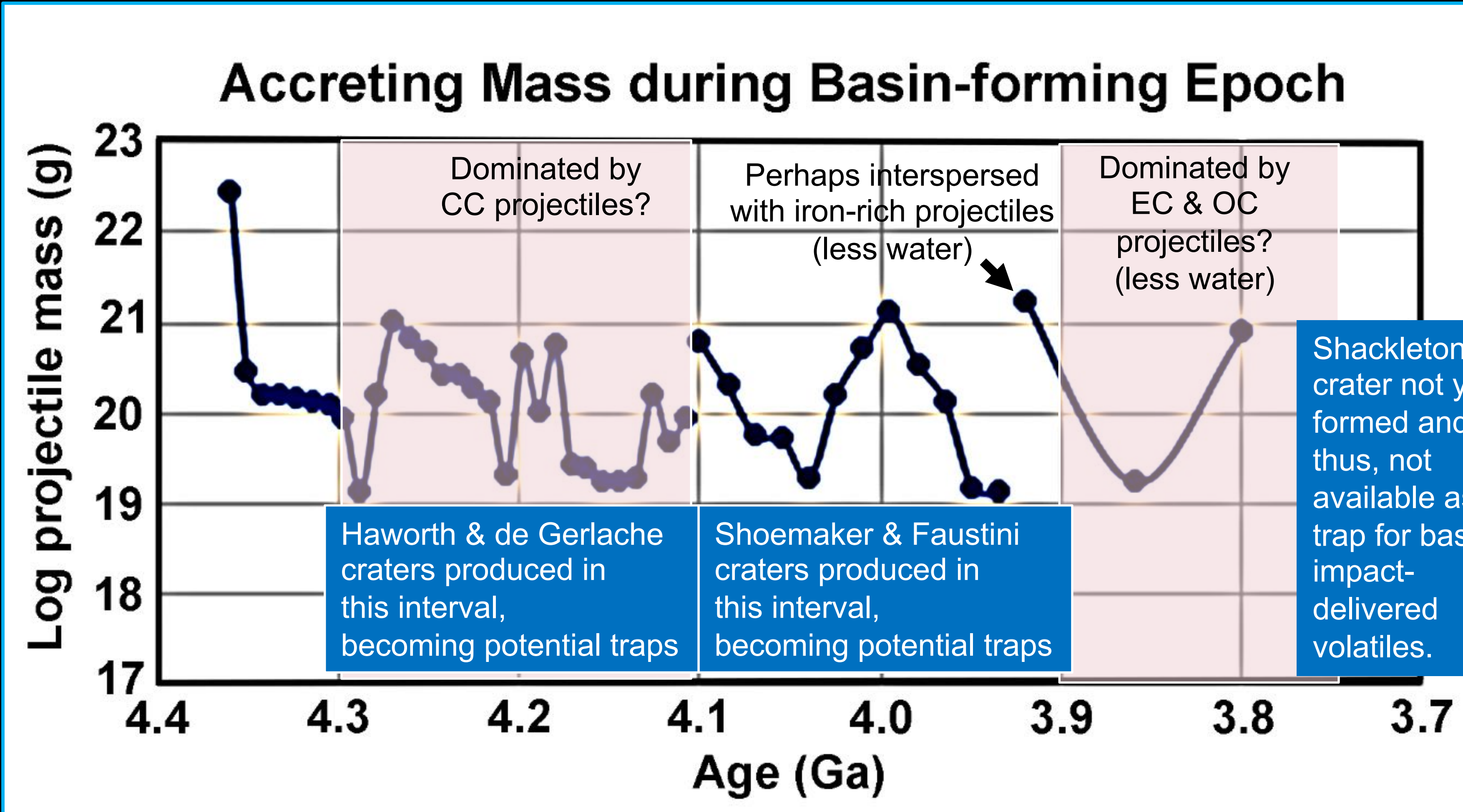
Delivered to surface by impacting asteroids & comets (throughout lunar history, but particularly during the basin-forming epoch)

Vented volcanically from the lunar interior (e.g., at 4.3, 3.8, & 3.5 Ga)

Escaping the crustal rocks via moonquakes and impact events (throughout lunar history)

Delivered by impacting solar wind (throughout lunar history)

Examining the Mass Delivered by the Basin-forming Impacts



Shackleton crater not yet formed and, thus, not available as a trap for basin impact-delivered volatiles.

Volatile Sources – Thinking in Terms of Geologic Evolution

LPI/David A. Kring

Volatile sources

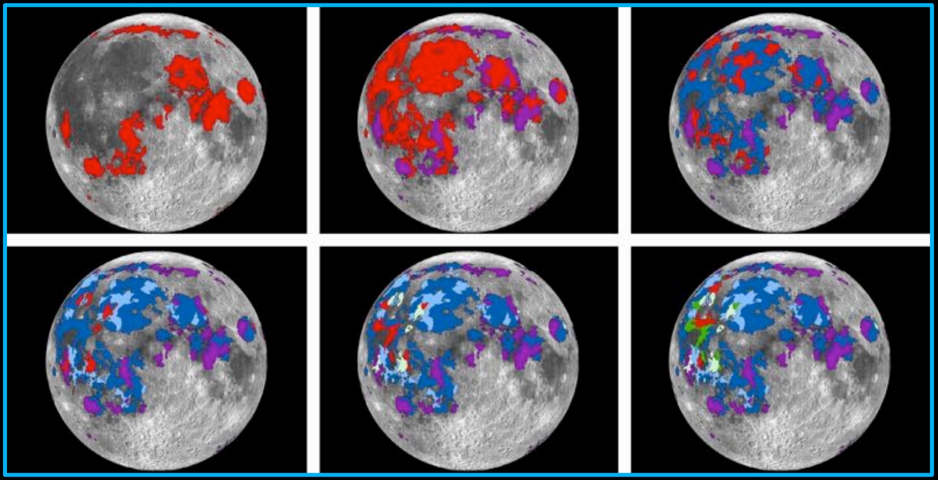
Delivered to surface by impacting asteroids & comets (throughout lunar history, but particularly during the basin-forming epoch)

Vented volcanically from the lunar interior (e.g., at 4.3, 3.8, & 3.5 Ga)

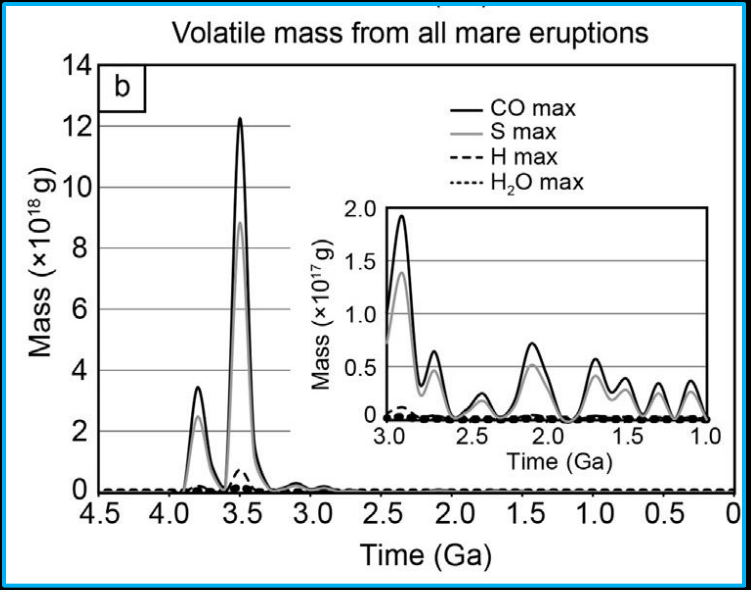
Escaping the crustal rocks via moonquakes and impact events (throughout lunar history)

Delivered by impacting solar wind (throughout lunar history)

Examining the Mass Delivered by Volcanic Venting

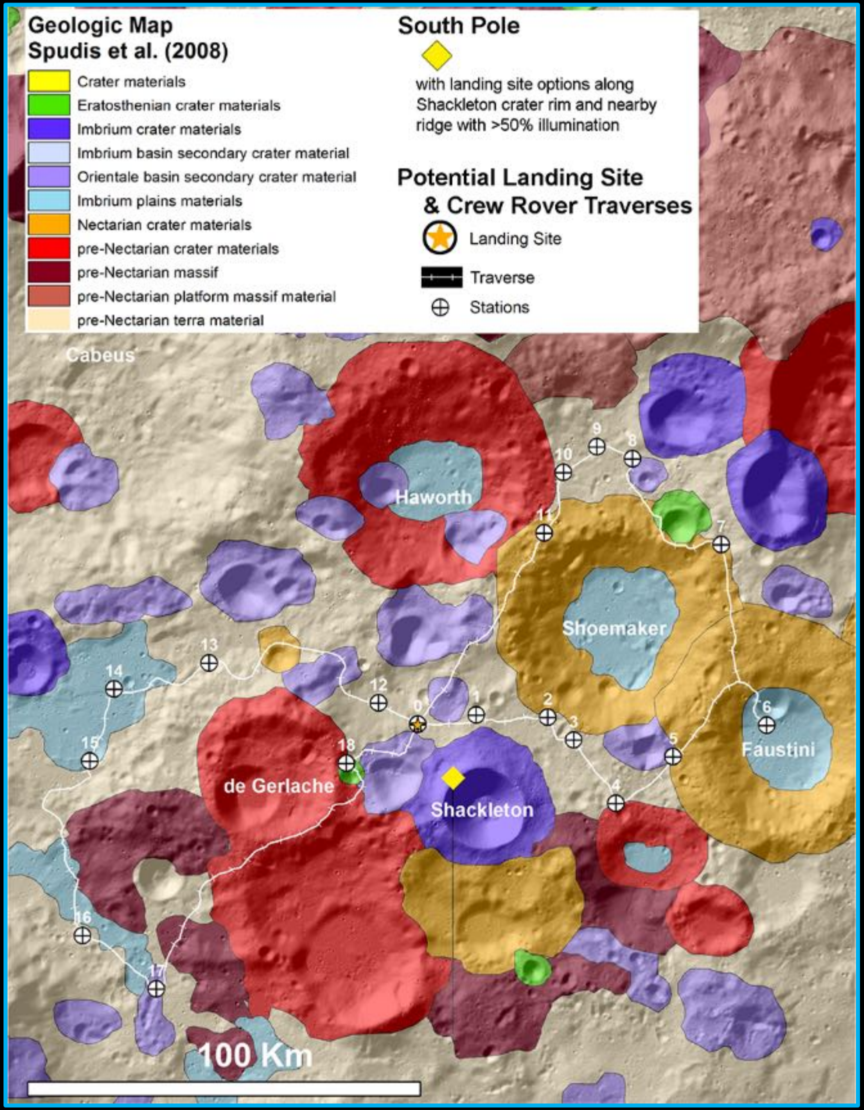


Needham & Kring (2017)



- Based on Apollo sample analyses, pulses of volatiles may have been deposited c. 3.8 and 3.5 Ga.
- Based on lunar meteorite samples analyses, volatiles may have been deposited as early as 4.3 Ga.
- Volatiles were potentially trapped in Haworth, de Gerlache, Shoemaker, and Faustini, but not in Shackleton (which did not yet exist).
- Those volatiles may have been buried by a thin insulating layer of ejecta from Shackleton, if not reworked by ballistic sedimentation.

Geologic Evolution & Implications for Ice Distribution

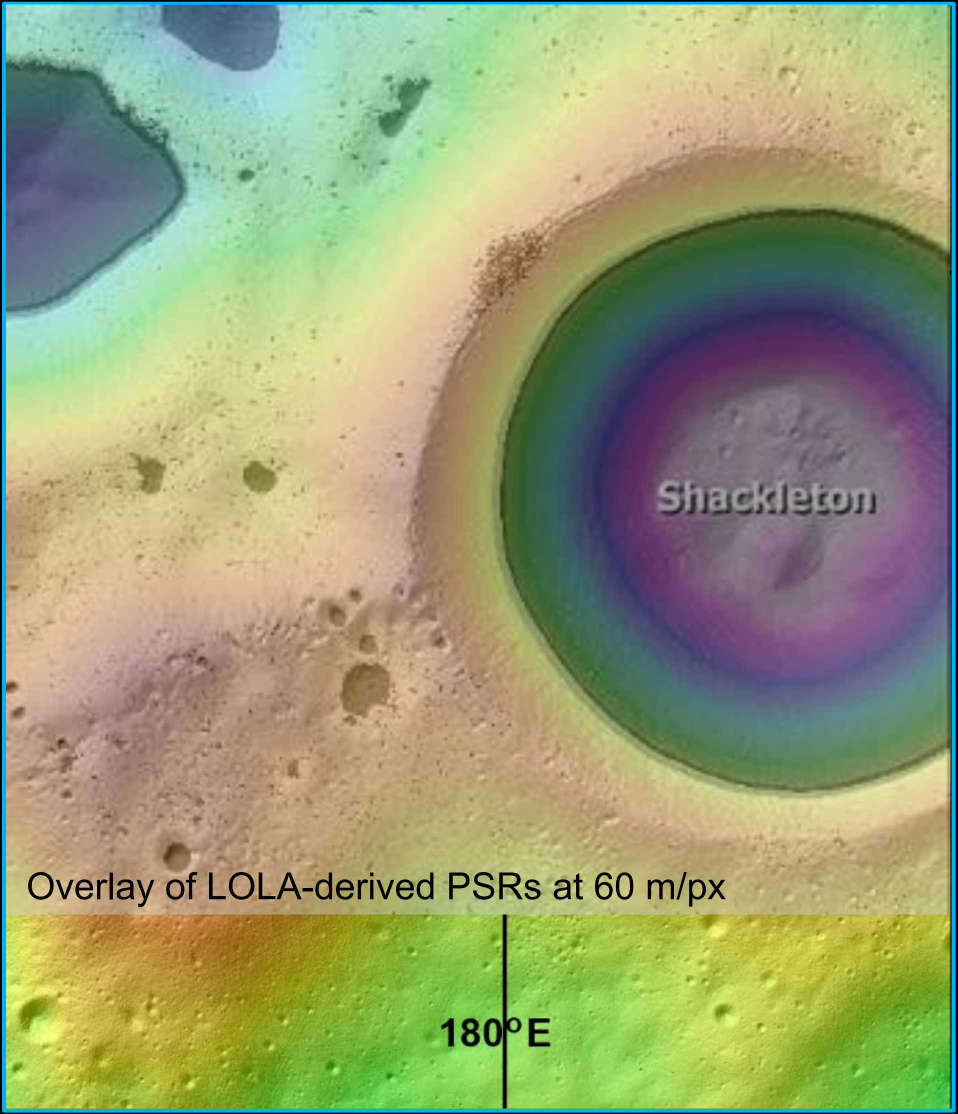


Geologic reality

That type of geologic evolution of craters in the south polar region would produce a "stratigraphy" with different volatile abundances, as well as variable lateral abundances, and depositional units with different compositions.

Younger craters could punch into those ice deposits. The younger craters would also only be able to capture volatiles from later processes; i.e., impacting asteroids, comets, and solar wind.

Science & ISRU Opportunities



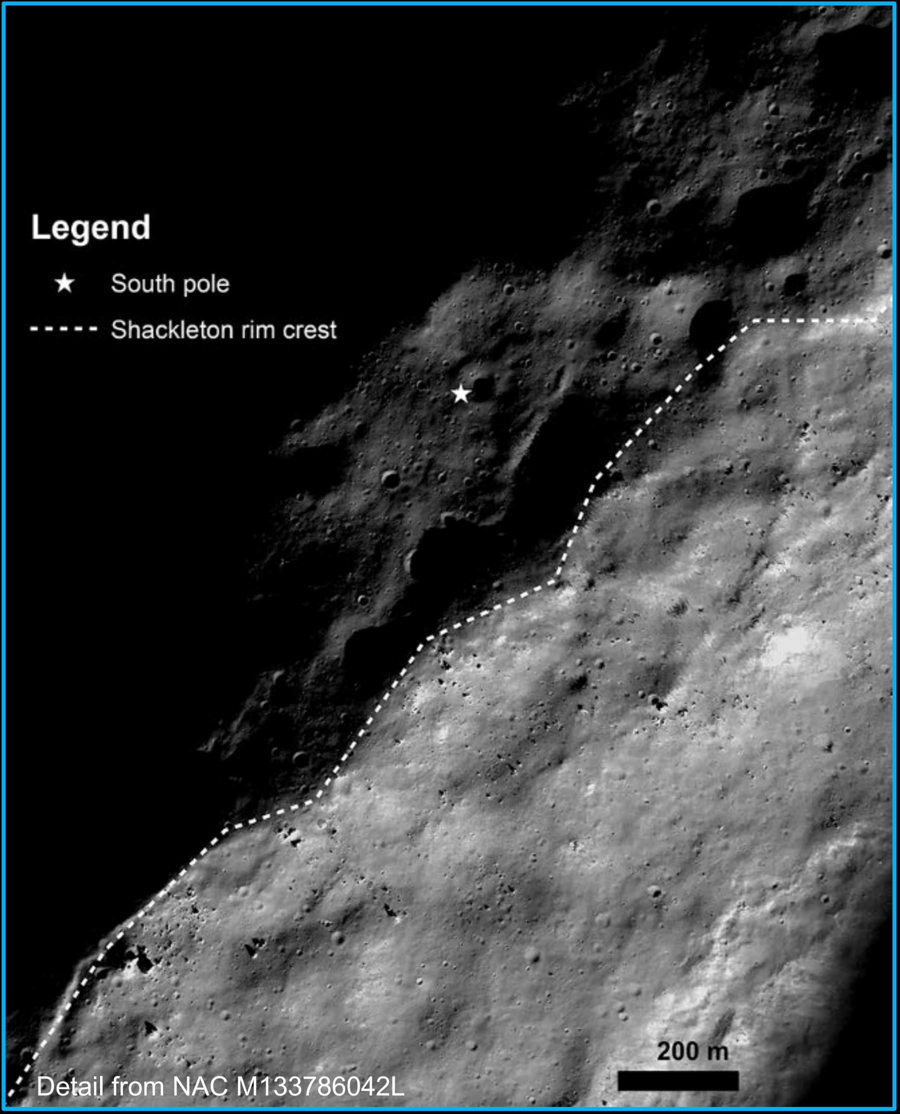
Small PSRs along rim?

LOLA data remind us that there may be small PSRs along the rim of Shackleton crater; e.g., within small craters and along scarps.

Small PSRs may also be cast by boulders, similar to Shadow Rock at the Apollo 16 landing site.

These are suitable sites for sampling potentially volatile-richer regolith in special environmental sample containers.

Science & ISRU Opportunities

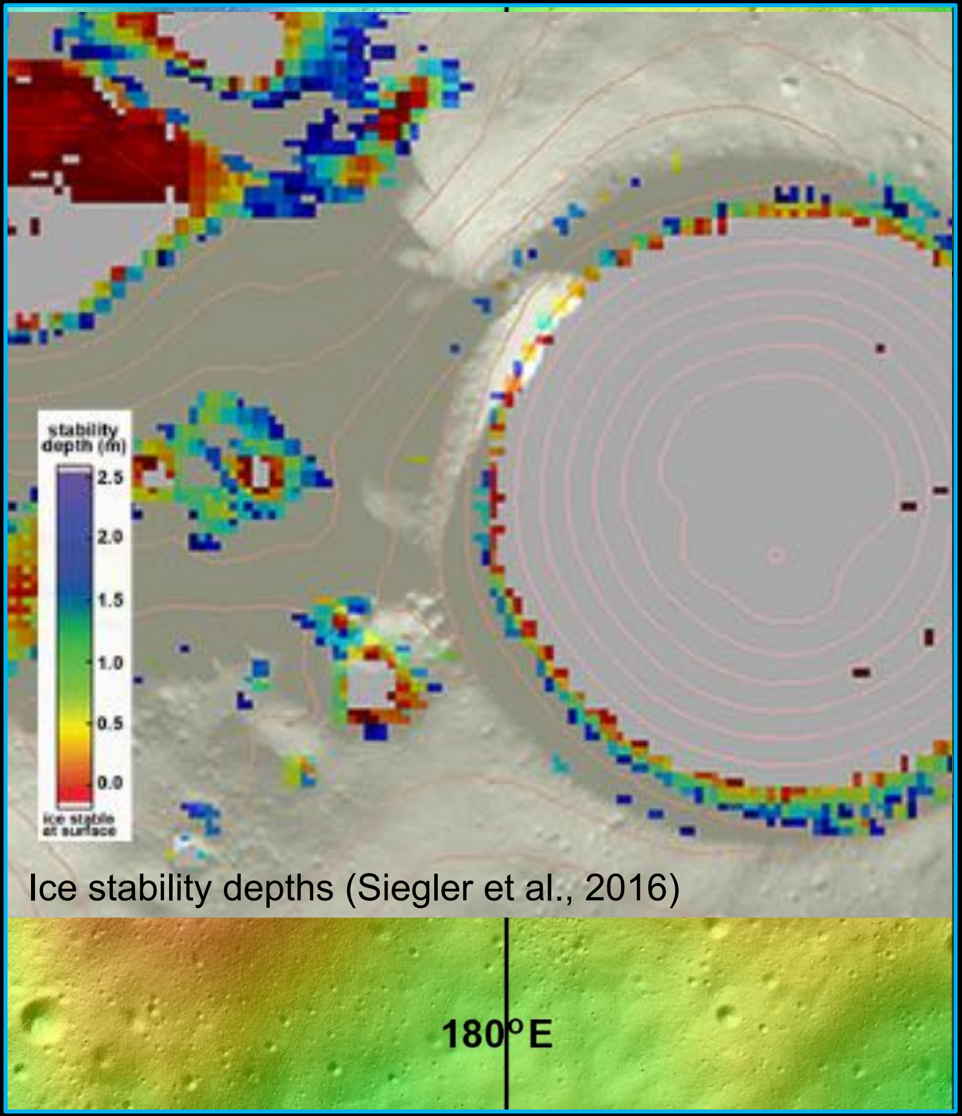


Small PSRs along rim?

Small PSRs may lurk within a few hundred meters of the south pole.

These small pockets will be geologically young and may have only been traps for solar wind volatiles and those delivered by small impact events.

Science & ISRU Opportunities



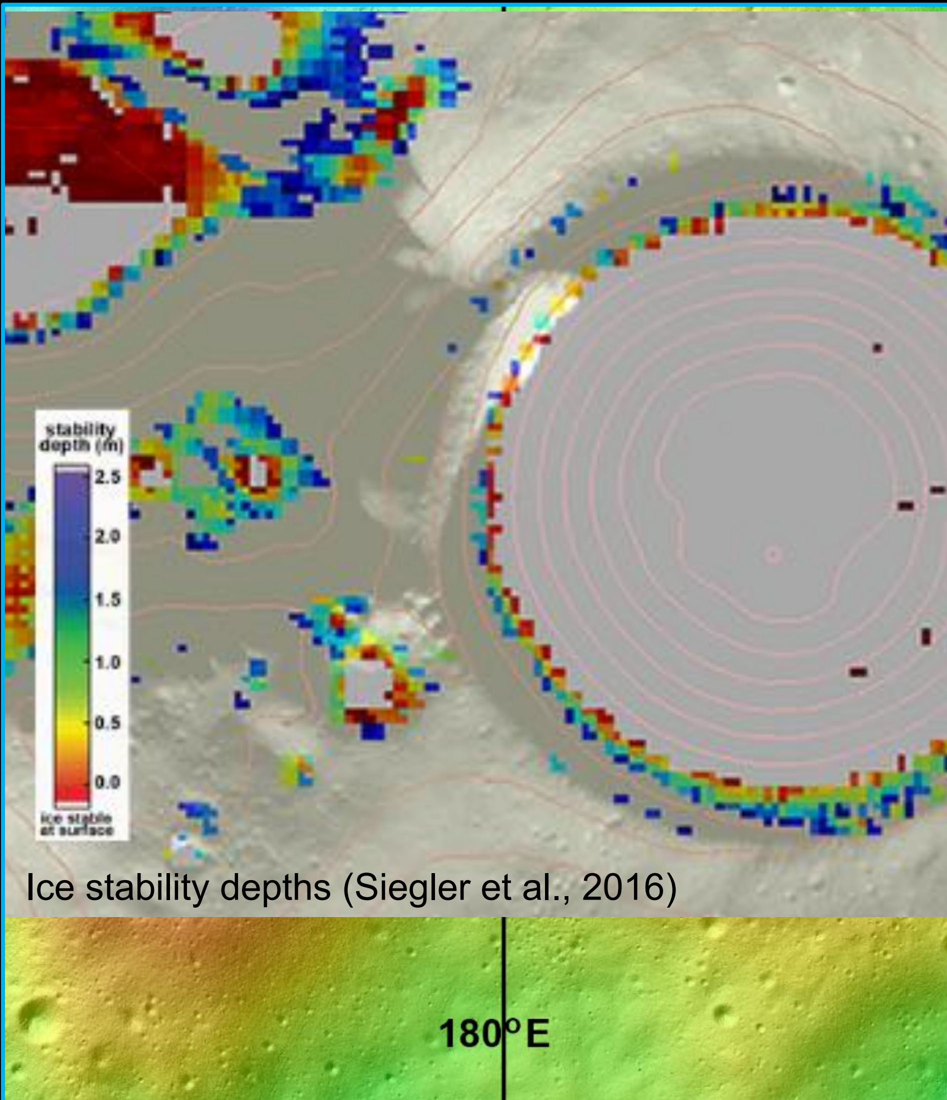
Ice stability depths (Siegler et al., 2016)

Ices at or near surface?

Models indicate volatiles may exist within a few meters of the surface (Siegler et al. 2016; Speyerer et al. 2016). If crew have no mobility, they can:

- Trench to discern distribution in real-time, including lateral variability
- Drill to recover core for sample return in special environmental containers
- In both cases, mass spectrometry could potentially be employed to measure volatile compositions, but it would be better if done robotically, as space suit degassing may affect result if done by crew.

Science & ISRU Opportunities



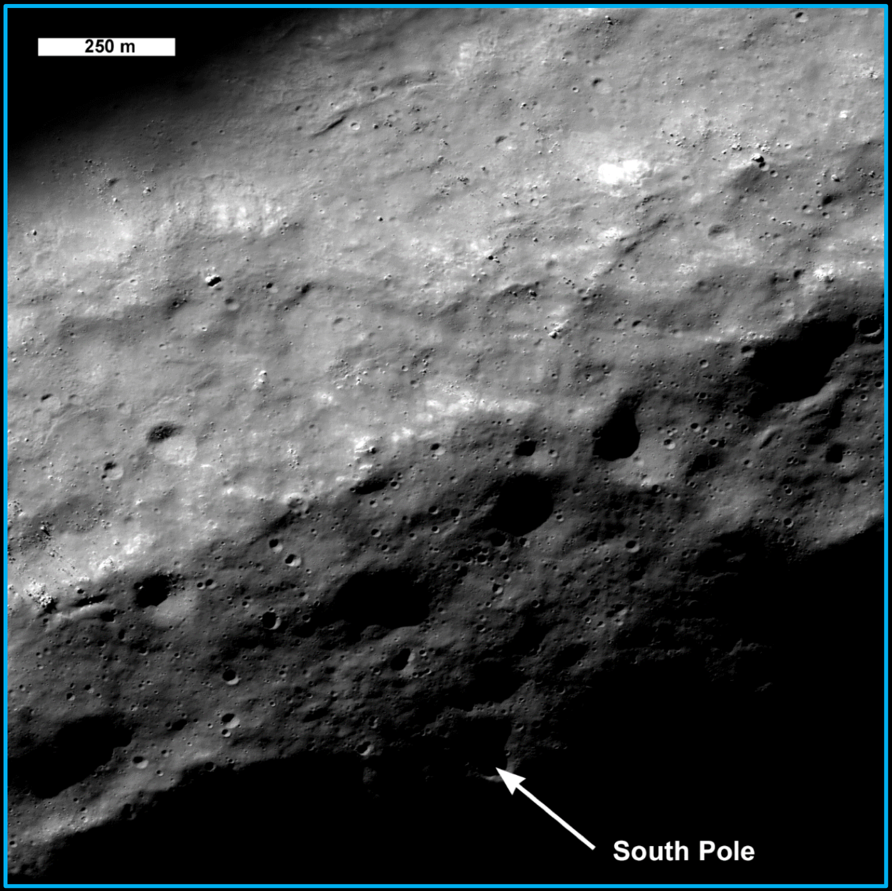
Ice stability depths (Siegler et al., 2016)

Ices at or near surface?

If mobility is available:

- Survey the subsurface using ground penetrating radar (GPR) and a neutron spectrometer (NS). This method will provide the greatest assessment of resource potential.
- The survey could be conducted with a small robotic rover or with a crew rover.
- Preliminary trafficability studies around Shackleton (e.g., Bickel & Kring 2019 – at this conference) are favorable for rover ops, but more analyses are needed.

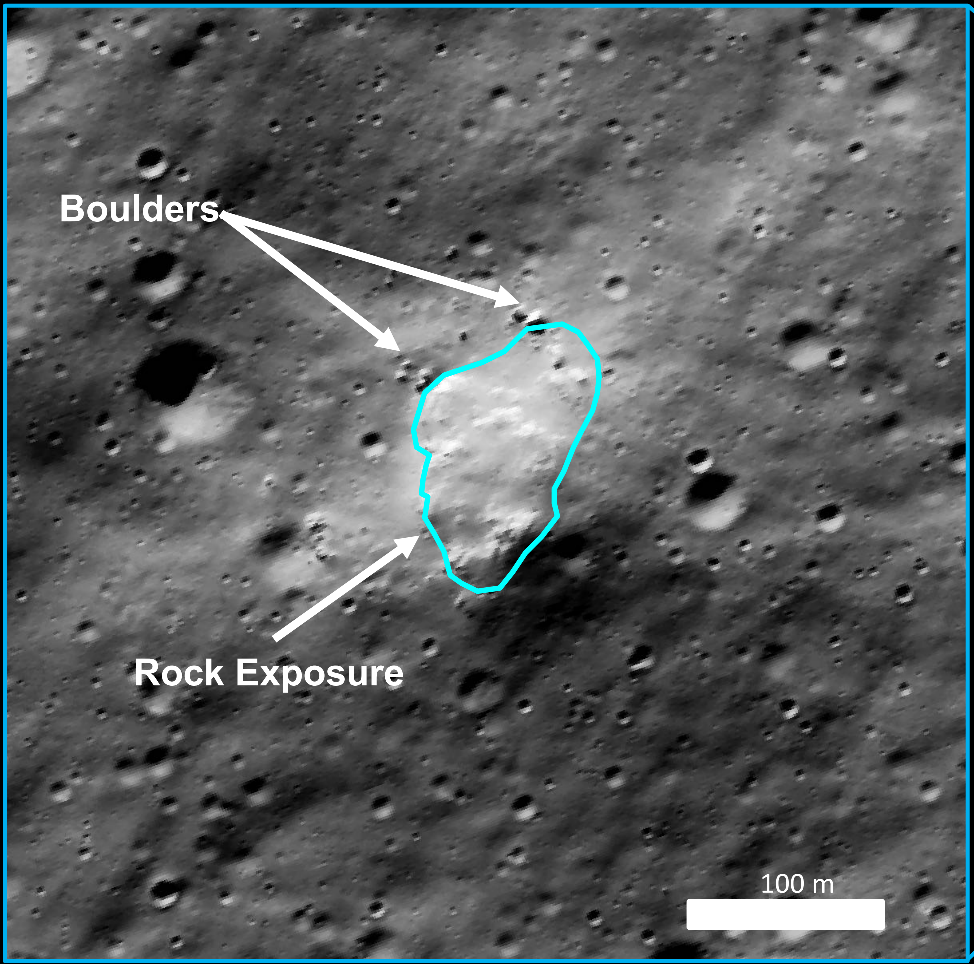
Other Scientific Opportunities



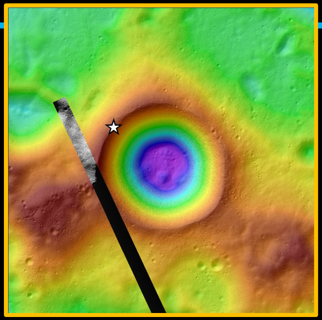
LROC/GSFC/ASU (Posted by Mark Robinson)

- Most accessible samples will be Shackleton ejecta. Potentially, that will include Shackleton impact melts, from which an age can be ascertained.
- The regolith may also contain impact melt from SPA and other pre-Nectarian and Nectarian-age impacts; fragments of the original highland crust, with components from the lunar magma ocean and later intrusives; plus cryptomare from SPA.
- Samples will provide an opportunity to study polar regolith processes.

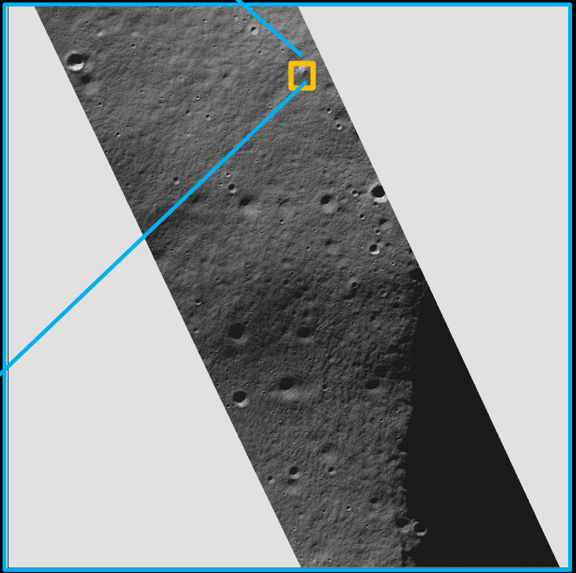
Rock Exposures in Shackleton Ejecta Blanket



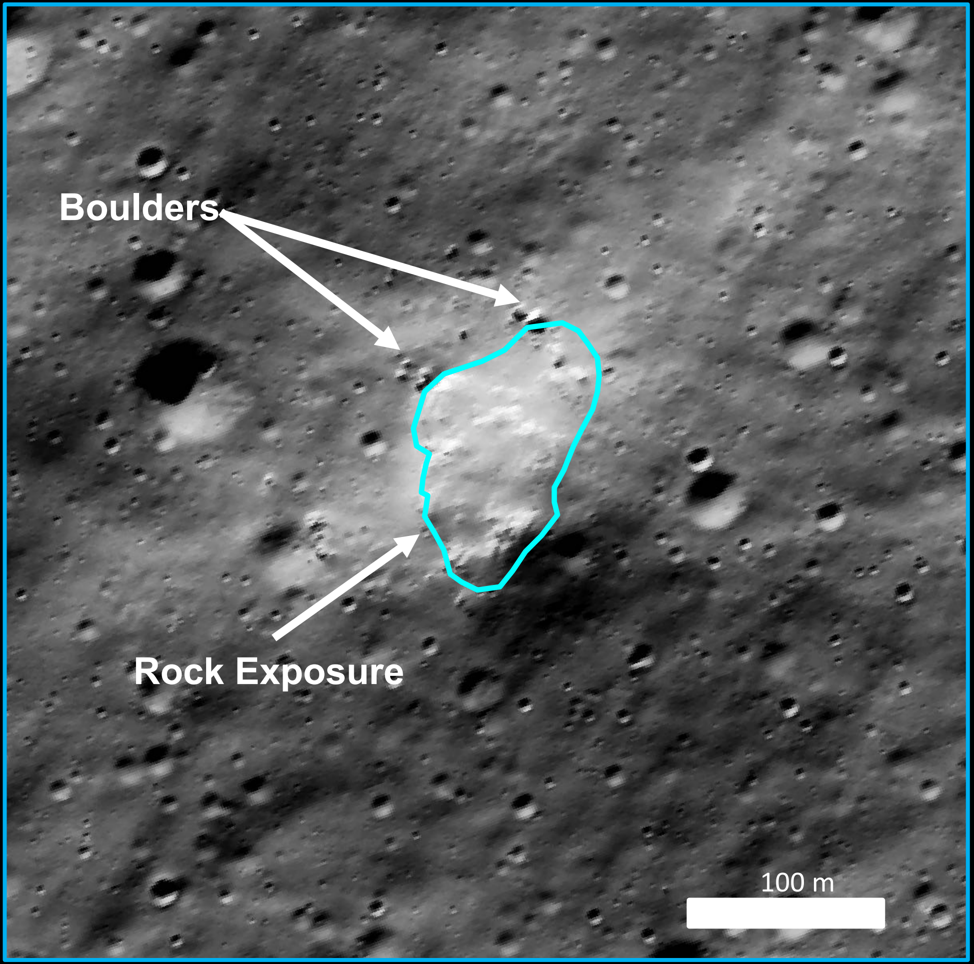
Detail of NAC M140048583LE



LOLA DEM (5 m/px) over hillshade



Rock Exposures in Shackleton Ejecta Blanket

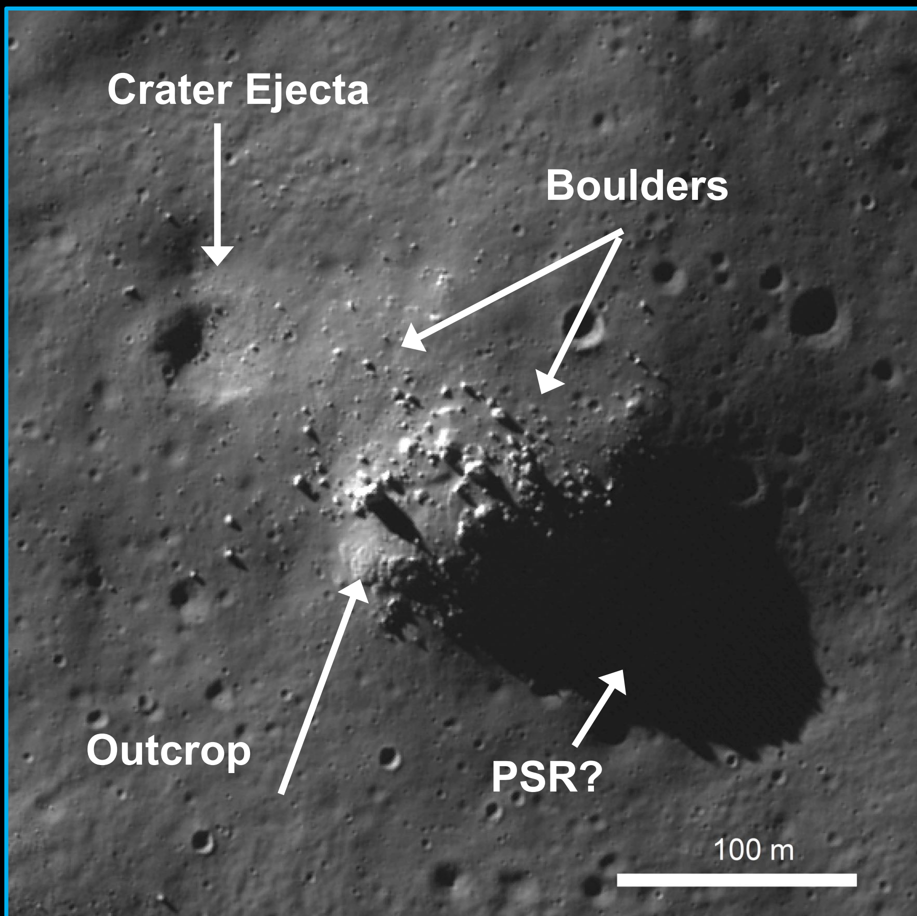


Detail of NAC M140048583LE

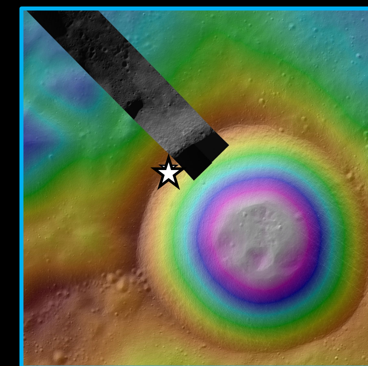
Rock exposures

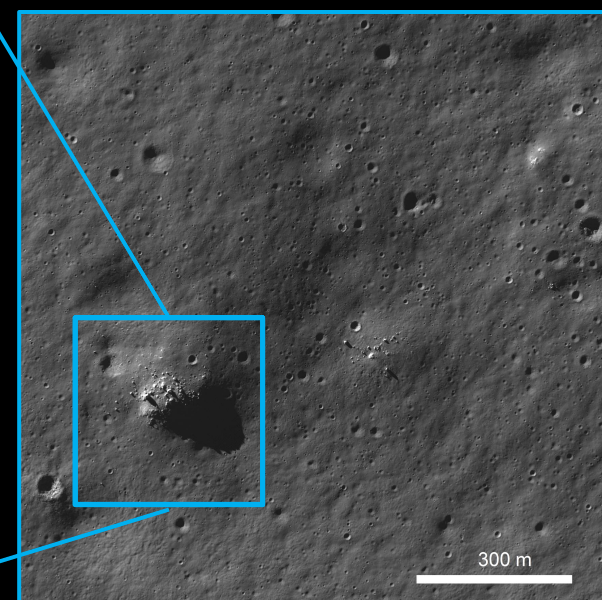
- Boulders are emergent from the Shackleton ejecta blanket.
- Rock exposures can be quite large, in this case ~100 m in diameter. That is similar in size to many highway road cuts on Earth and may provide a similar level of geologic context across the length of the exposure.
- Nearby regolith should provide smaller samples of the boulder lithology and many other lithologies, albeit in smaller clast sizes.

Collecting Rock Samples on the Shackleton Crater Rim



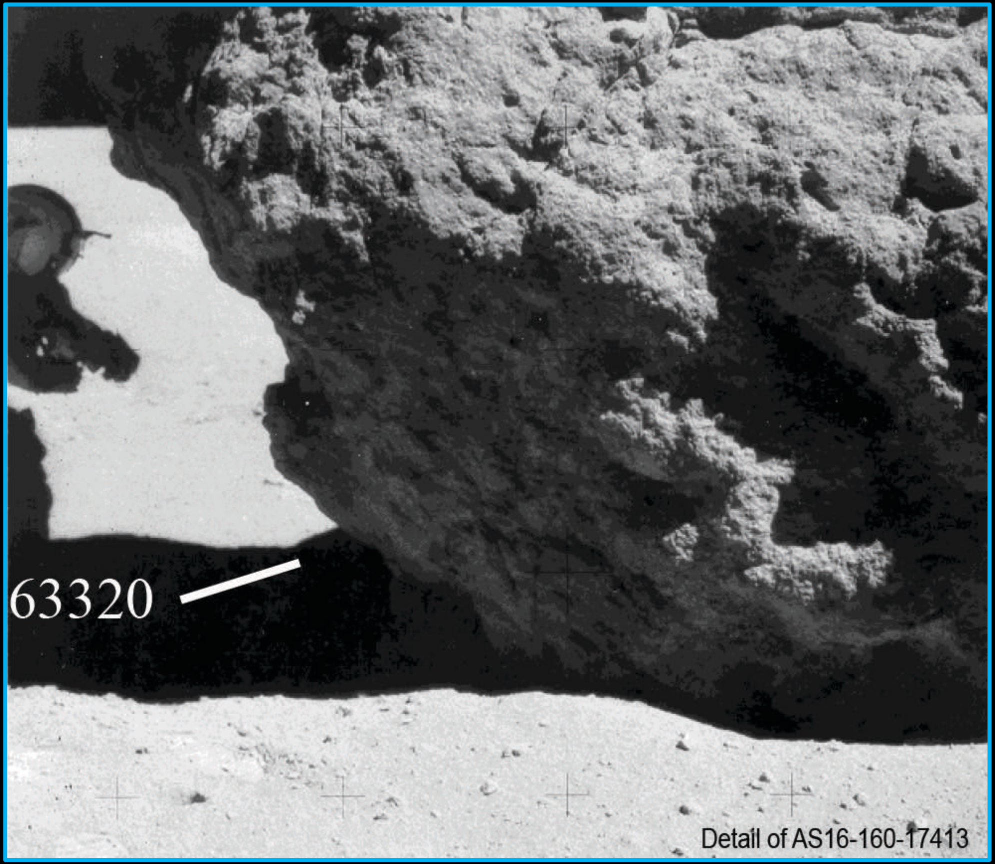
Outcrop and boulders near a fresh crater. There may be a Permanently Shadowed Region (PSR) behind the outcrop mound.





Detail of NAC M140197843RE

Samples from Permanently Shadowed Locations



Charlie Duke photographs John Young at Station 13's Shadow Rock. Duke sampled the regolith at the deepest point of the shadow by getting on his knees.

We have sampled PSRs before

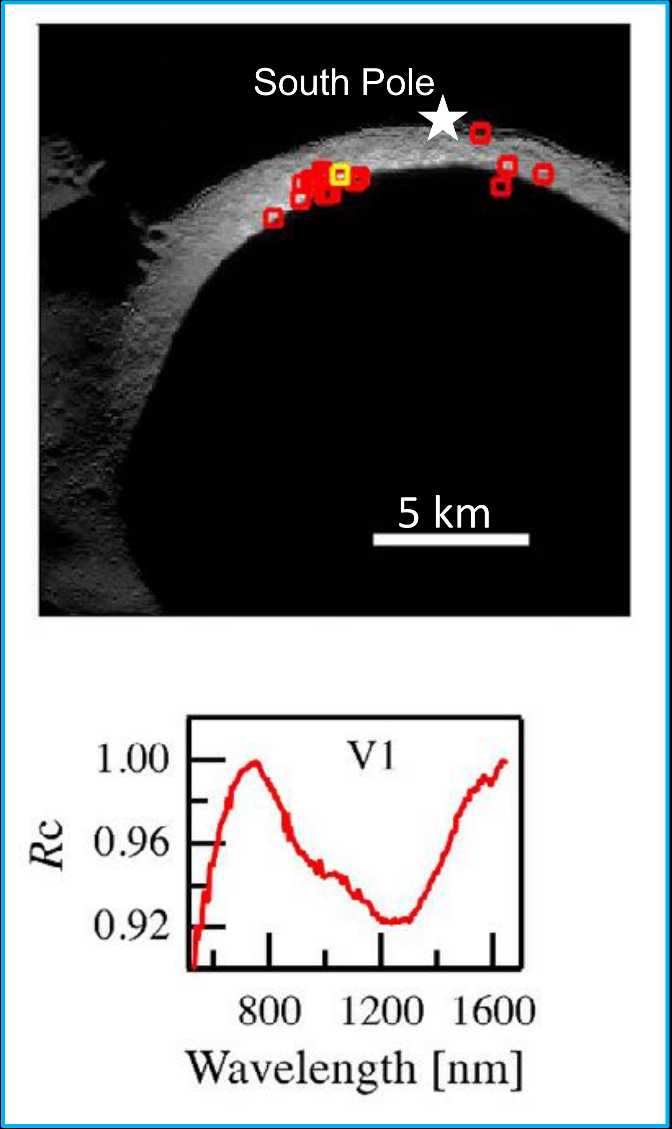
Small PSRs were identified at the Apollo landing sites.

Astronauts were unaffected when they approached and entered the PSRs

Here – at the Apollo 16 landing site – an astronaut steps into a shadowed location.

No physical differences in these shadowed soils were noted by astronauts

Collecting Rock Samples

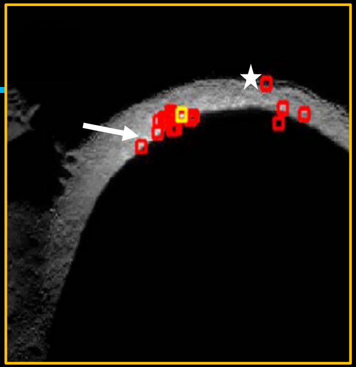


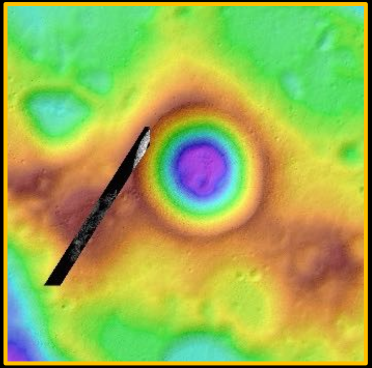
Lithological hints

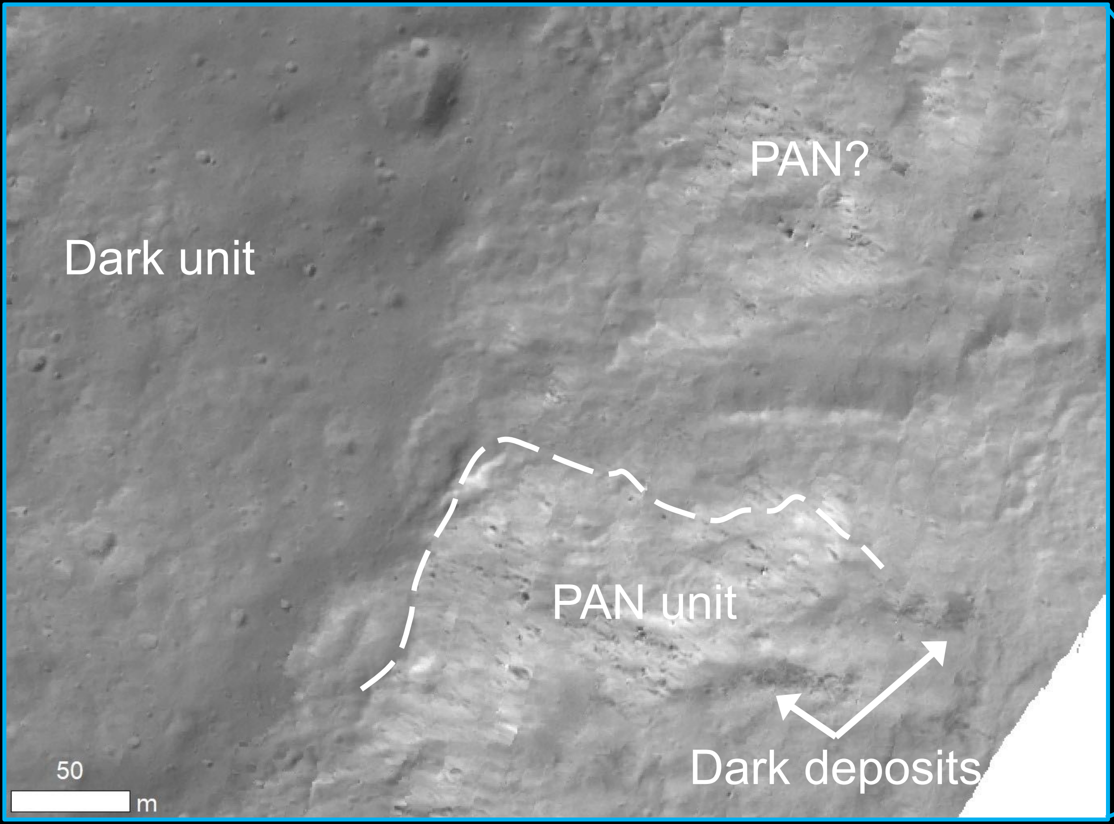
- Pure anorthosite may be dominating 500 × 500 m areas on the wall of Shackleton crater, the locations of which are shown here in red boxes (Yamamoto et al. GRL 2012; Lemelin et al. 2017).
- If similar material was ejected during the impact event, then pure anorthosite may be sampled on the crater rim.
- Sample collection by crew requires a modern equivalent of the Apollo geological tool kit; keep it simple.

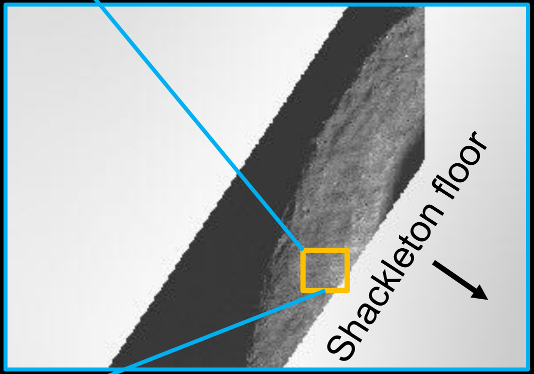
Pure Anorthosite (PAN)

PAN in Shackleton crater wall:
Is it a coherent block of crust
or is it a megabreccia?



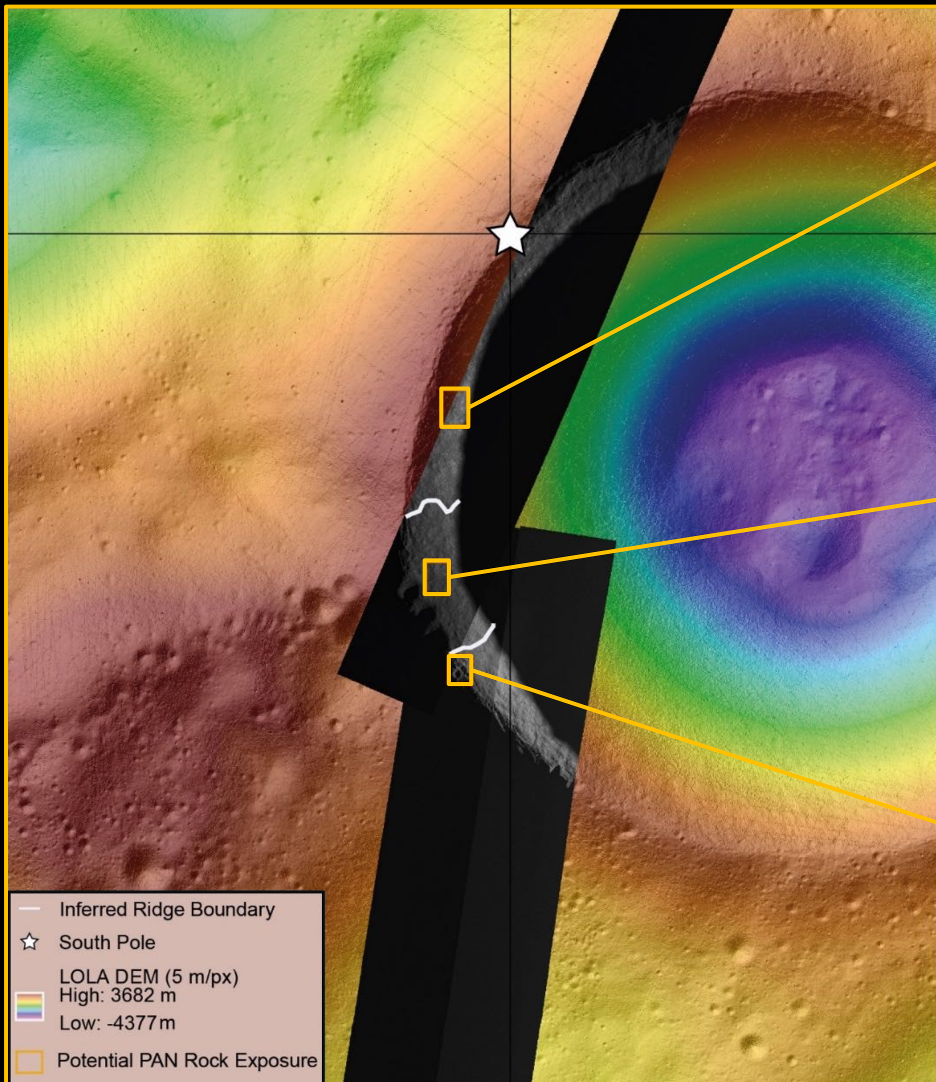




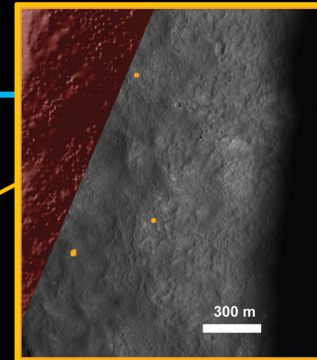


Detail of NAC M133786042LE

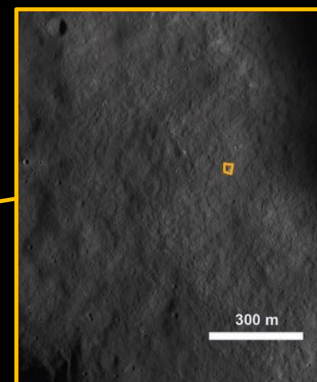
Ridge may be composed of Different Material



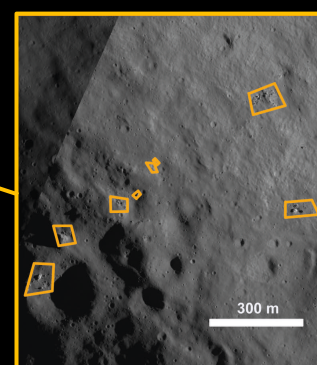
(LROC NAC M146833333L and M146928260L/R)



North of the ridge there are 3 potential PAN rock exposures. The surface is rough and has a higher albedo.



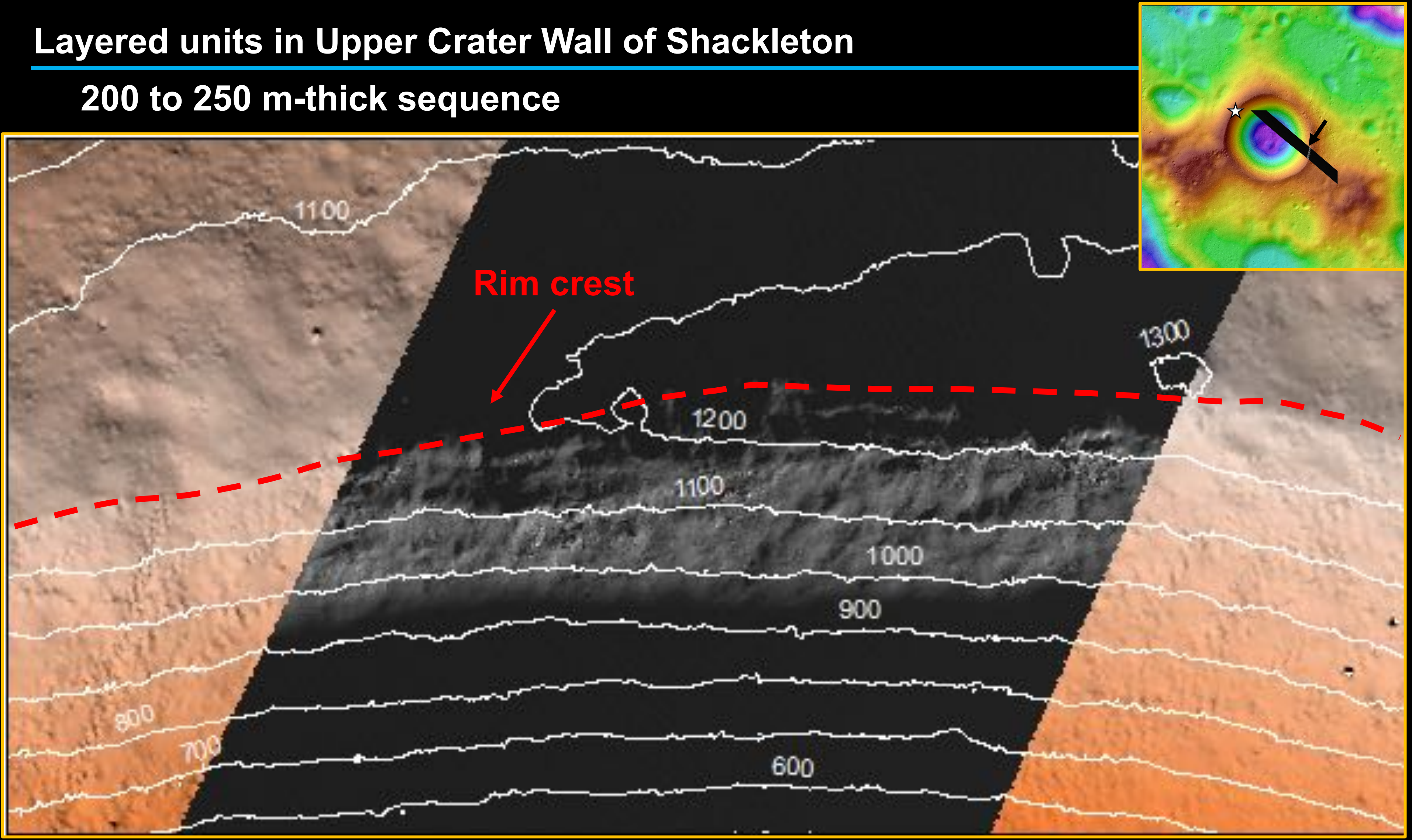
On the ridge there is only one potential PAN rock exposure. There is a smooth surface and relatively dark coloured albedo.



Below the ridge there are multiple potential PAN rock exposures. The surface is smooth and has a dark coloured albedo.

Layered units in Upper Crater Wall of Shackleton

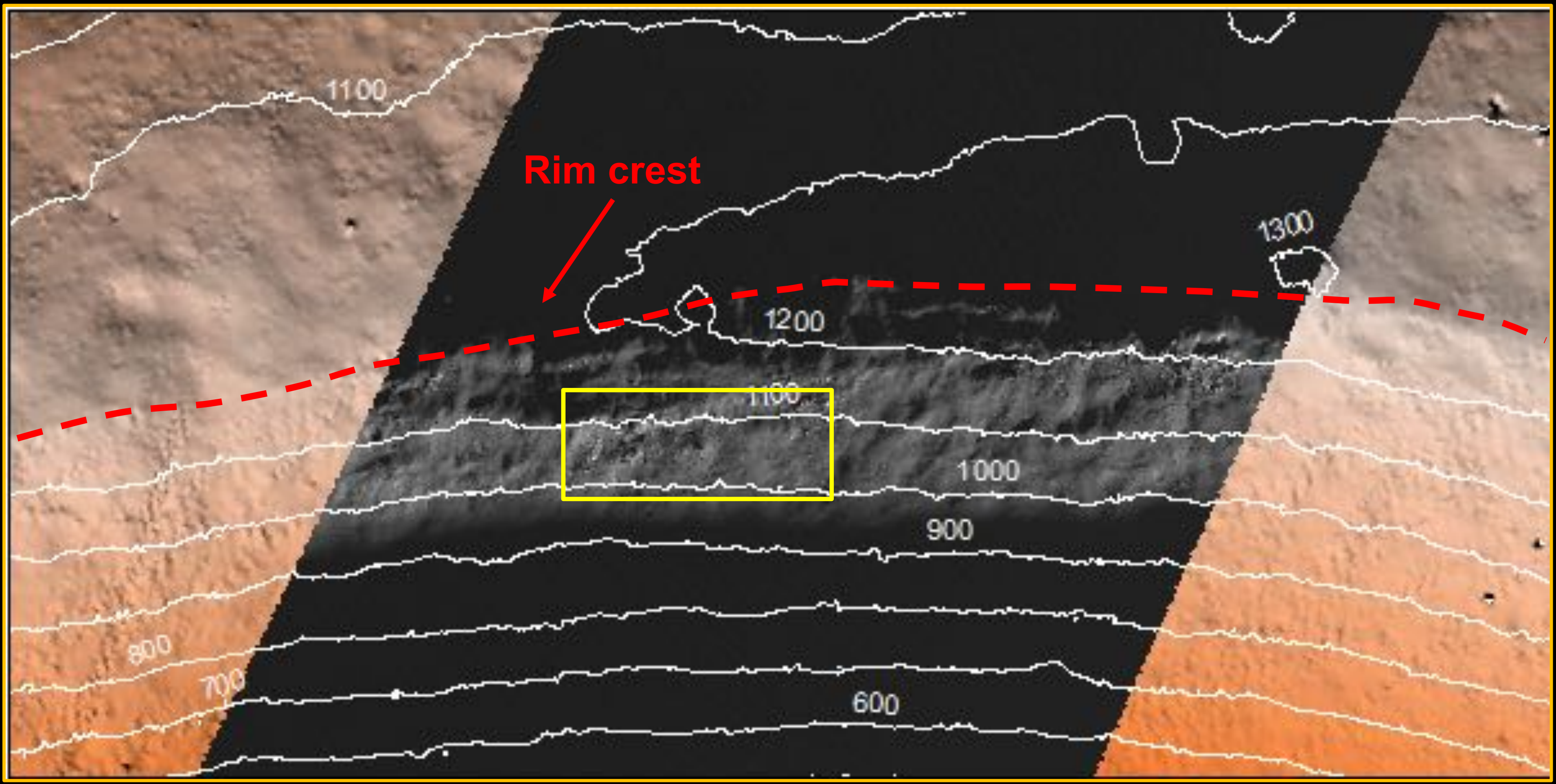
200 to 250 m-thick sequence



NAC ID M133154995R

Contours (100m interval) overlaid NAC image (~0.9m/px) and LOLA RGB shaded relief (5m/px) map

Layered units in Upper Crater Wall of Shackleton

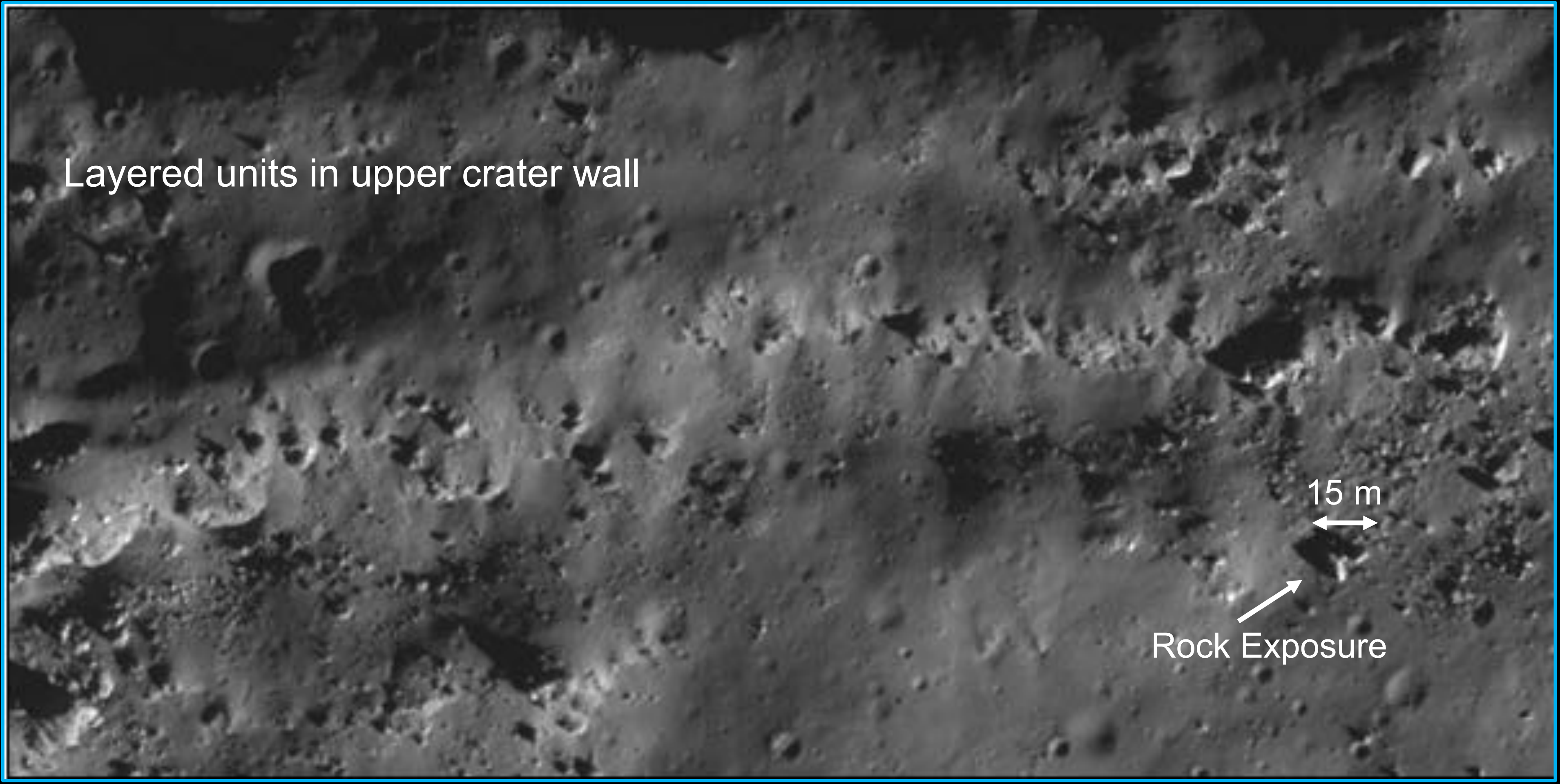


NAC ID M133154995R

Contours (100m interval) overlaid NAC image (~0.9m/px) and LOLA RGB shaded relief (5m/px) map

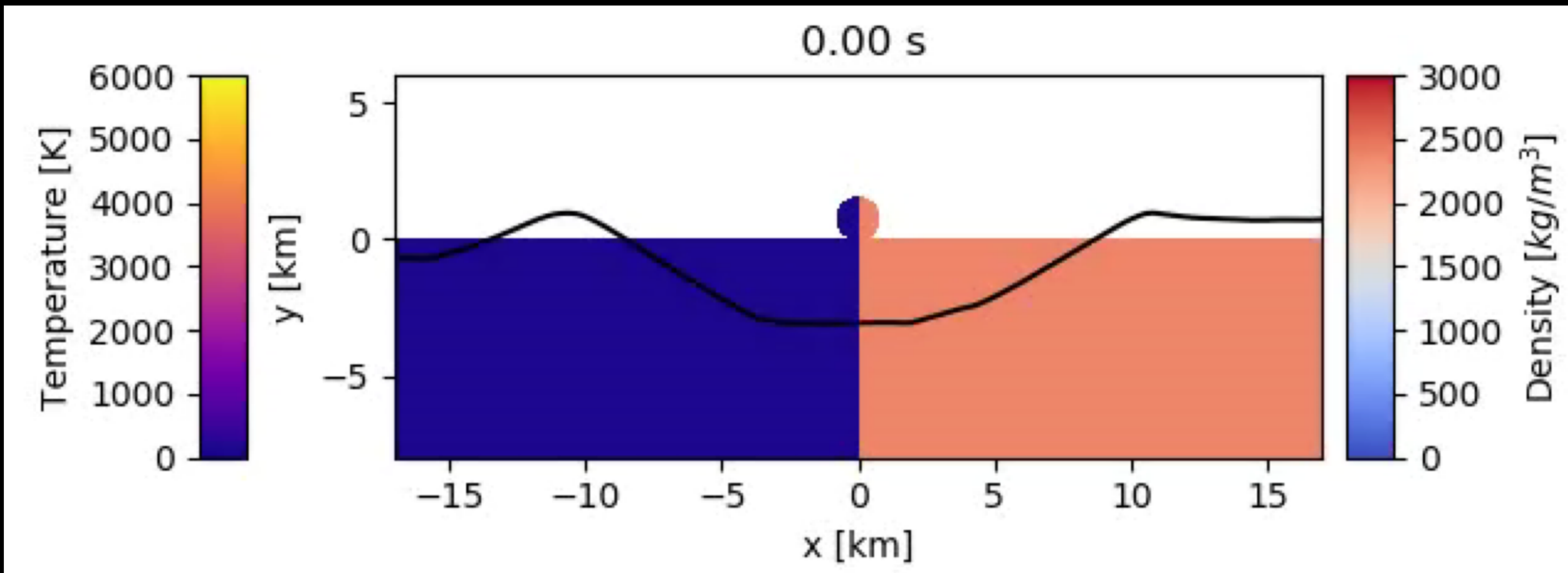
Probable Impact Ejecta Layers from Older Craters

Layer thicknesses up to 10s of meters; total sequence thickness ~200 to 250 m



Detail of NAC ID M133154995R

Shackleton Crater: An iSALE simulation

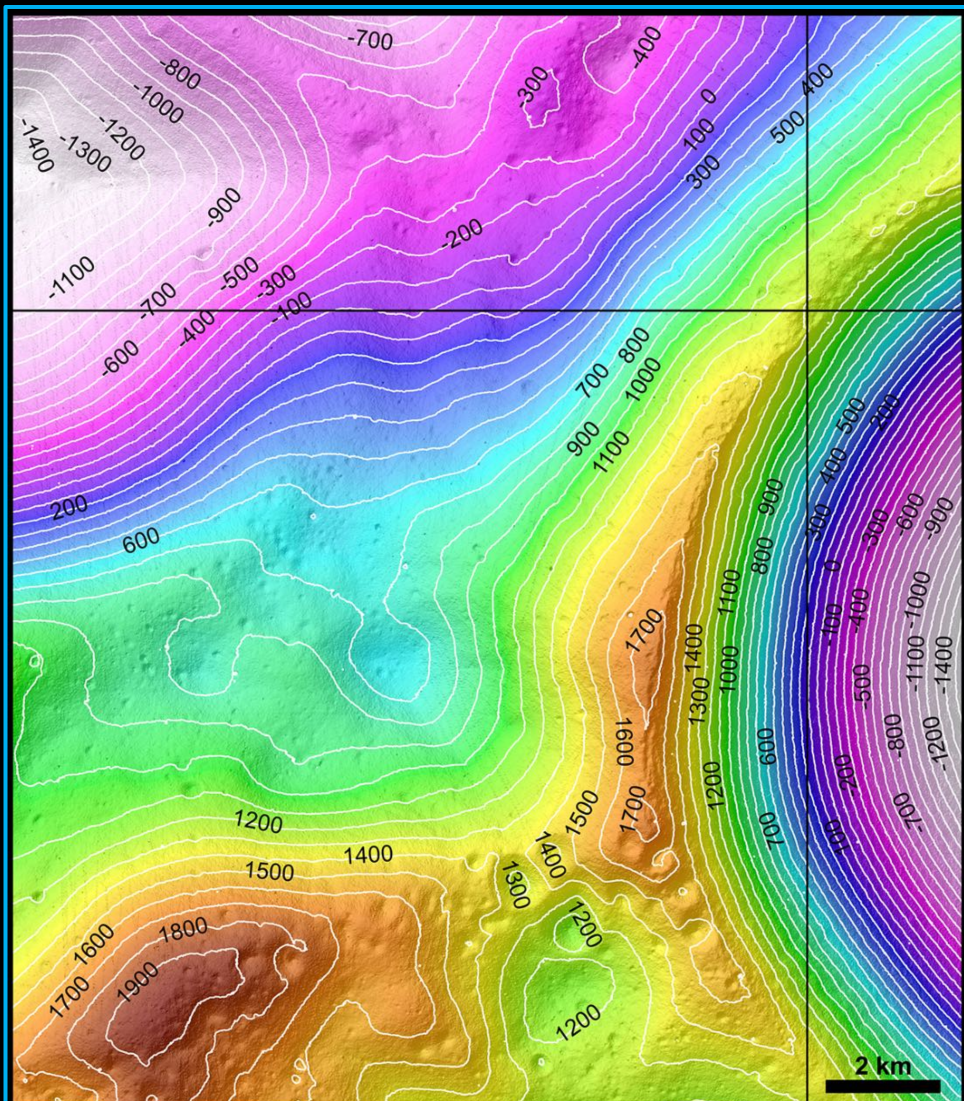


Impactor:
- Material: Dunite (ANEOS)
- Reference density: 3300 kg m^{-3}
- Porosity: 27.5%
- Density (after porosity): 2400 kg m^{-3}
- Diameter: 1.5 km
- Velocity: 15 km s^{-1} at 90°

Target:
- Material: Gabbroic Anorthosite (Tillotson EoS)
- Reference density: 2970 kg m^{-3}
- Porosity: 18.5%
- Density (after porosity): 2400 kg m^{-3}

→ ~150 m of ejecta on crater rim

EVA on Shackleton Crater Rim



Assume, for a moment, that crew have no mobility (as in Apollo 11).

An EVA from the south pole, along the rim towards the lower left quadrant, requires a climb of about 140 m over a distance of 2 km.

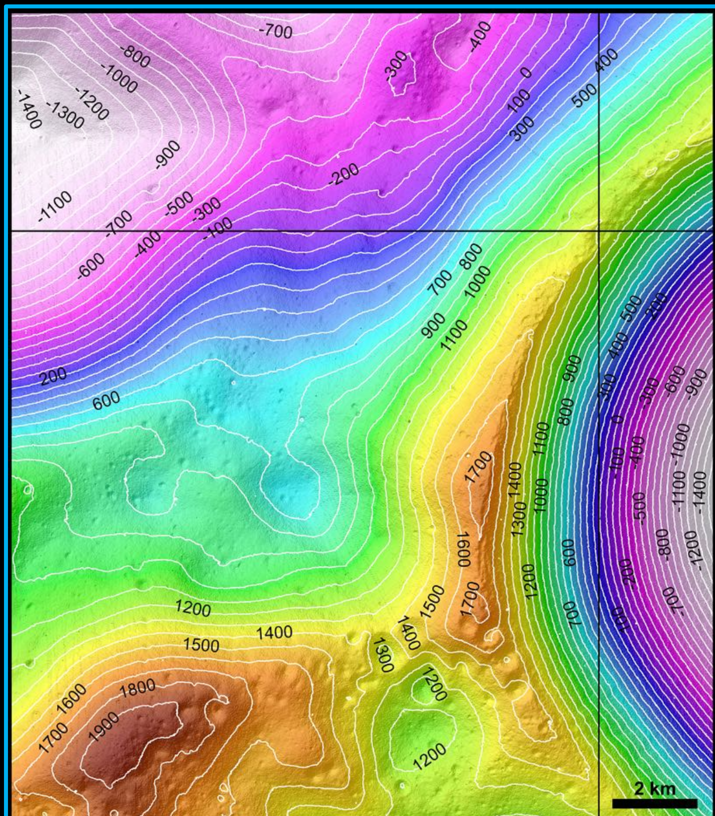
If one continues along the rim crest, then an elevation change of ~470 m is required.

The ridge that abuts the crater rim rises to ~1900 m or ~600 m above the south pole.

A landing site closer to the intersection of the crater rim with that ridge is another option. From that location, an EVA to a PSR near a 1200 m contour would require a descent of about 500 m.

Rocket plume effects and contamination of nearby PSRs need to be evaluated. (See paper by Metzger et al. at this conference.)

Augmenting Crew Capability with a Rover



Assume, instead, an unpressurized rover (UPR) or small pressurized rover (SPR) is pre-deployed prior to crew landing.

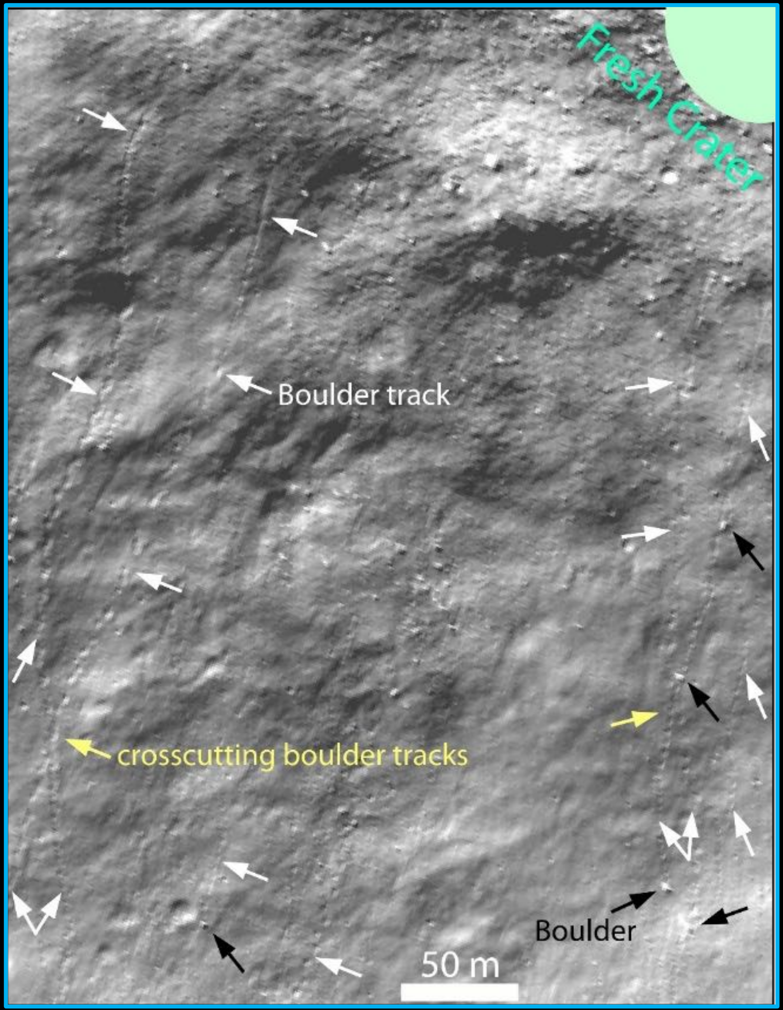
That would greatly enhance crew productivity over a larger area.

Pre-deployment would provide an asset for tele-operated surveys before and between crew landings.

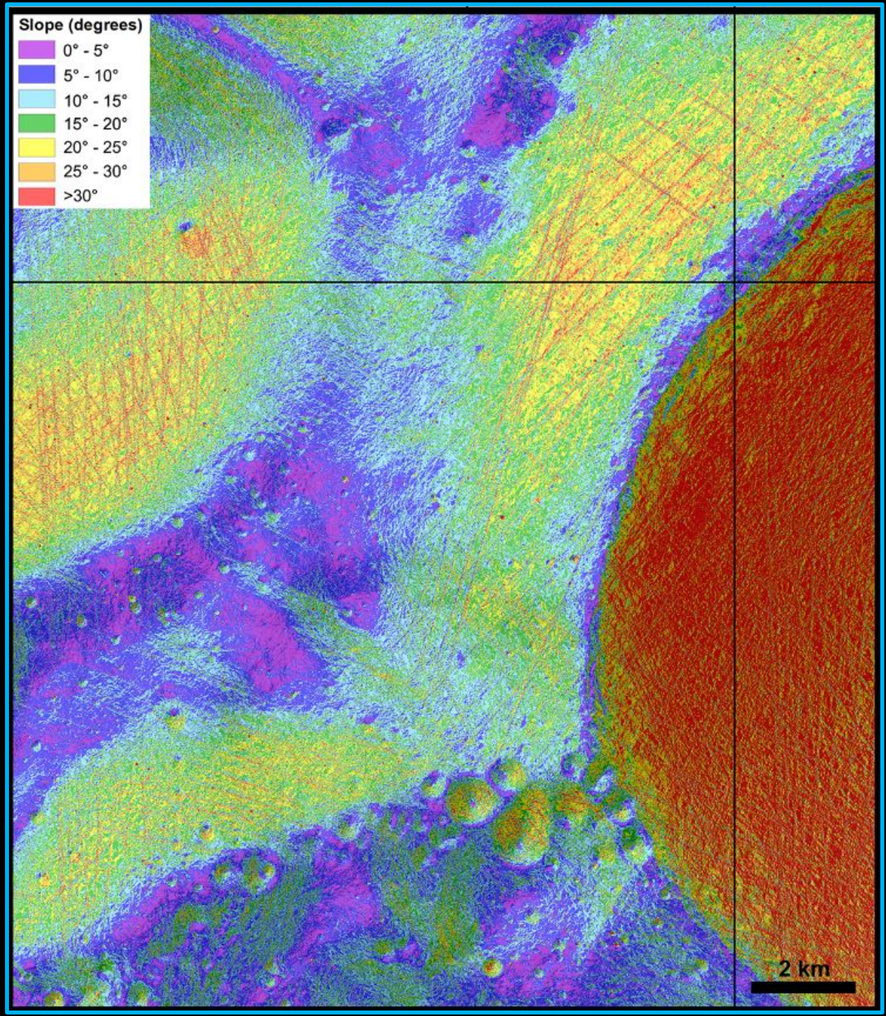
It would also provide a visible milestone towards a sustainable exploration program.

Parameters that may Limit Mobility

Good news: Bearing Capacity – See presentation by Bickel at this conference.



Challenging News: Slope – Will constrain traverse options in the south polar region.



Final Thoughts

- PSRs (e.g., craters) in the south polar regions may have trapped volatiles from different sources, depending on the age of the catchments. Volatiles will be heterogeneously distributed vertically, laterally, and have variable compositions.
- If EVA are limited to the rim of Shackleton, rocky targets will be dominated by crater ejecta. That debris may include PAN and debris from older cratering events.
- Extreme topography may limit crew EVA options if the crew does not have mobility assets.
- Even with rovers, trafficability conditions, particularly slope, may limit crew traverse options in some areas.
- Thus, linking the points of greatest illumination with areas of other operational interests (volatile resources and highest-priority science objectives) may be a challenge.
- Other landing sites would greatly expand opportunities for science and exploration.