State of Knowledge of Lunar Polar Ice and Volatiles

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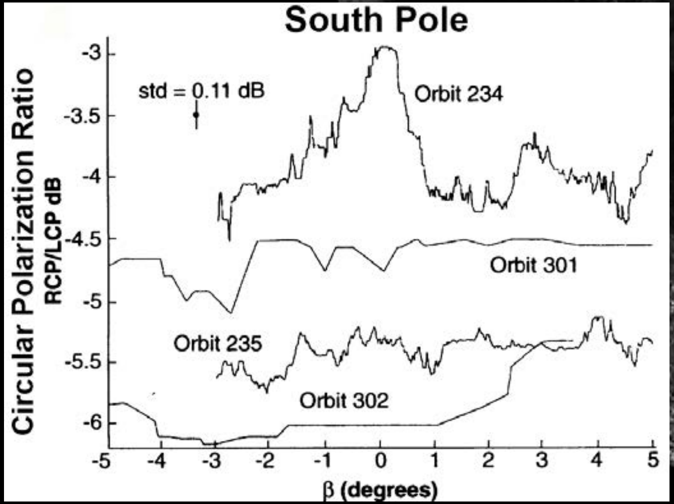
Polar Volatile Deposits

Water and other volatiles being trapped at the lunar poles was first proposed by Watson et al. (1961) *JGR* **66**, 1598-1600, and further developed by Arnold (1979) *JGR* **84**, 5659-5668.

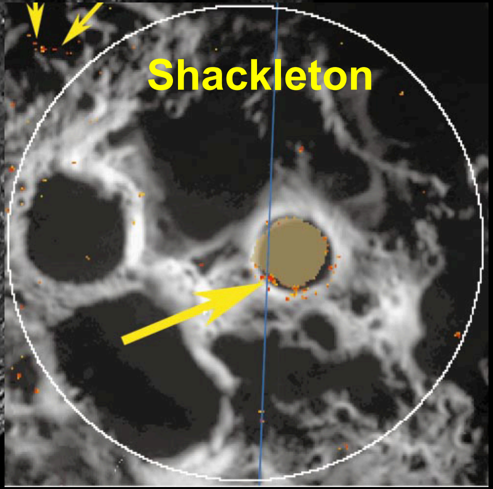
Clementine

Nozette et al. (1998) *Science* **274**, 1495-1498



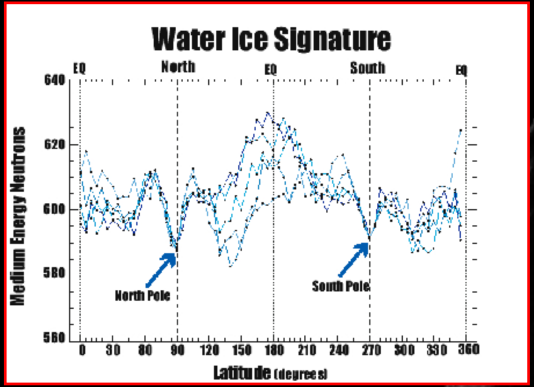
Arecibo

Nozette et al. (2001) *JGR* **106**, 23,253-23,266

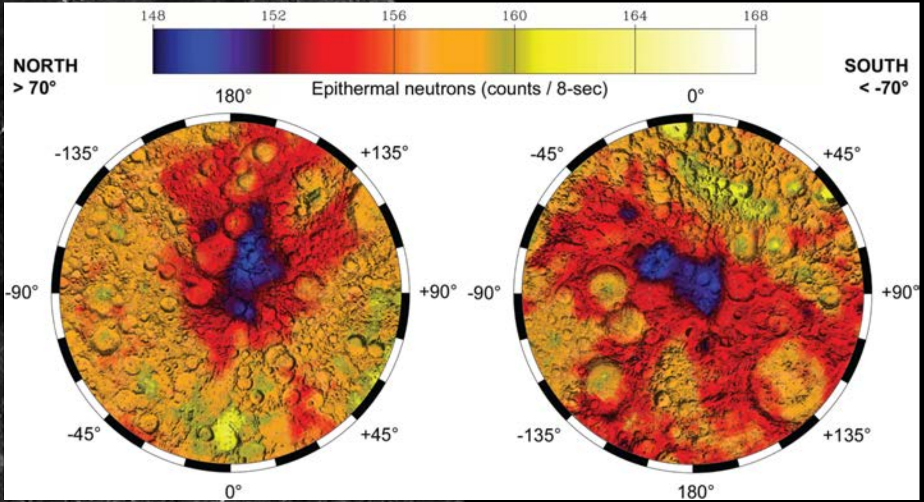


Polar Volatile Deposits

Lunar Prospector

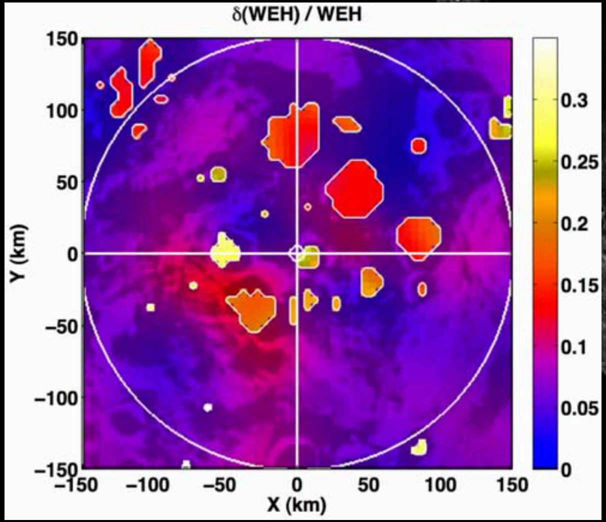


Feldman et al. (1998) *Science* **281**, 1496-1500.



Hydrogen in PSRs – better resolution needed.

Lawrence et al. (2006) *JGR* **111**, E08001, doi:10.1029/2005JE002637

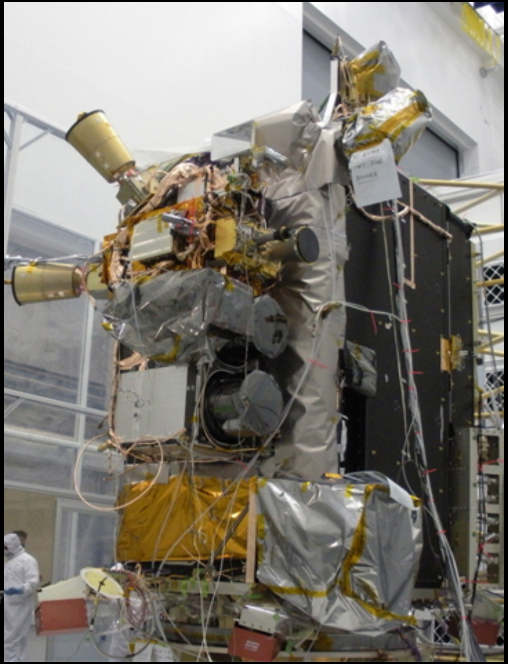


Using a pixon-based image reconstruction algorithm improved spatial resolution.

Elphic et al. (2007) *GRL* **34**, L13204, doi:10.1029/2007GL029954

Lunar Reconnaissance Orbiter

RADIATION: Cosmic Ray Telescope for the Effects of Radiation



INFRARED | Diviner Lunar Radiometer Experiment

ULTRAVIOLET | Lyman Alpha Mapping Project

NEUTRONS | Lunar Exploration Neutron Detector

ELEVATION | Lunar Orbiter Laser Altimeter

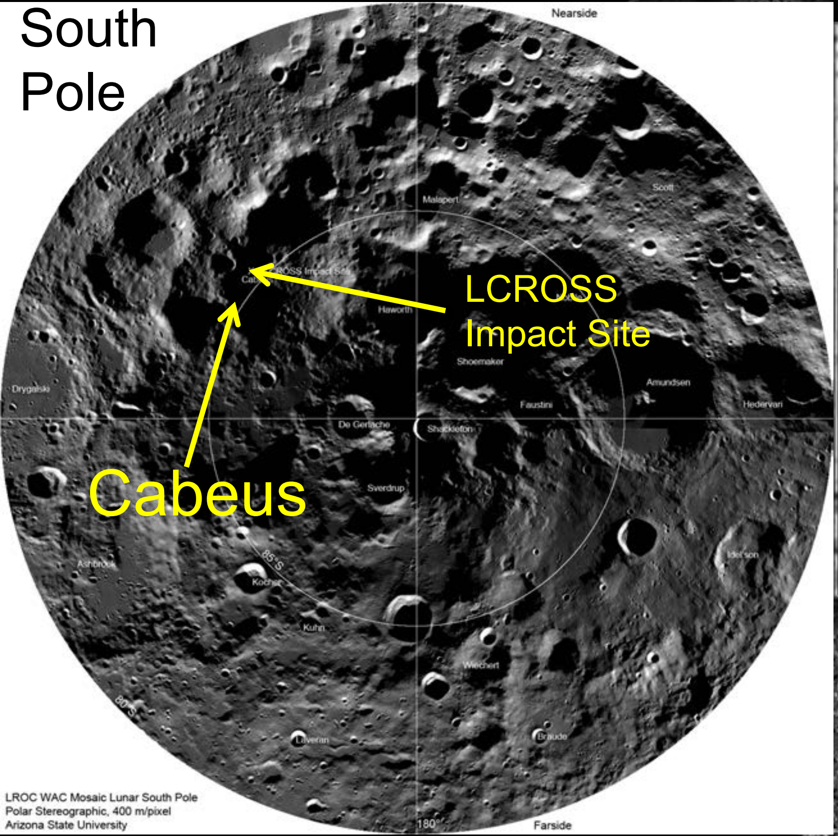
SUNLIGHT | Lunar Reconnaissance Orbiter Camera

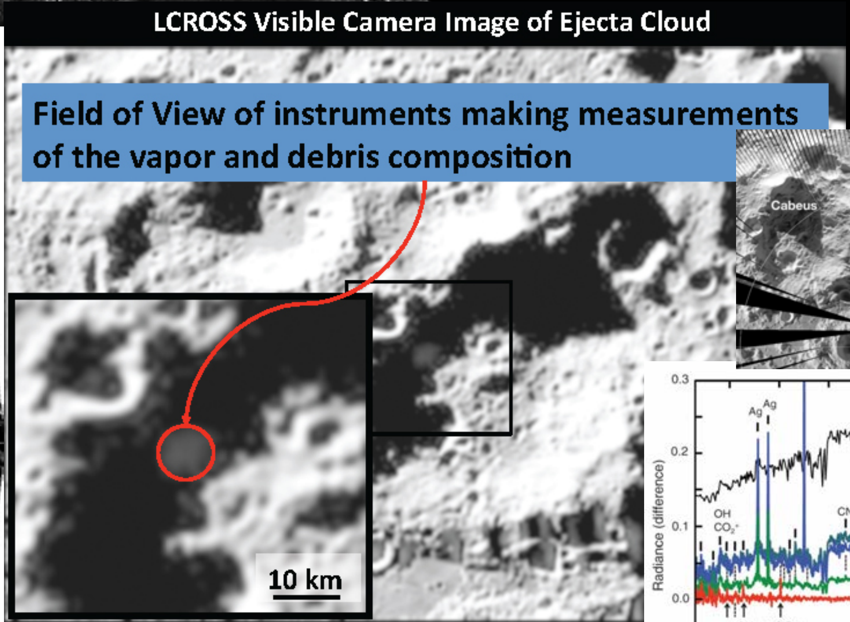
RADAR | Mini-RF Technology Demonstration

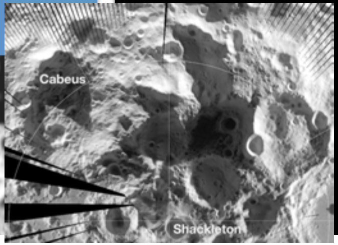
Lunar Crater Observation and Sensing Satellite (LCROSS) – impacted 9 Oct. 2009

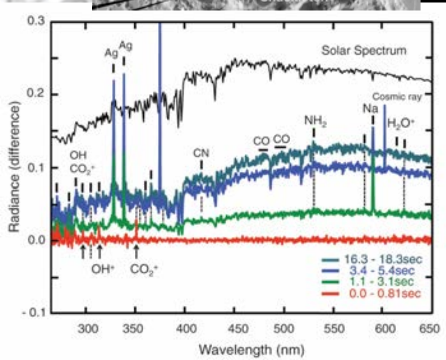
Launch: 18 June 2009

Polar Volatile Deposits





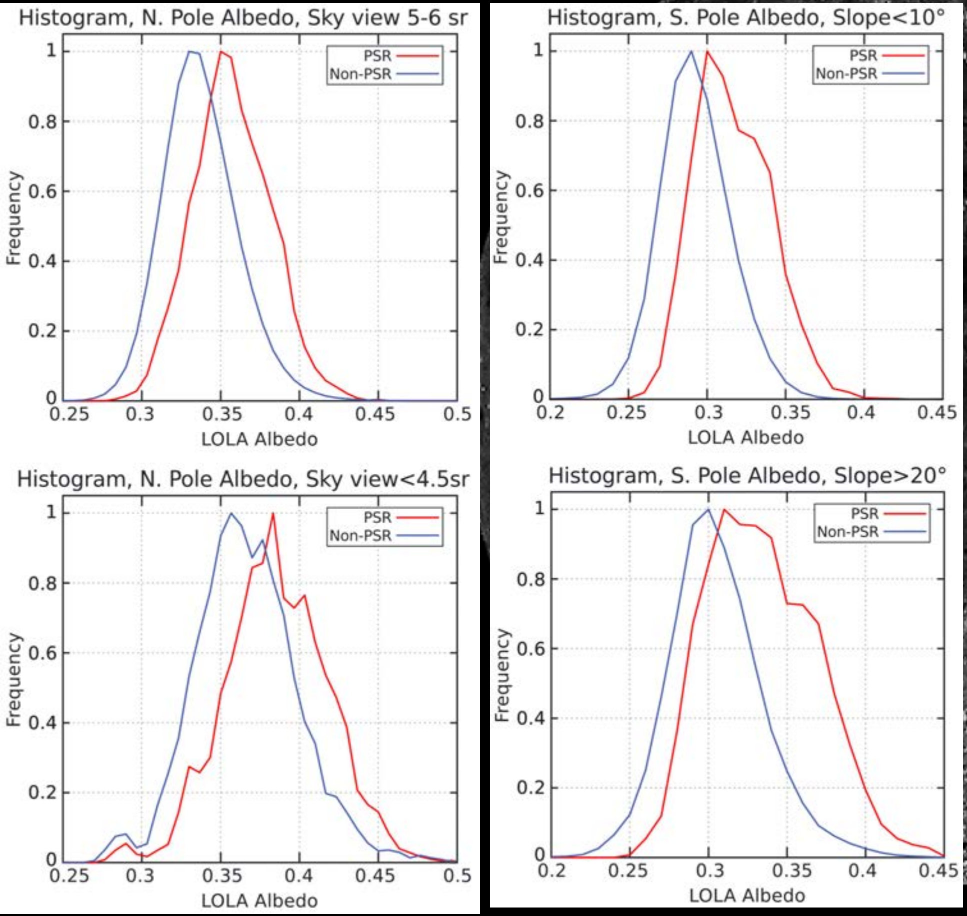




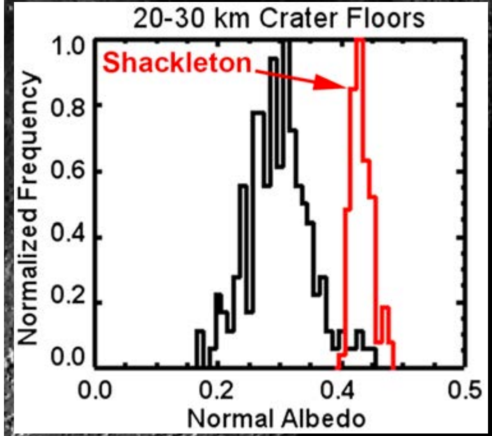
5.6 ± 2.9% H_2O plus many other volatiles.

Colaprete et al. (2010) *Science* **330**, 463-468.
Colaprete et al. (2012) *Space Sci. Rev.* **167**, 3-22.

Polar Volatile Deposits



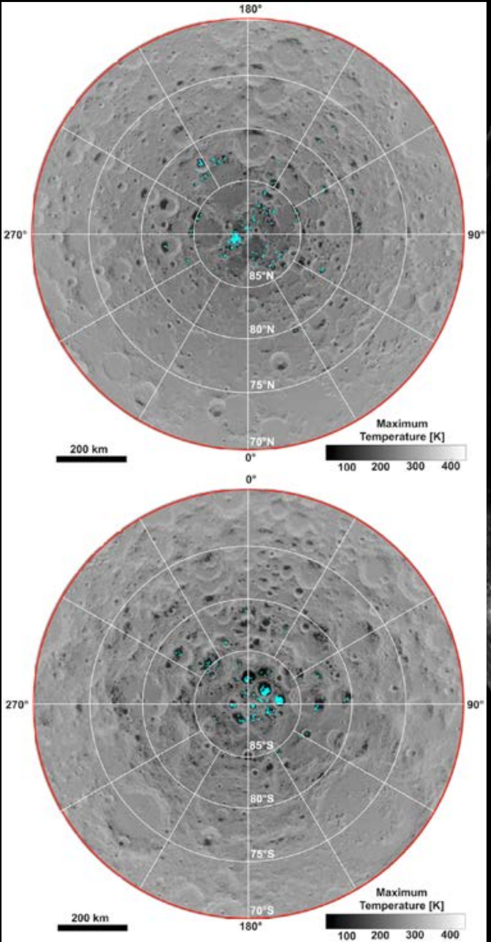
- Regions within PSRs are more reflective than polar surfaces that are sometimes illuminated.
- Water frost and a reduction in effectiveness of space weathering are offered as possible explanations.



Shackleton most reflective in its size range. Models = 3-14 wt.% water ice

Lucey et al. (2014) *JGR* **119**, 1665–1679.
Fisher et al. (2017) *Icarus* **292**, 74-85.

Polar Volatile Deposits



- LOLA reflectance and Diviner temperature data for the best places to find polar water-ice

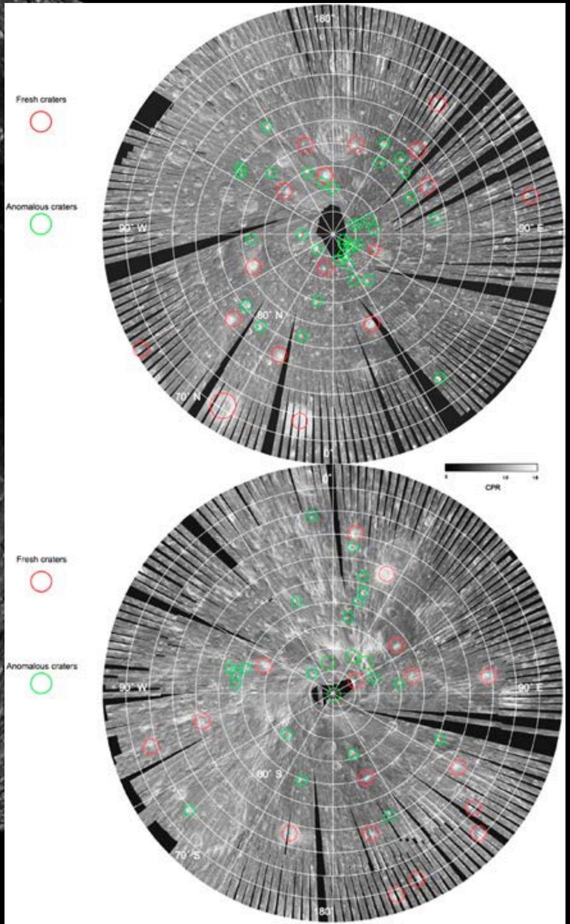
Fisher et al. (2017) *Icarus* **292**, 74-85.

Polar Volatile Deposits

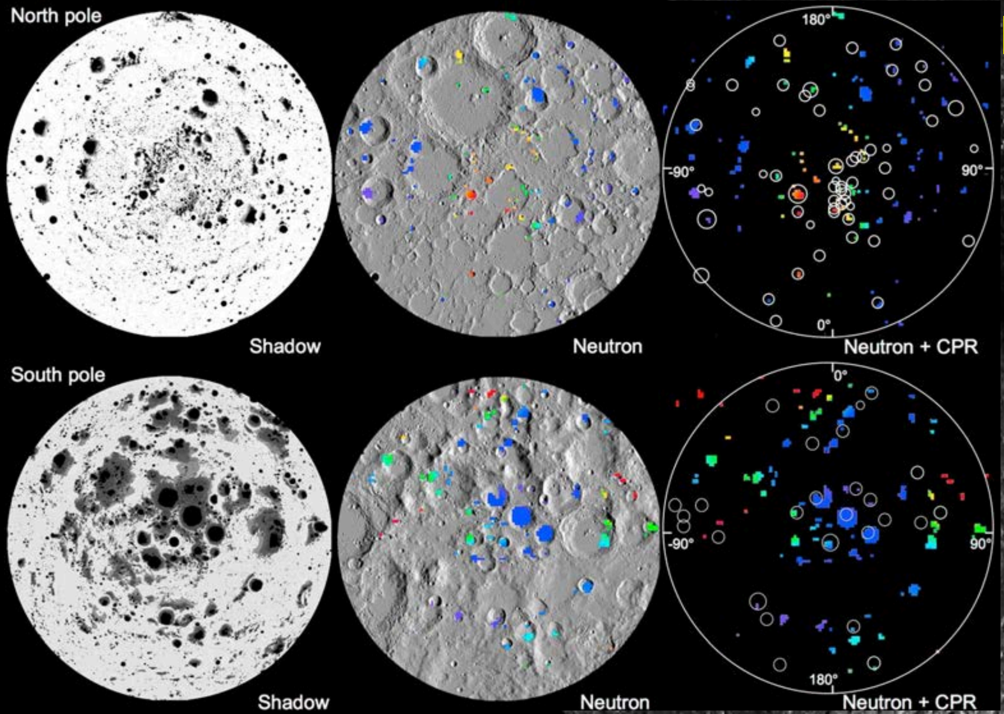
Mini-RF (fully operational): Radar Circular Polarization due to rock abundance or buried water ice.

- **Rock Abundance**: high-CPR inside and outside craters;
- **Water-Ice**: high-CPR only inside craters – “anomalous”.

Spudis et al. (2013) *JGR* **118**, 2016-2029



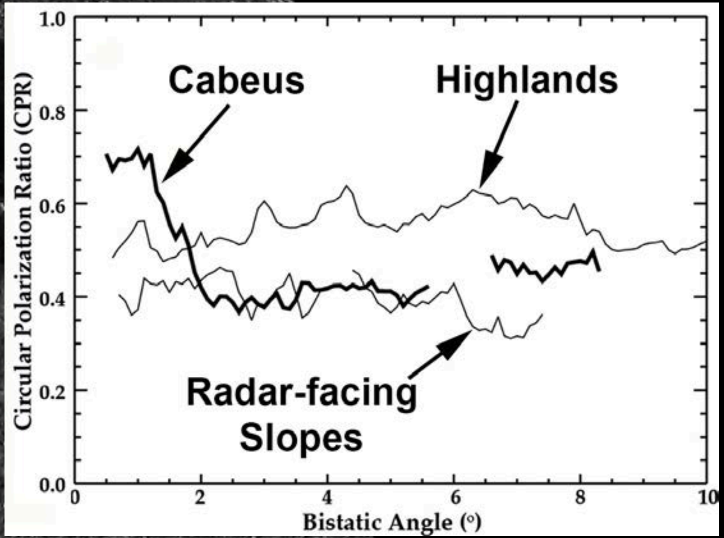
Polar Volatile Deposits



White circles = anomalous high-CPR craters intersect with high H abundances.

Spudis et al. (2013) *JGR* **118**, 2016-2029

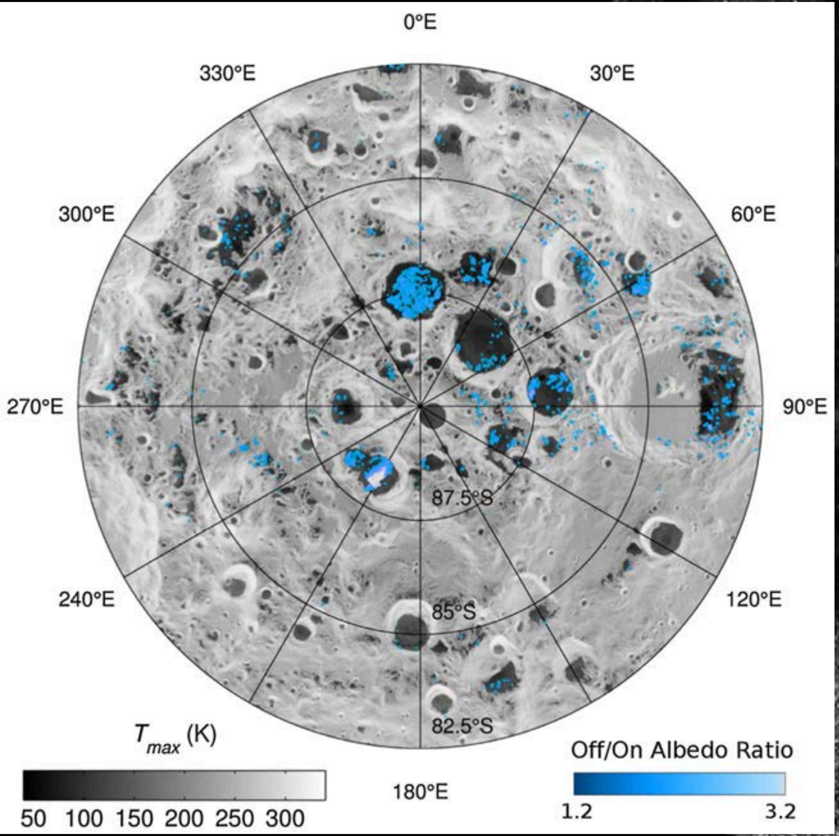
Mini-RF (Arecibo transmitting mode):

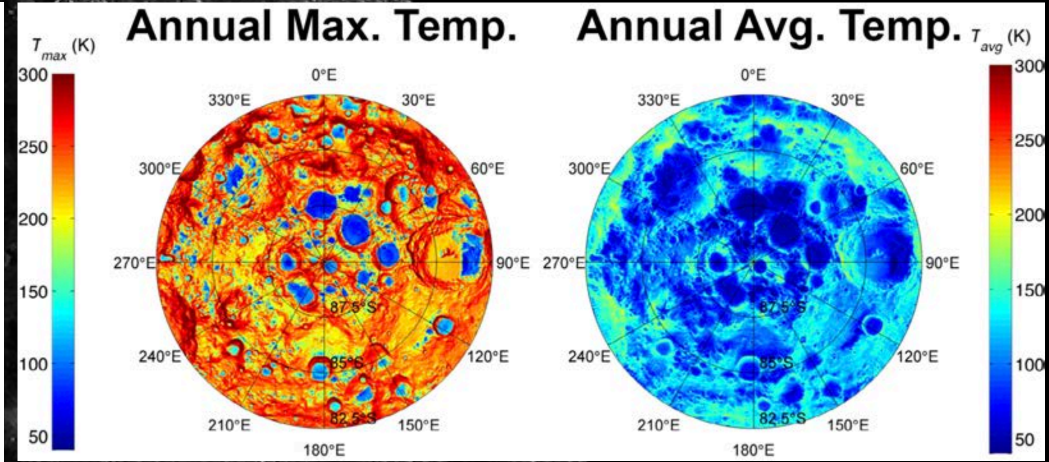


Cabeus: area targeted not in permanent shadow. Radar response consistent with buried water ice.

Patterson et al. (2017) *Icarus* **283**, 2-19

Polar Volatile Deposits



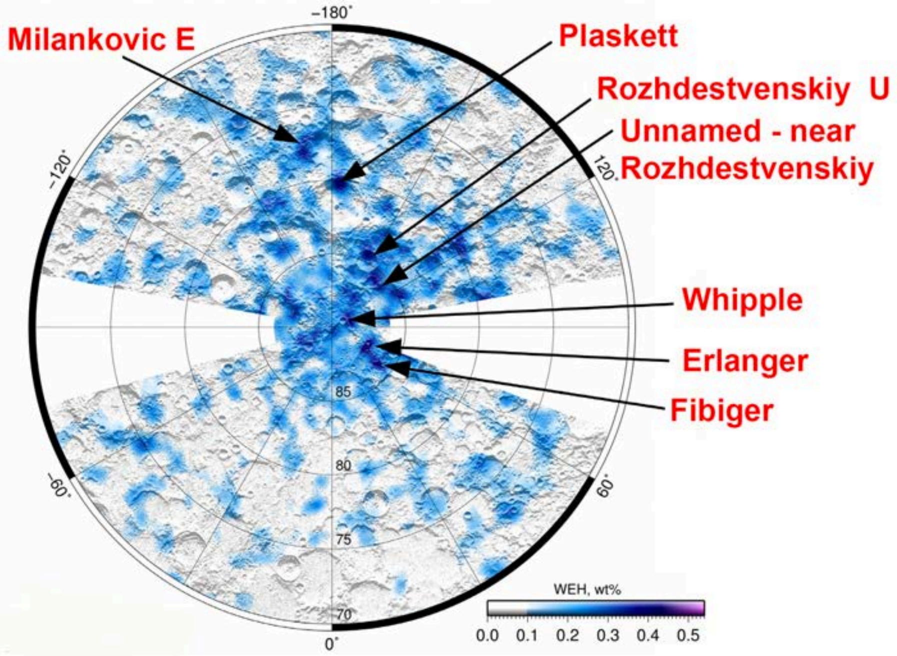


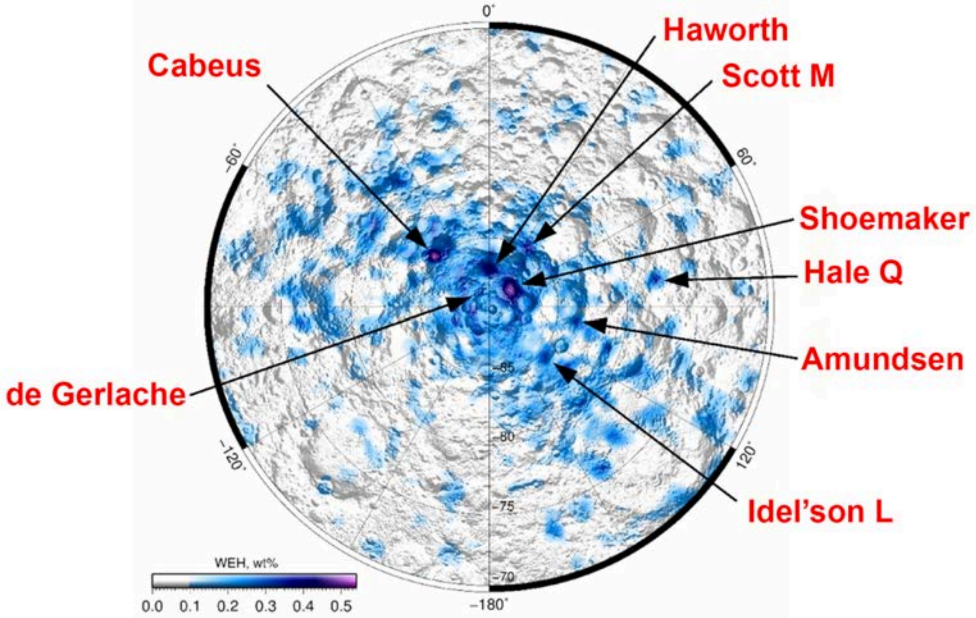
LAMP: UV reflectance in South Pole PSRs. Observe a strong change in spectral behavior at locations <110 K, consistent with cold-trapped surface ice. ***Water ice layers >100 nm thick***.

Hayne et al. (2015) *Icarus* **255**, 58-69

Polar Volatile Deposits

LEND: Converted neutron count data to "Water-Equivalent-H" in top ~1 meter

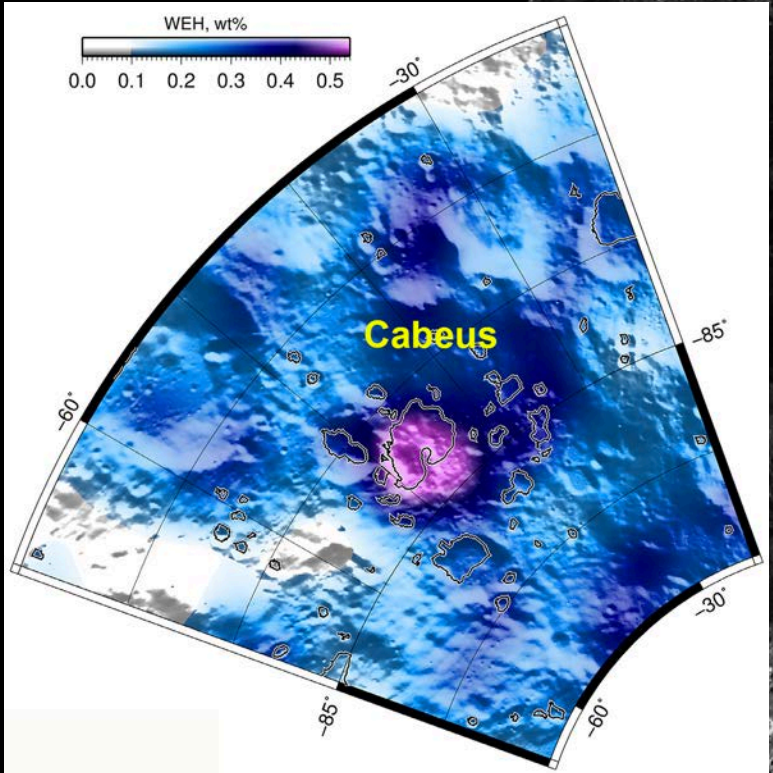


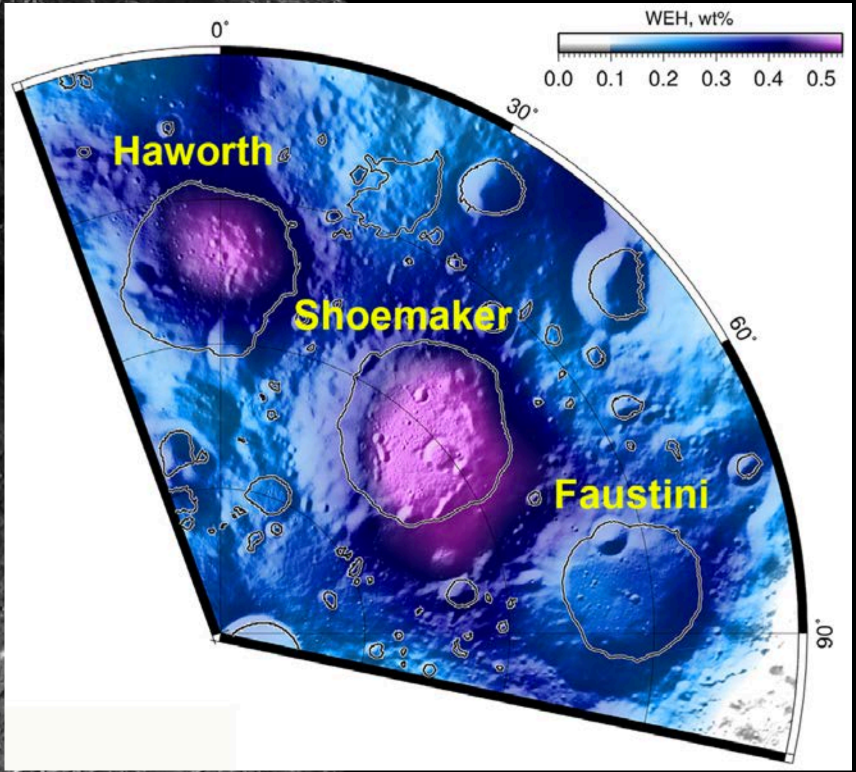


Up to 0.55 wt.% water

Sanin et al. (2017) *Icarus* **283**, 20-30

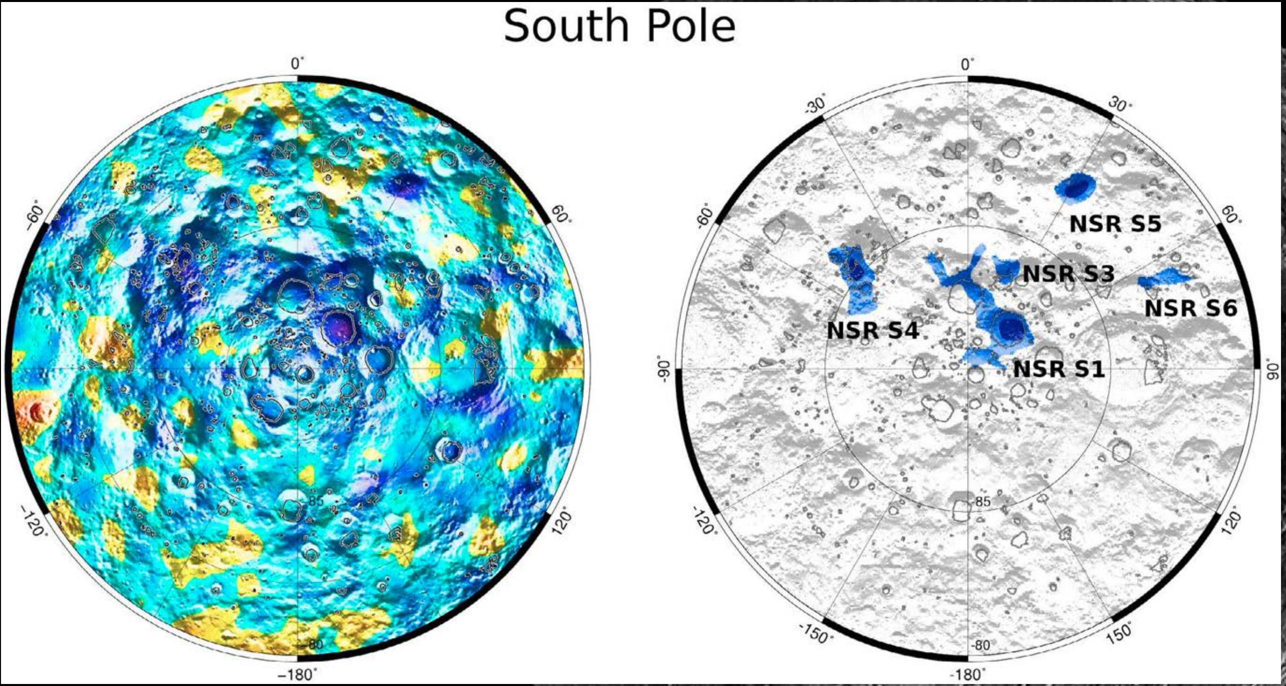
Polar Volatile Deposits





Sanin et al. (2017) *Icarus* **283**, 20-30

Polar Volatile Deposits



Mitrofanov et al. (2012) *JGR* **117**, E00H27, doi:10.1029/2011JE003956

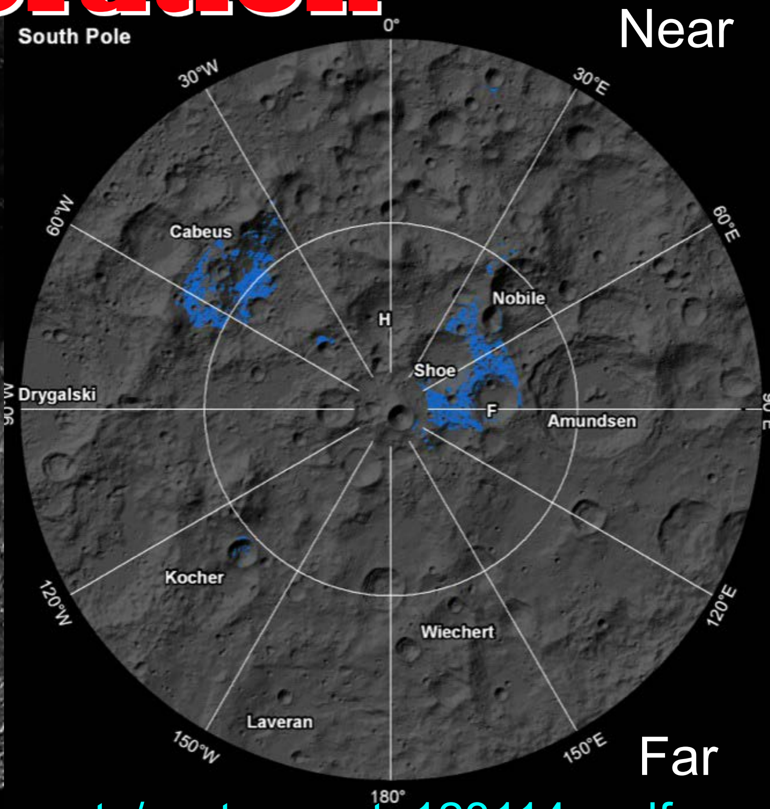
LEND: Neutron Suppression Regions (NSRs) in & around Permanently Shadowed Regions (PSRs).
Science and exploration targets.

Using Orbital Data to Plan Surface Exploration

South Pole

- Hydrogen >150 ppm.
- Average T < 110K:
  - Preserves subsurface ice for geologic time.
- Slope < 10 degrees:
  - Navigable by current rovers.
- Outside and adjacent to PSR:
  - Lighting available.

Cabeus and Shoemaker/Nobile vicinities meet general criteria and have some Earth visibility.



http://www.lpi.usra.edu/leag/reports/vsat_report_123114x.pdf

Using Orbital Data to Plan Surface Exploration

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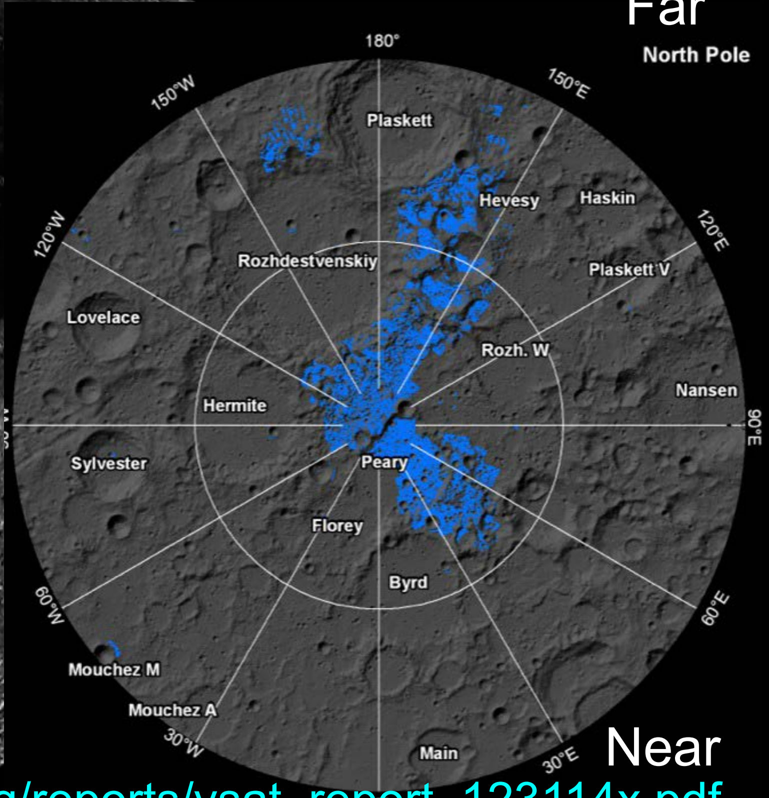
- Outside and adjacent to PSR:
  - Lighting available.

Peary vicinity meets general criteria and has Earth visibility.
Substantial area of farside also meet general criteria.



http://www.lpi.usra.edu/leag/reports/vsat_report_123114x.pdf

Using Orbital Data to Plan Surface Exploration

- Prospecting should be in AND around PSRs.
- Do we really need to go into a PSR to harvest volatile deposits?
- Rovers don’t need to all be RTG-powered (cheaper).
- Solar-powered rovers can last multiple day-night cycles at lunar poles (Resource Prospector mission study).

Why should we undertake Surface Prospecting?

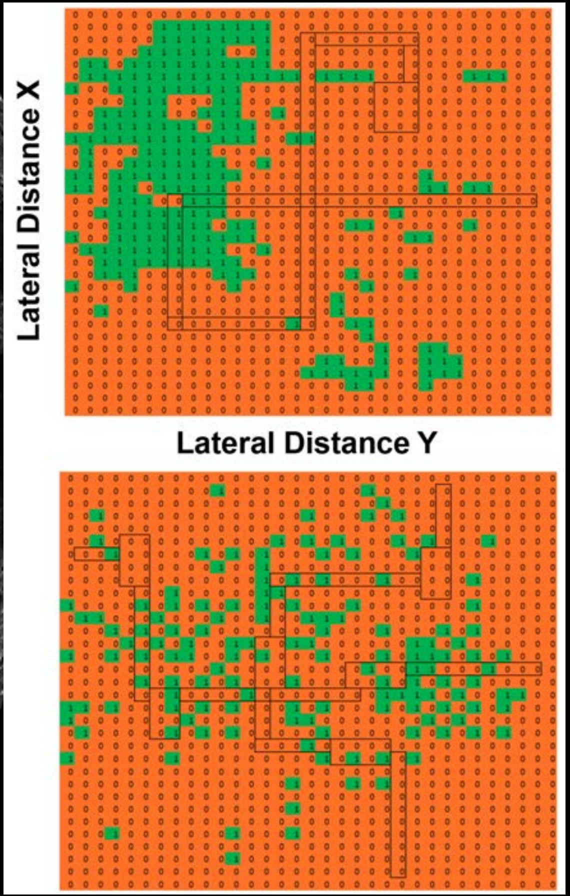
Need to know the following:

- 3D distribution;
- Form;
- Composition;
- Regolith geotechnical properties;
- Ease of extractability;
- Quantify the refining process for and transport and storage of potential life support consumables and rocket fuels.

PVD Exploration Program

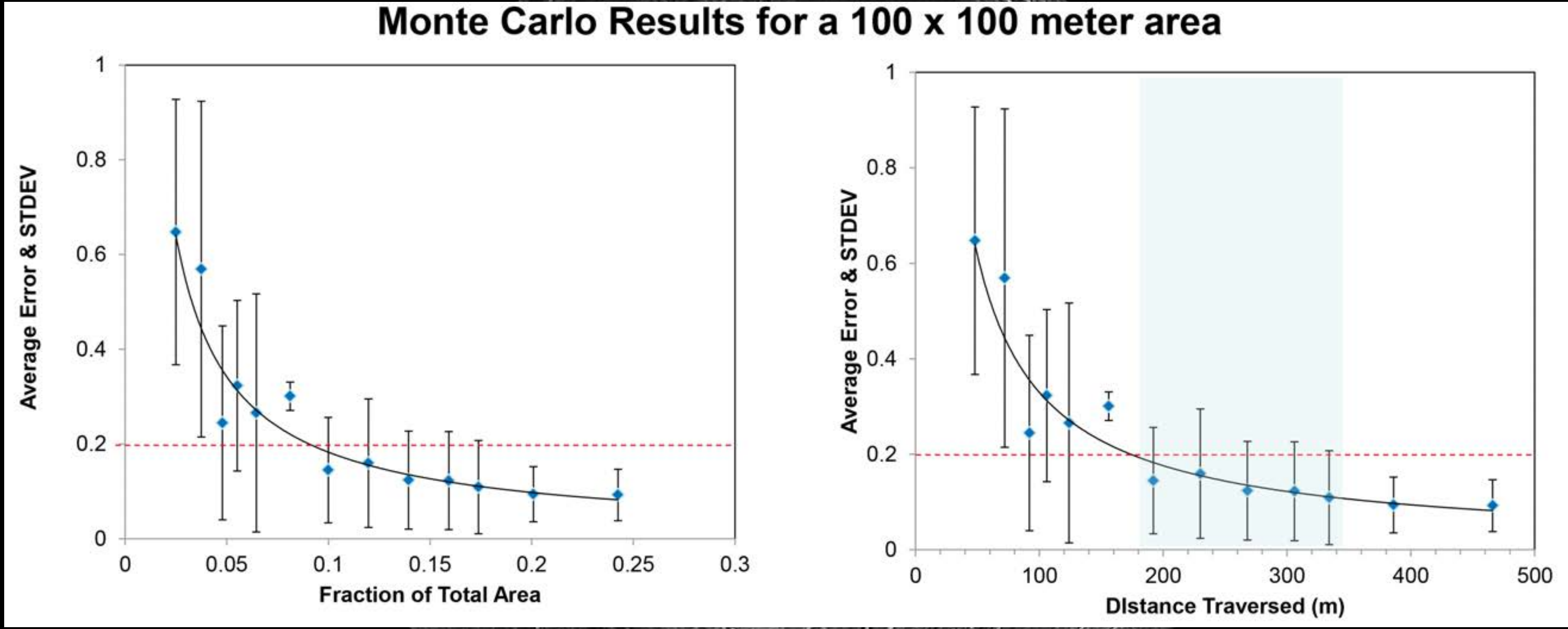
Prospecting must characterize a sufficient area to evaluate the resource potential.

- Terrestrial mining companies have worked this problem.
- Harder for the Moon as the “Mineral Model” is very uncertain.
- Monte Carlo runs tested the uncertainty in sampling as a function of total distance or area coverage.
- Sampled concentration was compared to “True concentration”, calculated for each run, and the error in sampling calculated (Error = [True – Sampled]/True).



Credit: Colaprete & the RP Team

PVD Exploration Program



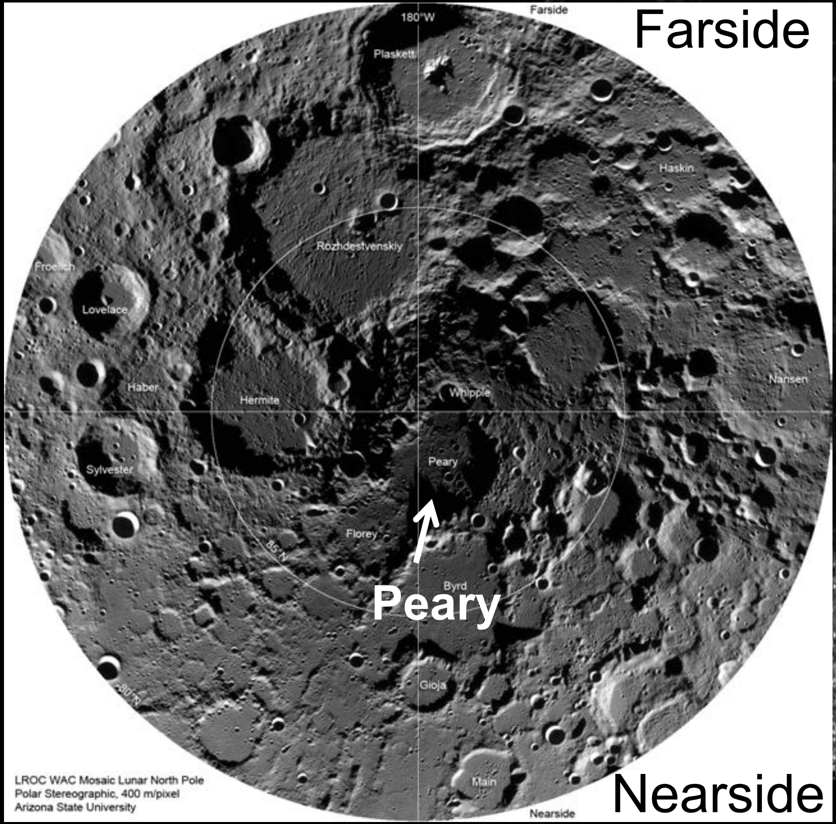
<u>Minimum</u>: need to traverse 180 m within a prospect

<u>Goal</u>: 320 m.

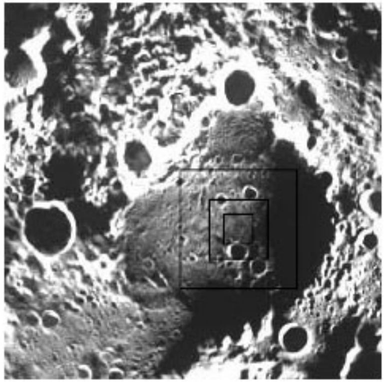
Credit: Colaprete & the RP Team

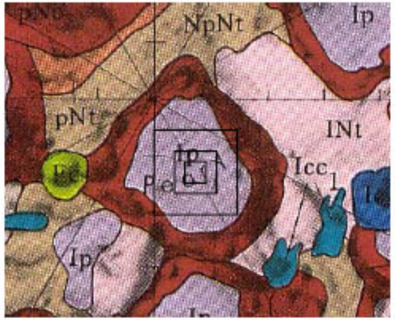
Exploring Polar Volatiles – First Step

Peary Crater PSR – North Pole



Peary Crater





(Clementine uvvis color ratio image not available)

Location (longitude, latitude): 30.00, 88.50

Scientific Rationale:
Polar volatiles
Impact process

Resource Potential:
Highlands regolith
Enhanced hydrogen in permanently shadowed polar craters (water ice?)

Operational Perspective:
Highlands terrain
Polar location
Areas of permanent shadow

NASA References:
Exploration Systems Architecture Study (2005)
Geoscience and a Lunar Base (1990)

PVD Exploration Program

1. Low cost LCROSS-type missions to various PSRs.
2. Penetrators containing mass spectrometers deployed to larger PSRs (short-lived).
3. Static landers direct to a PSR. These could contain RTG-powered rovers.
4. Resource-Prospector-type rovers for short duration visits to accessible PSRs.
5. RTG-powered rovers that would land in sunlight and traverse into PSRs.
6. “Hoppers” to visit areas within a PSR and potentially visit several PSRs.

Initial Data

- Elemental abundances and isotopic composition.
- Variability both at the surface and in the subsurface.
- Regolith geotechnical properties.
- Physical form (ice layer, ice-regolith mixture, etc.).
- Environmental data.
- ISRU demonstrations.

Instruments

- IR-Vis-UV spectrometer(s).
- Oven.
- Mass spectrometer(s).
- Drill (+/- coring capability).
- Penetrometer.
- High-resolution camera(s).
- Other may be required depending on the mission goals.

Strategy for Exploring PVDs

Initially undertake in situ science at the different PSRs at both the South and North poles:

- Mission Options 1 (“LCROSS”) and 2 (Penetrators) could be deployed to the large neutron suppression areas deep with in PSRs. (e.g., Cabeus, Haworth, Shackleton, Nobile, West of Peary).
- Mission Options 3 (static landers) and 4 (solar-powered rovers) could be deployed to craters that are in partial shadow (e.g., Peary, western Hermite, western Rhozhdestvenskiy W).
- Mission Options 5 (RTG rovers) and 6 (hoppers) are suggested for detailed PSR investigations if mission opportunities are limited and/or if rovers cannot enter the region.

Exploration of Lunar Polar Volatile Deposits

- Exploration and science synergies.
- Private sector interest in these resources that have science benefits.
- International interest in the polar volatiles – 6 landed missions to the south pole between now and 2025.
- Initial in situ investigations that leads to cryogenic storage and sample return.
- Technology development in cryogenic sampling, transport, & curation.
- Feed forward to other destinations (Mars, Comets, Ocean Worlds).
- Enabling sustainable interplanetary human space travel.

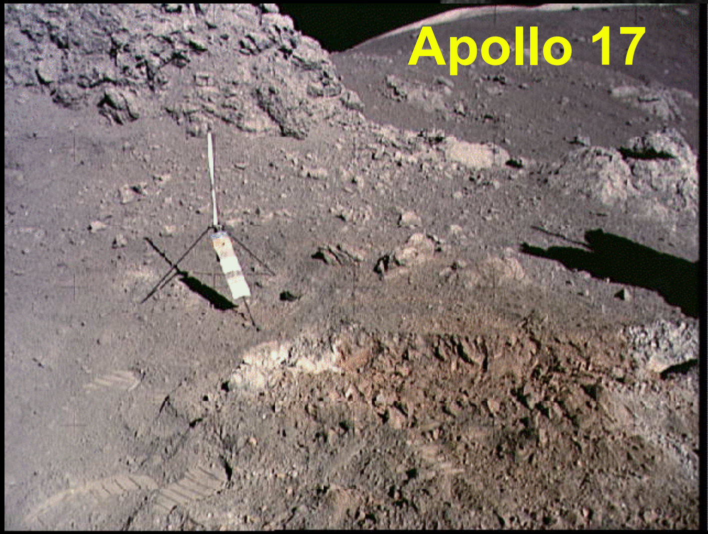
Space Transportation Needs Fuel. Can the Moon Supply It?

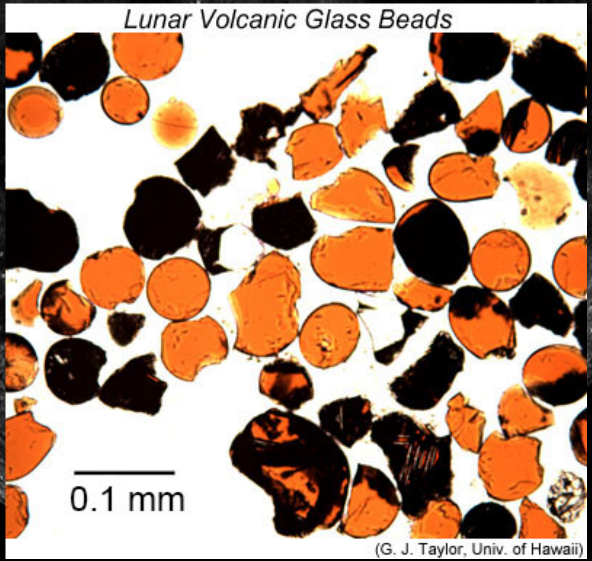
Yes – **BUT**:

- Need to understand if resources are reserves (prospecting!).
- Water is the resource so Oxygen and Hydrogen will be the fuels derived.
- Most engines being developed = LOx-Methane.
- Need development of LOx-H engines to stimulate the market for extraterrestrial-derived fuels (Moon AND Mars).

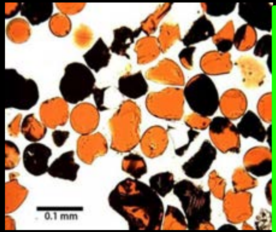
What did we learn from Apollo?

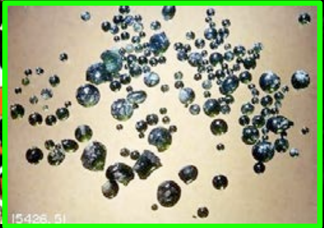
- Fire fountain eruptions occurred numerous times on the Moon.
- Substantial samples returned by Apollo 15 (1971; 15426) & Apollo 17 (1972; 74220).
- BUT what we got from Apollo will be important for the future.

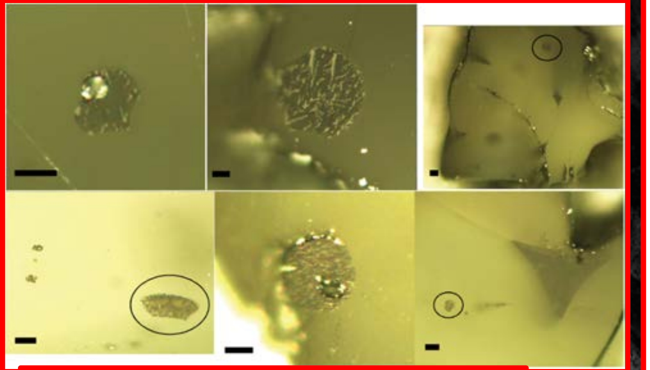




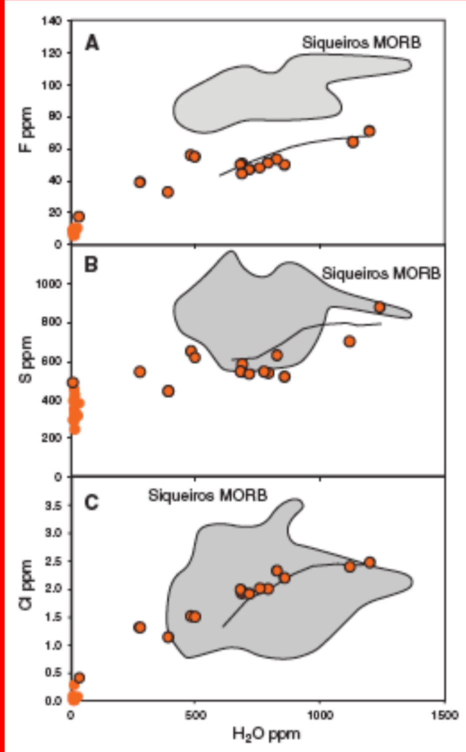
Endogenous Volatiles





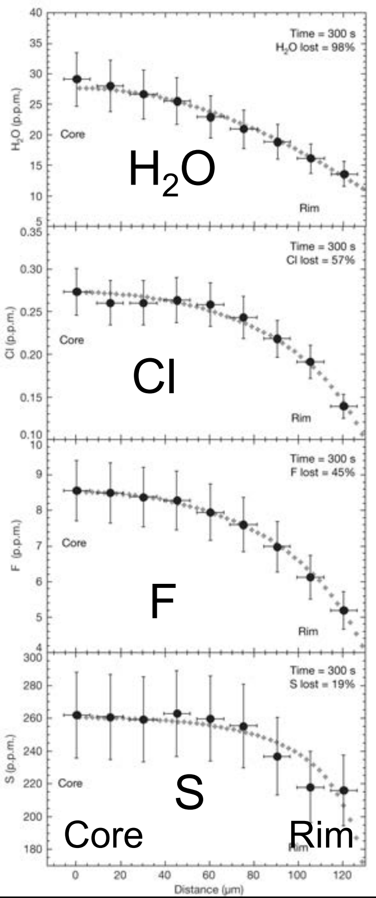


Hauri et al. (2011)
Science **333**, 213-215

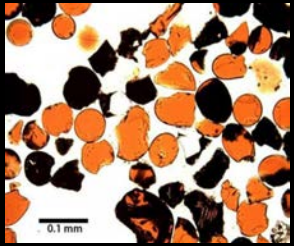


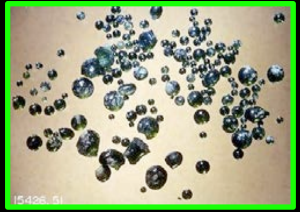
Melt Inclusions in Olivine

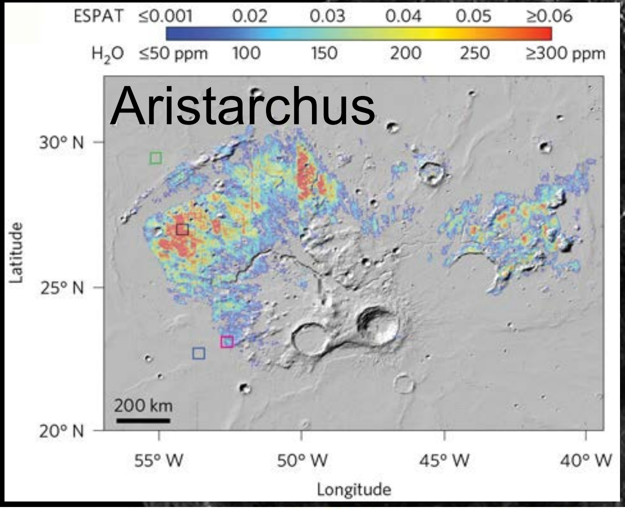
Saal et al. (2008)
Nature **454**,
192-195

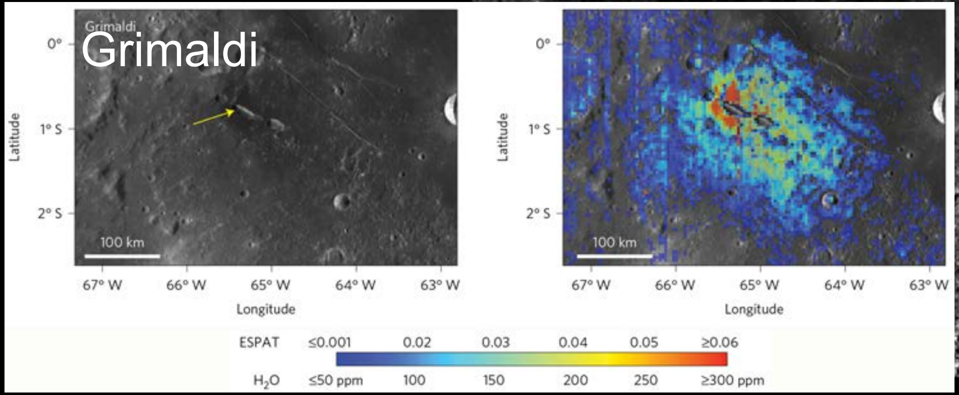


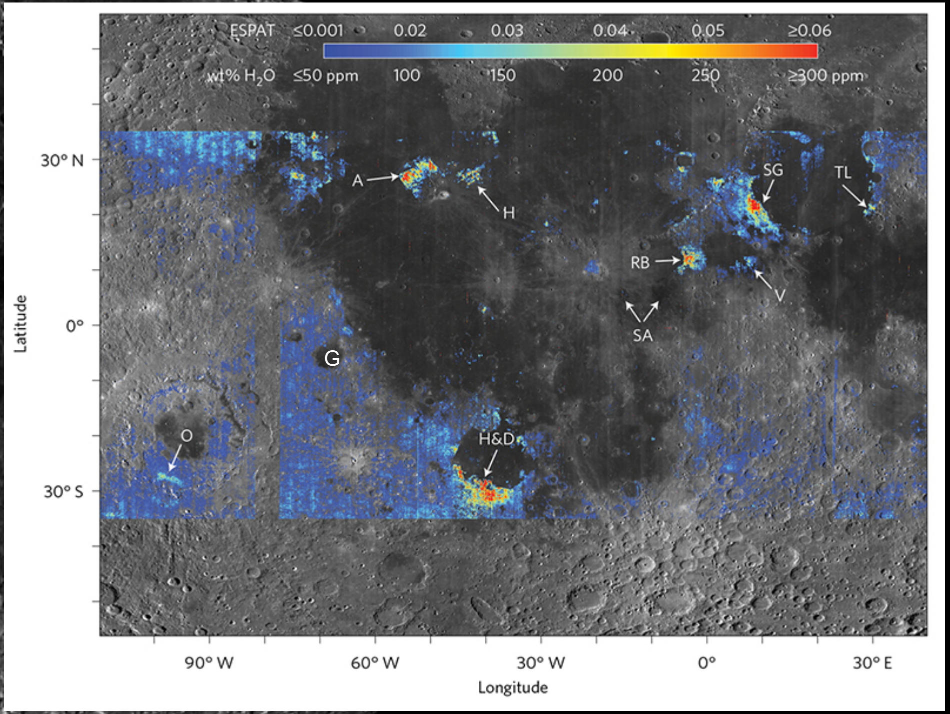
Non-Polar Volatile Deposits











Milliken & Li (2017) *Nat. Geosci.* **10**, 561-565.

Take Home Messages

The Moon is not the end-game!
It is an enabling asset as the gateway for humans to explore the Solar System!

Resources can bring the Moon into our economic sphere of influence and drive a new area of economic growth.