Abstract #1599

English

Bringing the Moon into our Sphere of Economic Influence: The Importance of Lunar Resources

The Lunar Exploration Analysis Group (LEAG) has developed a comprehensive Lunar Exploration Roadmap (LER: http://www.lpi.usra.edu/leag/roadmap/) that is centered on three themes: Science (lunar and Solar System), Feed Forward (how the Moon can be used to enable human exploration of other planetary bodies), and Sustainability. This is a living document that is regularly updated on the basis of new information, with the next update occurring in 2017. Apart from political will, the main enabler of this roadmap is the presence of lunar resources. In 2011 LEAG published the outline of a 3-phase robotic precursor campaign focused on these resources (http://www.lpi.usra.edu/leag/reports/RoboticAnalysisLetter.pdf). Based upon the wealth of lunar orbital data that has identified the resource potential, the next step is to get to the surface and establish if the resources are in fact reserves. This requires surface mobility and the ability to examine the subsurface regolith to a depth of several meters, at the ≤10 centimeter resolution, in order to establish resource form, composition, distribution, and extractability. Such Resource Prospectors need to be sent to a number of areas that show good resource potential from orbital data – this would represent Phase 1 of the LER implementation plan. Lunar volatile deposits around the poles or in pyroclastic deposits are the resources in question here. In 2014 LEAG formulated a Specific Action Team (SAT) at the request of NASA HEOMD to define polar exploration targets for volatile deposits and the best candidates can be found in the report, which was submitted in early 2015 (http://www.lpi.usra.edu/leag/reports/vsat_report_123114x.pdf). Phase 2 of the implementation plan would require ISRU pilot plants to be set up at 2-3 of the best sites defined in Phase 1 with the best of these being fully developed for ISRU production in Phase 3. This phased implementation requires strong collaboration and cooperation with the mining industry and will define important “commercial on ramps” through public-private partnerships. Refinement of lunar volatile resources into life support consumables and rocket fuel not only enables human exploration of the Moon but could (through establishment of cis-lunar refueling depots) send and return humans to Mars and beyond. Finally, establishing this cis-lunar infrastructure could also enable refueling of Earth-orbiting satellite infrastructure to prolong their lifetime and reduce the build up of “space junk” that is a growing hazard around our planet.

French

No abstract title in French

No French resume

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Clive R. Neal is a Professor of Planetary Geology at the University of Notre Dame. He has been involved in the study of the Moon since 1986 using Apollo samples, lunar meteorites, as well as remotely sensed data from missions since Apollo. He has also served on mission and research review panels, including being the Chair of the Lunar Sample Allocation subcommittee for CAPTEM 2005-2009, and was a member of the Senior Review panel for NASA's Planetary Science Division in 2012 and chaired that panel in 2014. He is the current chair of NASA's Lunar Exploration Analysis Group, a group that he chaired from 2006-2010. In 2015, he received the NASA "Wargo Award" for contributions to the integration of exploration and planetary science throughout his career.

Jerry Sanders will be presenting on behalf of Dr. Neal who is unable to attend.

BRINGING THE MOON INTO OUR SPHERE OF ECONOMIC INFLUENCE: THE IMPORTANCE OF LUNAR RESOURCES

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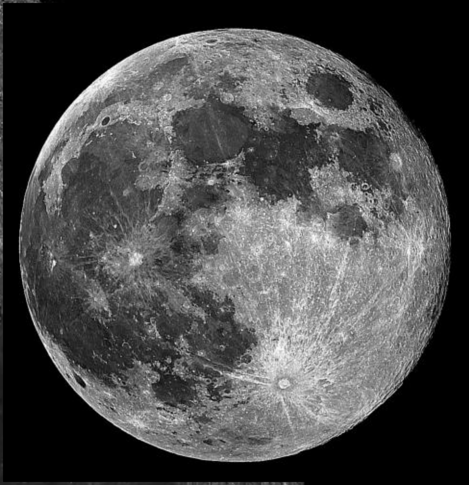
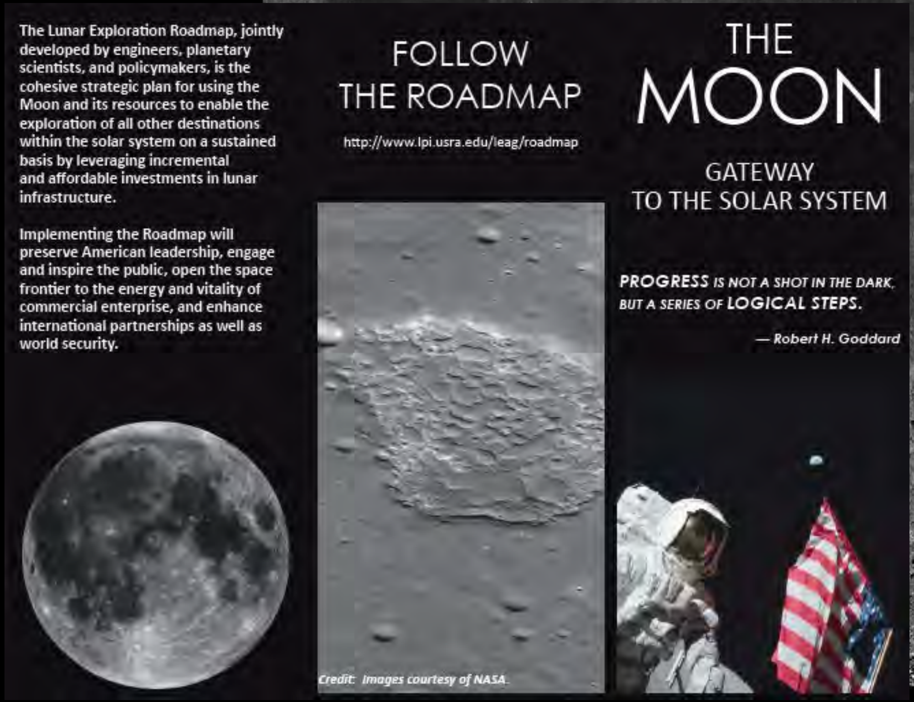
LEAG LUNAR EXPLORATION ROADMAP

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

2007: LEAG tasked by the NASA Advisory Council during the VSE to develop a comprehensive Lunar Exploration Roadmap (LER).





The Lunar Exploration Roadmap, jointly developed by engineers, planetary scientists, and policymakers, is the cohesive strategic plan for using the Moon and its resources to enable the exploration of all other destinations within the solar system on a sustained basis by leveraging incremental and affordable investments in lunar infrastructure.

Implementing the Roadmap will preserve American leadership, engage and inspire the public, open the space frontier to the energy and vitality of commercial enterprise, and enhance international partnerships as well as world security.

FOLLOW
THE ROADMAP

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

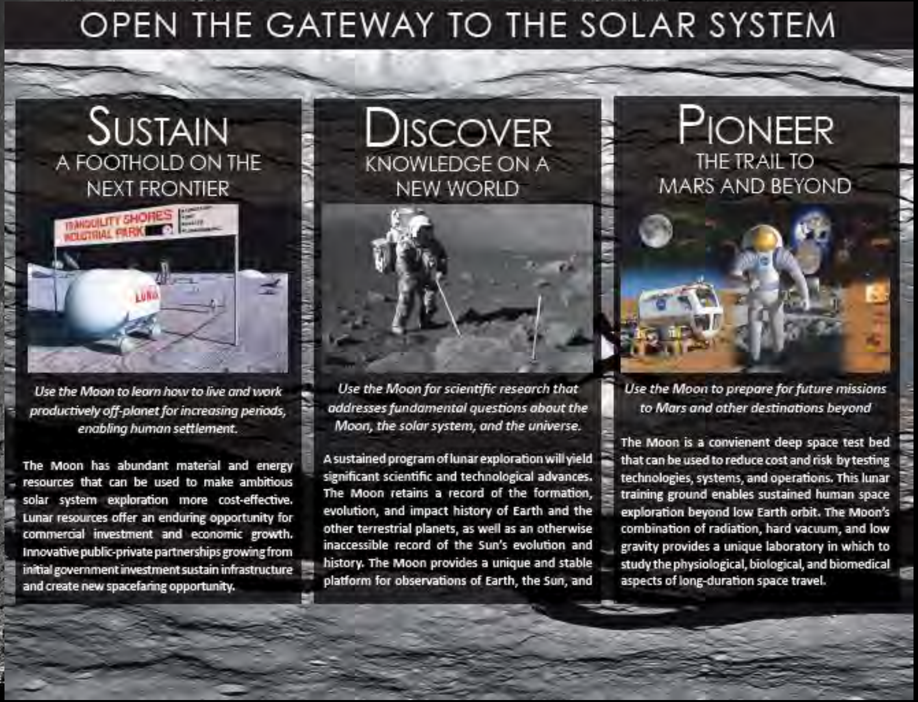
Credit: Images courtesy of NASA

THE
MOON

GATEWAY
TO THE SOLAR SYSTEM

***PROGRESS** IS NOT A SHOT IN THE DARK, BUT A SERIES OF **LOGICAL STEPS**.*

— Robert H. Goddard



OPEN THE GATEWAY TO THE SOLAR SYSTEM

SUSTAIN
A FOOTHOLD ON THE
NEXT FRONTIER

Use the Moon to learn how to live and work productively off-planet for increasing periods, enabling human settlement.

The Moon has abundant material and energy resources that can be used to make ambitious solar system exploration more cost-effective. Lunar resources offer an enduring opportunity for commercial investment and economic growth. Innovative public-private partnerships growing from initial government investment sustain infrastructure and create new spacefaring opportunity.

DISCOVER
KNOWLEDGE ON A
NEW WORLD

Use the Moon for scientific research that addresses fundamental questions about the Moon, the solar system, and the universe.

A sustained program of lunar exploration will yield significant scientific and technological advances. The Moon retains a record of the formation, evolution, and impact history of Earth and the other terrestrial planets, as well as an otherwise inaccessible record of the Sun's evolution and history. The Moon provides a unique and stable platform for observations of Earth, the Sun, and

PIONEER
THE TRAIL TO
MARS AND BEYOND

Use the Moon to prepare for future missions to Mars and other destinations beyond

The Moon is a convienent deep space test bed that can be used to reduce cost and risk by testing technologies, systems, and operations. This lunar training ground enables sustained human space exploration beyond low Earth orbit. The Moon's combination of radiation, hard vacuum, and low gravity provides a unique laboratory in which to study the physiological, biological, and biomedical aspects of long-duration space travel.

LEAG LUNAR EXPLORATION ROADMAP

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

Why should we go back 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 LUNAR EXPLORATION ROADMAP

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

THEMES → GOALS → OBJECTIVES → INVESTIGATIONS/INITIATIVES

Three Themes:

- Science (Sci)
- Feed Forward (FF)
- Sustainability (Sust)

- Community effort.
- Living document.

Sustainability is the key:

- Don't abandon assets – leverage them;
- Commercial "on ramps" are defined;
- International cooperation is critical.

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LEAG LUNAR EXPLORATION ROADMAP

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

THEMES → GOALS → OBJECTIVES → INVESTIGATIONS/INITIATIVES

Sustainability Theme:

Sustained lunar activities are only possible when they are *sustainable* through ongoing return of value.

Self-sustained settlement is most defensible when strongly linked to science and feeding forward to other destinations in the Solar System.

The role of commercial activity as an indispensible aspect of sustainability.

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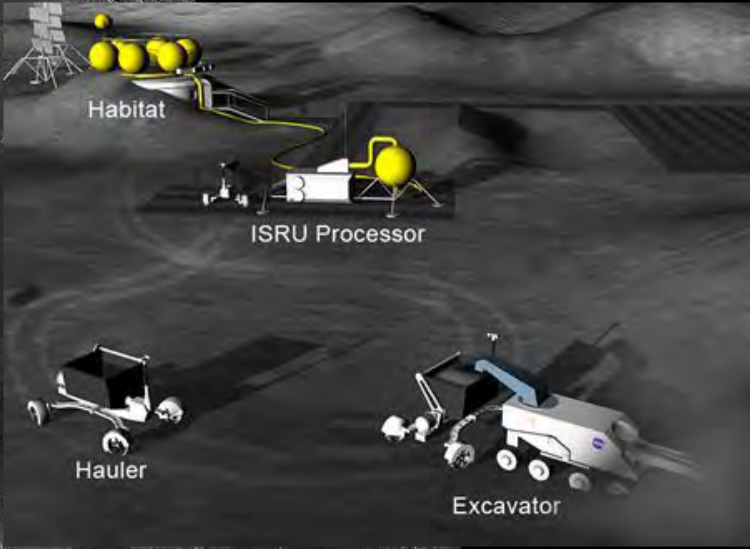
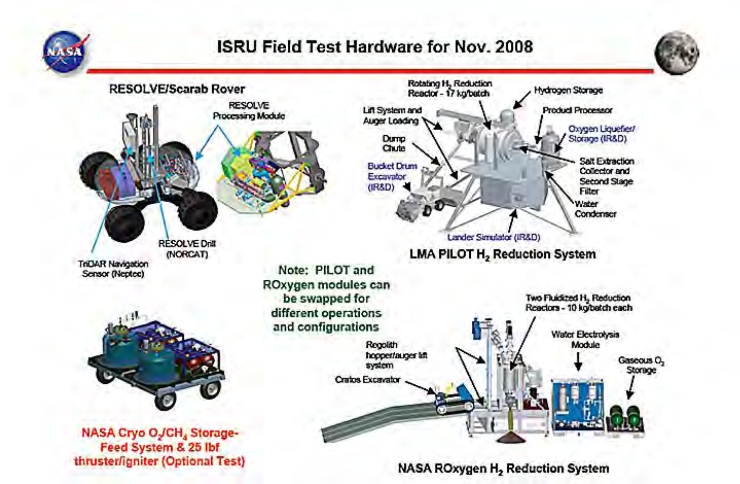
MAKING EXPLORATION SUSTAINABLE

- In Situ Resource Utilization (ISRU) is the *game changer* – produce fuel and consumables on the lunar surface to enable human exploration of other airless bodies and Mars.
- Use the Moon to explore the Solar System due to the much reduced "gravity well" and presence of resources.
- Enables international cooperation and commercial participation (i.e., jobs!) in space exploration by starting at the Moon with the goal to go much further.




ISRU Field Test Hardware for Nov. 2008

RESOLVE/Scarab Rover

LMA PILOT H_2 Reduction System

Note: PILOT and ROxygen modules can be swapped for different operations and configurations

NASA Cryo O_2/CH_4 Storage-Feed System & 25 lbf thruster/igniter (Optional Test)

NASA ROxygen H_2 Reduction System

IMPLEMENTING SUSTAINABLE SOLAR SYSTEM EXPLORATION

Formulation of LER implementation strategy via a phased precursor program.

Phase 1: Lunar Resource Prospecting (multiple sites)

- Define composition, form, extent, environment, and accessibility/extractability of the resource;
- Quantify regolith geotechnical properties where the resource is found;
- Ability to traverse several kilometers and target resource-rich deposits for future missions.

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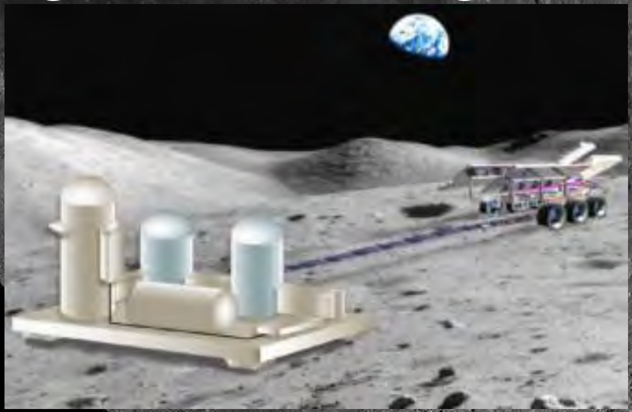
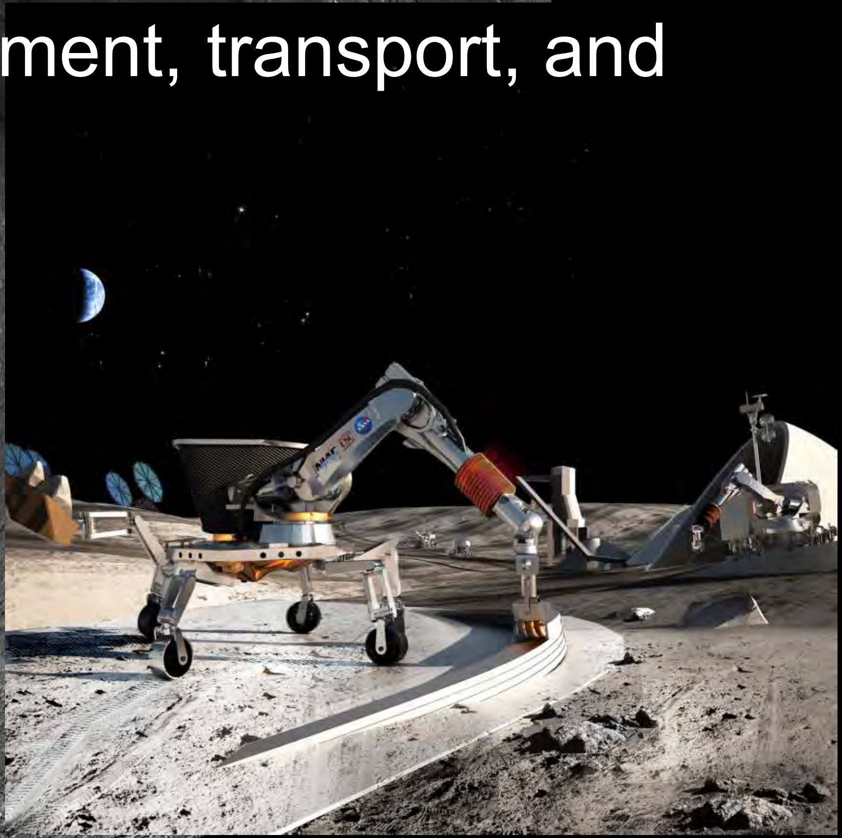
http://www.lpi.usra.edu/leag/reports/RoboticAnalysisLetter.pdf

IMPLEMENTING SUSTAINABLE SOLAR SYSTEM EXPLORATION

Phase 2: Lunar Resource Mining (2-3 sites)

- Feedstock acquisition and handling;
- Resource extraction, refinement, transport, and storage;
- Dust mitigation strategies.





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

IMPLEMENTING SUSTAINABLE SOLAR SYSTEM EXPLORATION

Phase 3: Lunar Resource Production (at the best site)

- Large scale production established prior to human return;

The campaign requires build-up of infrastructure at a site defined/characterized by initial prospecting and mining phases.

Production plant will provide consumables to lunar crews and enable future refuelable landers and cis-lunar refueling depots.

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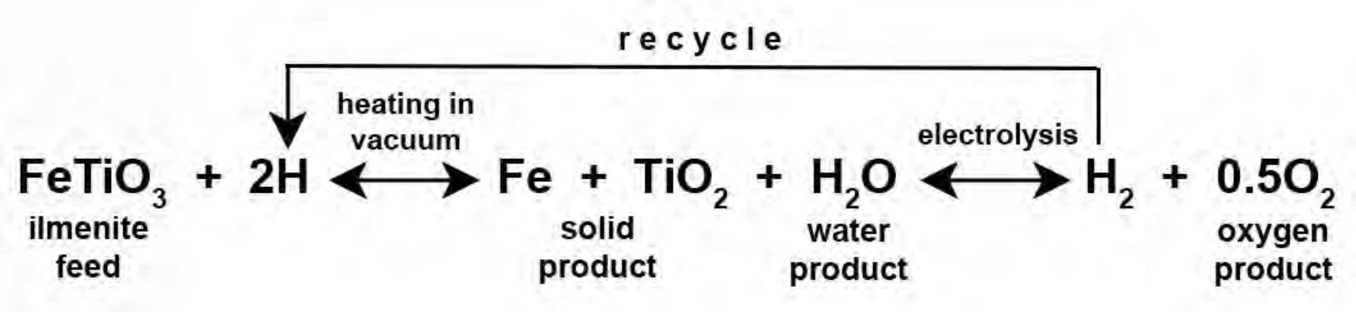
http://www.lpi.usra.edu/leag/reports/RoboticAnalysisLetter.pdf

WHERE ARE THE RESOURCES?

Science has demonstrated that solar wind proton implantation facilitates formation of water in mature regoliths, especially those containing ilmenite.

Haskin (1992) *Lunar Bases & Space Activities* **2**, 393-396

Living off the land! Water and Oxygen can be mined.



$$FeTiO_3 + 2H \longleftrightarrow Fe + TiO_2 + H_2O \longleftrightarrow H_2 + 0.5O_2$$

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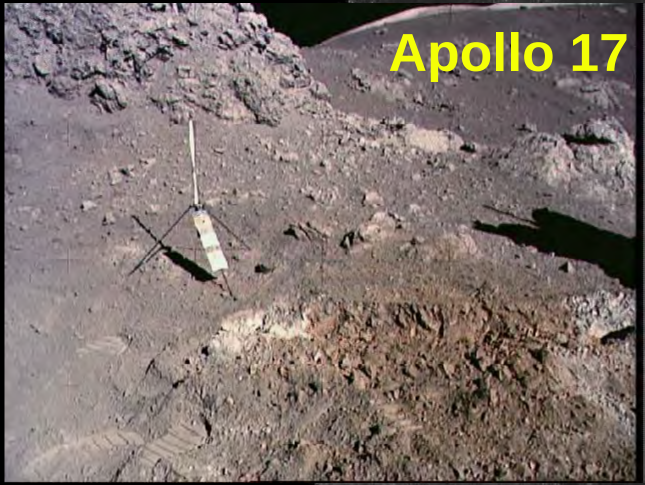
WHERE ARE THE RESOURCES?

Volcanic glasses contain endogenous water and other volatiles!



Volcanic glass beads from gas-charged fire fountaining.

Distinct from crystalline mare basalts.

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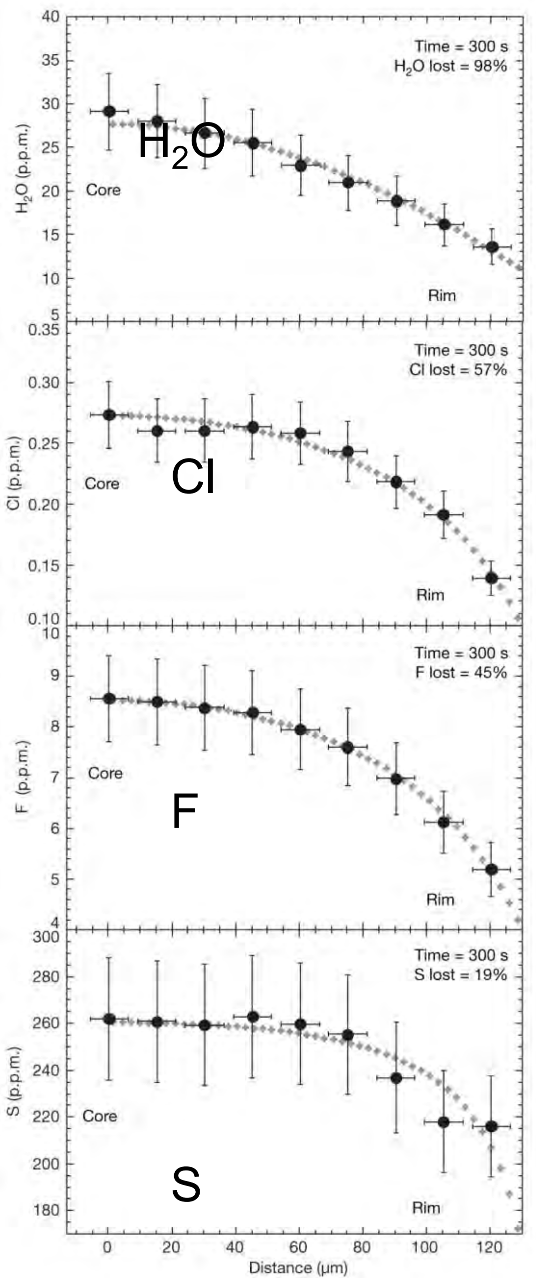
WHERE ARE THE RESOURCES?

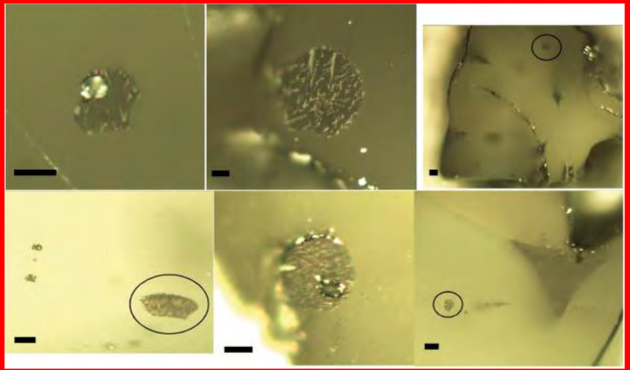
Lunar Endogenous Volatiles

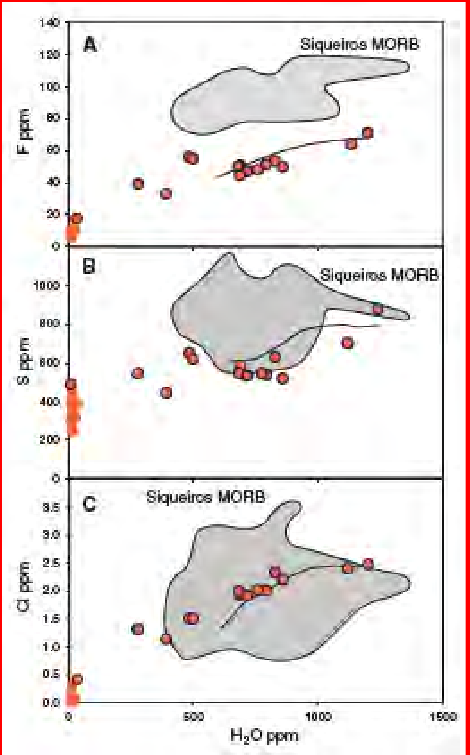
Saal et al. (2008)
Nature **454**, 192-195

Water in the Glass Parent Magma: 260-745 ppm

Apollo 15 Green Glass (VLT)







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

Melt Inclusions in Olivine

WHERE ARE THE RESOURCES?

Lunar Pyroclastic Glass Deposits

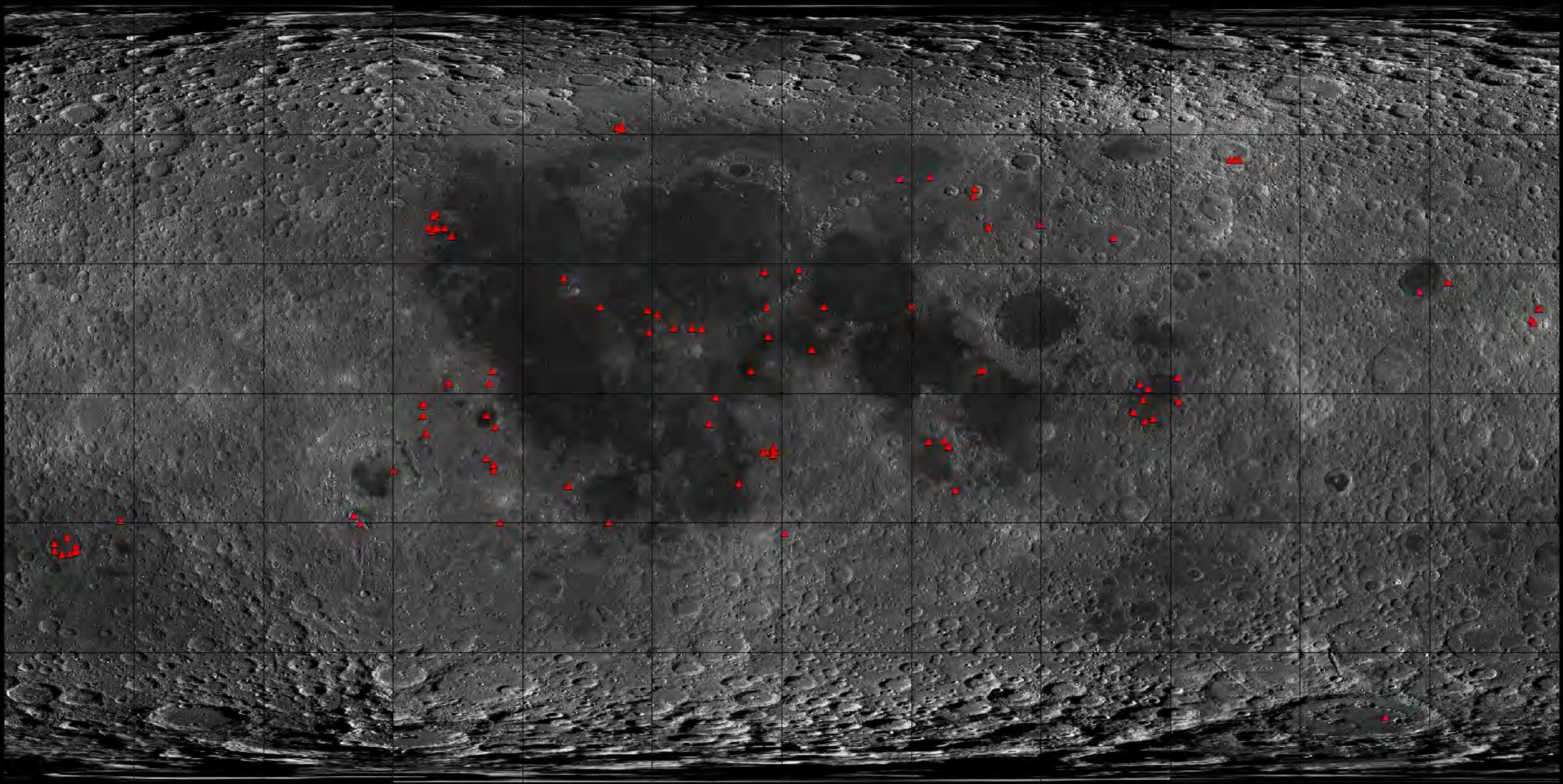


Photo courtesy of Lisa Gaddis, USGS

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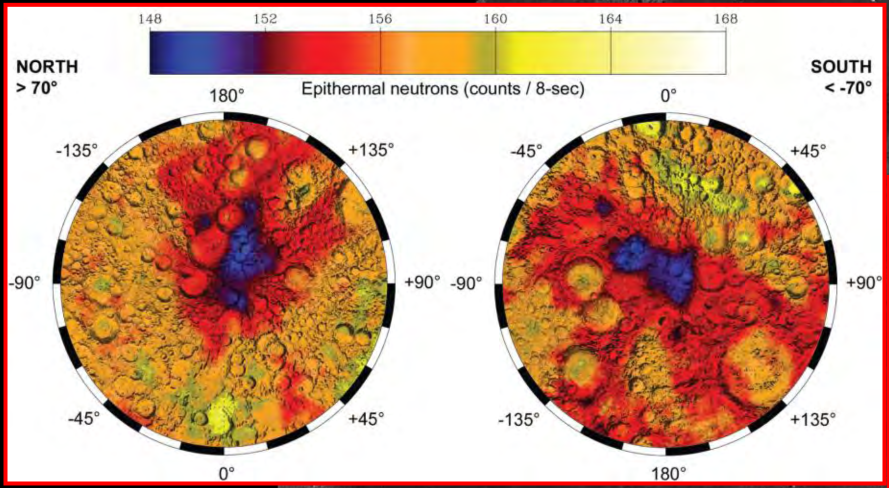
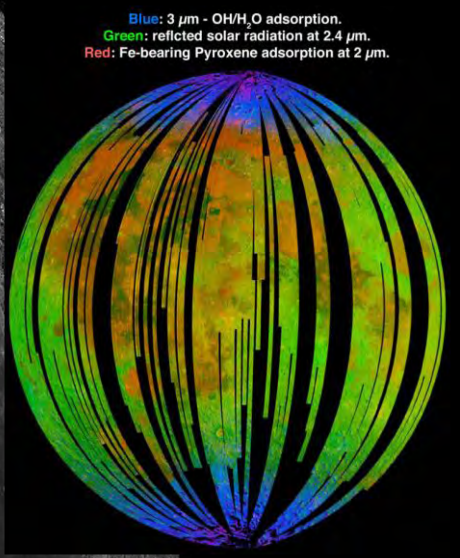
WHERE ARE THE RESOURCES?

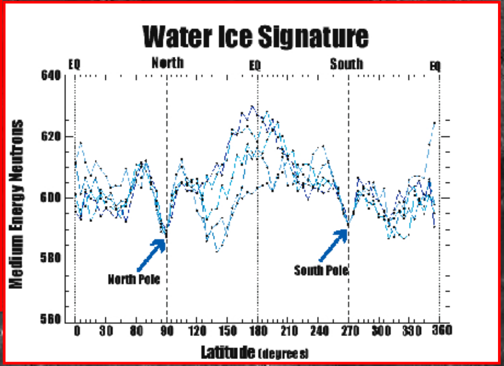
Exogenous Volatiles on the Moon

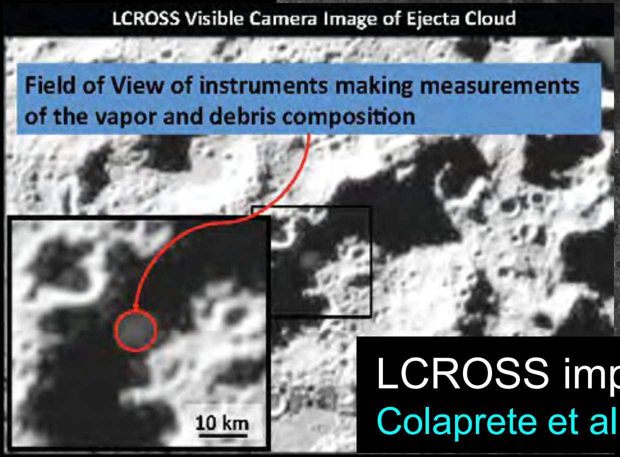


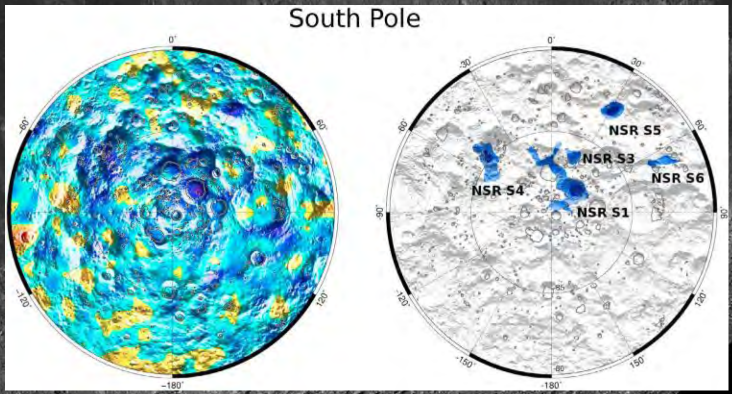
Hydrogen in PSRs – better resolution needed.
Lawrence et al. (2006) JGR 111, E08001, doi:10.1029/2005JE002637

"Moon Frost"
Pieters et al. (2009)
Science 326, 568-572









Hydrogen Deposits:
Lunar Prospector
Mitrofanov et al. (2012)
JGR 117, E00H27,
doi:10.1029/2011JE003956

LCROSS impact into Cabeus
Colaprete et al. (2010) Science 330, 463-468

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LEAG VOLATILES SPECIFIC ACTION TEAM (V-SAT) REPORT

Regions of Interest Finding #1

At both poles there are regions that are generally suitable for a common landing region:

1. Cabeus vicinity (south pole);
2. Shoemaker/Nobile vicinities (south pole);
3. Peary vicinity (north pole).

These are:

- Volatile rich (H > 150 ppm);
- Can maintain subsurface ice (average annual surface temperature < 110K);
- Modest slopes (10 degrees);
- Adjacent to locations similar to the LCROSS impact site in terms of H abundance and temperature;
- Availability of PSR from lit areas.

When including Earth visibility and lighting explicitly, the north polar Peary vicinity is slightly favored owing to somewhat more persistent lighting, with the Cabeus vicinity showing the least persistent lighting.

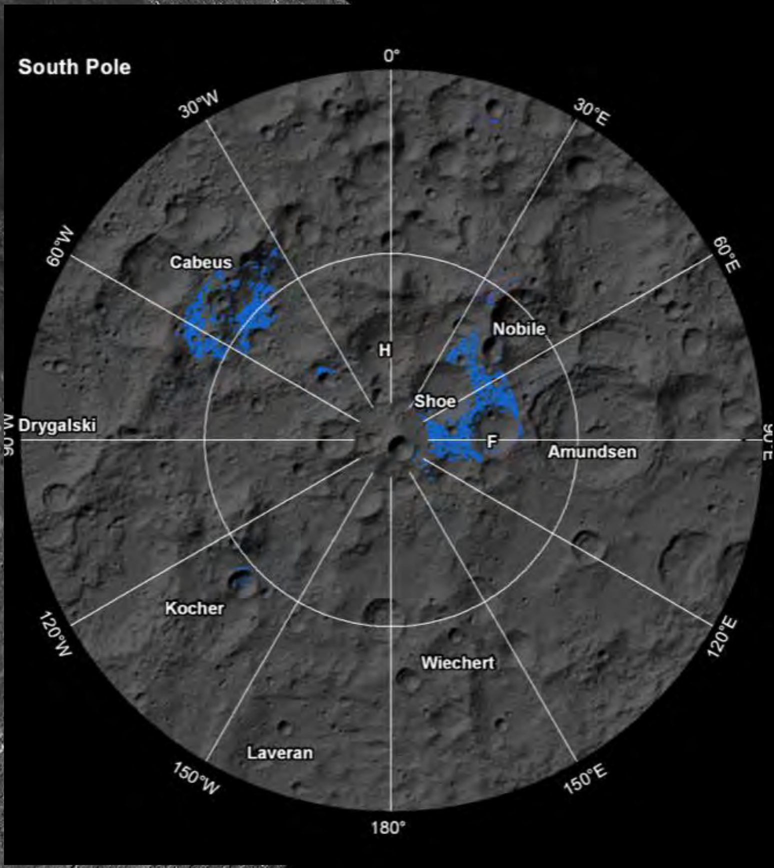
http://www.lpi.usra.edu/leag/reports/vsat_report_123114x.pdf

LEAG VOLATILES SPECIFIC ACTION TEAM (V-SAT) REPORT

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



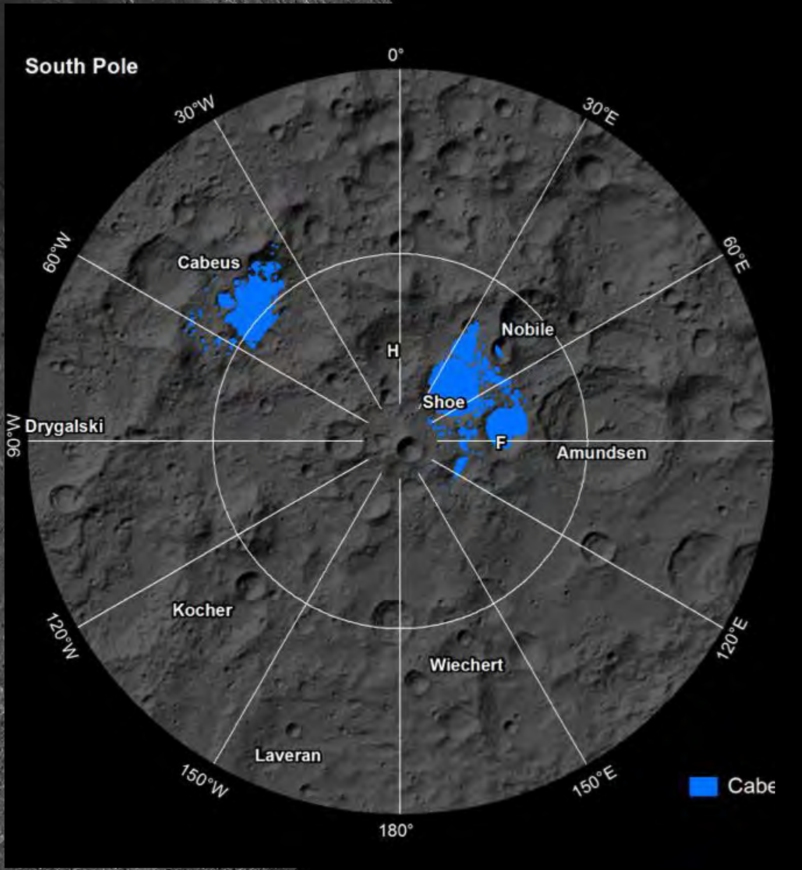
http://www.lpi.usra.edu/leag/reports/vsat_report_123114x.pdf

LEAG VOLATILES SPECIFIC ACTION TEAM (V-SAT) REPORT

South Pole

- Regions similar to LCROSS Cabeus site in H and annual average temperature.

Cabeus and Shoemaker/Nobile vicinities contain locations most similar to LCROSS site in H and temperature.



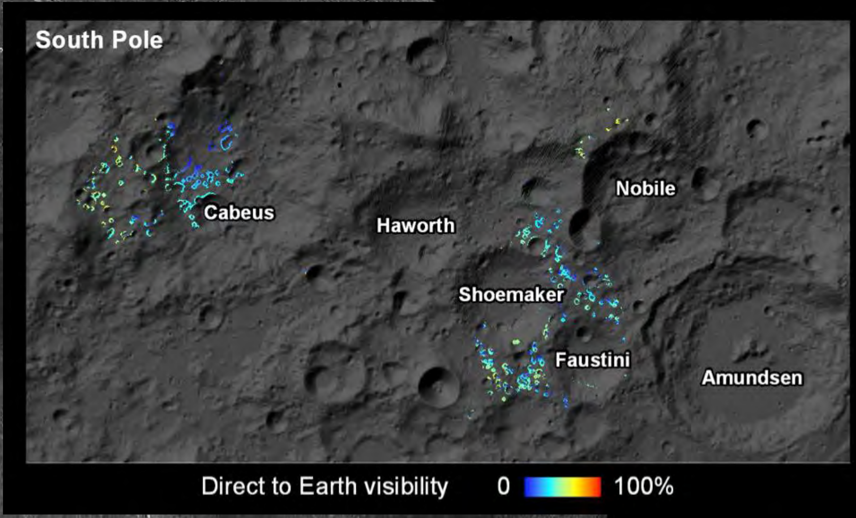
http://www.lpi.usra.edu/leag/reports/vsat_report_123114x.pdf

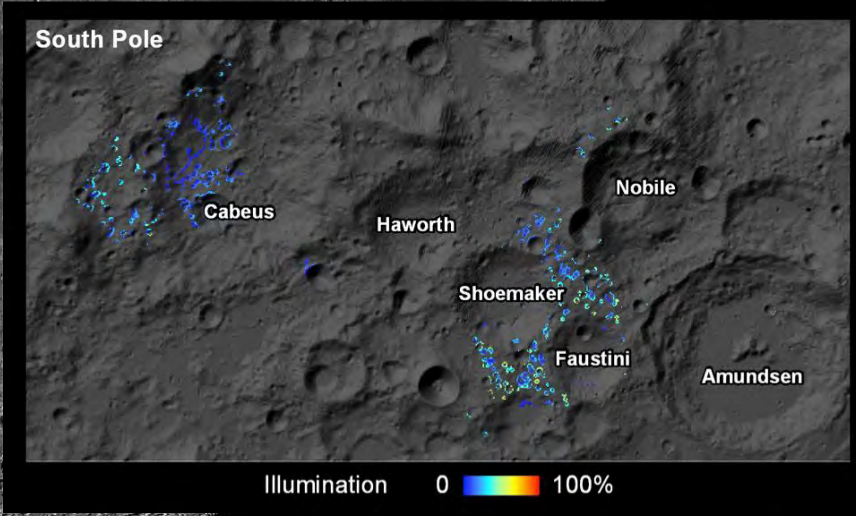
LEAG VOLATILES SPECIFIC ACTION TEAM (V-SAT) REPORT

South Pole

Direct to Earth Visibility: These areas meet the Hydrogen, Temperature, and Slope criteria, and are within 1 km of a Permanently Shadowed Region (PSR).

Proximity to Persistent Lighting: These areas meet the Hydrogen, Temperature, and Slope criteria, and are within 1 km of a PSR.
Availability of illumination is generally low with restricted regions having ~50% available lighting





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

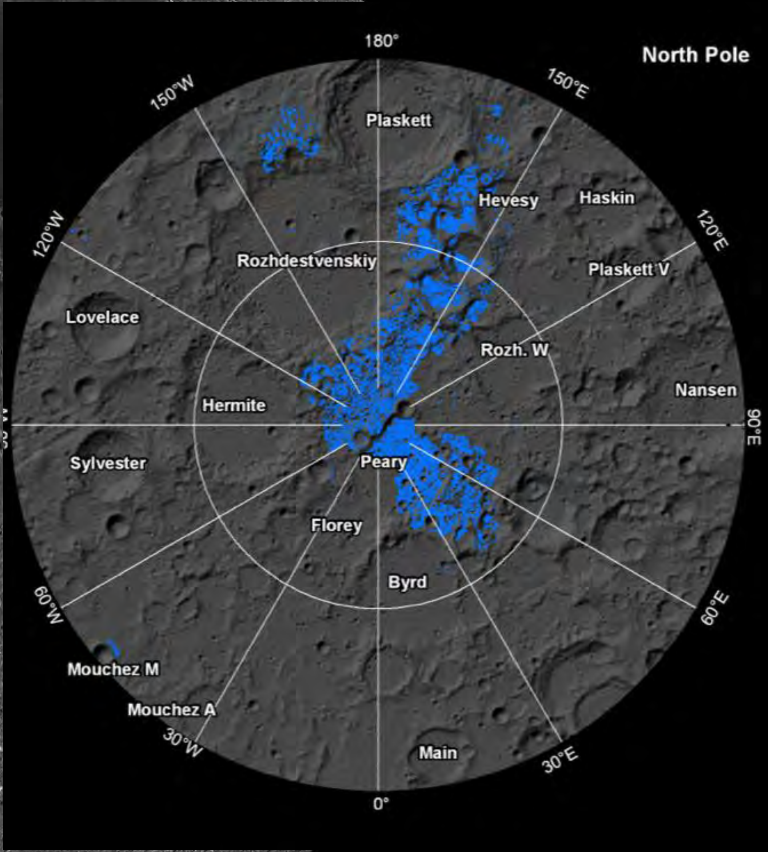
LEAG VOLATILES SPECIFIC ACTION TEAM (V-SAT) REPORT

North 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

Peary vicinity meets general criteria and has Earth visibility.

Substantial area of farside also meet general criteria.



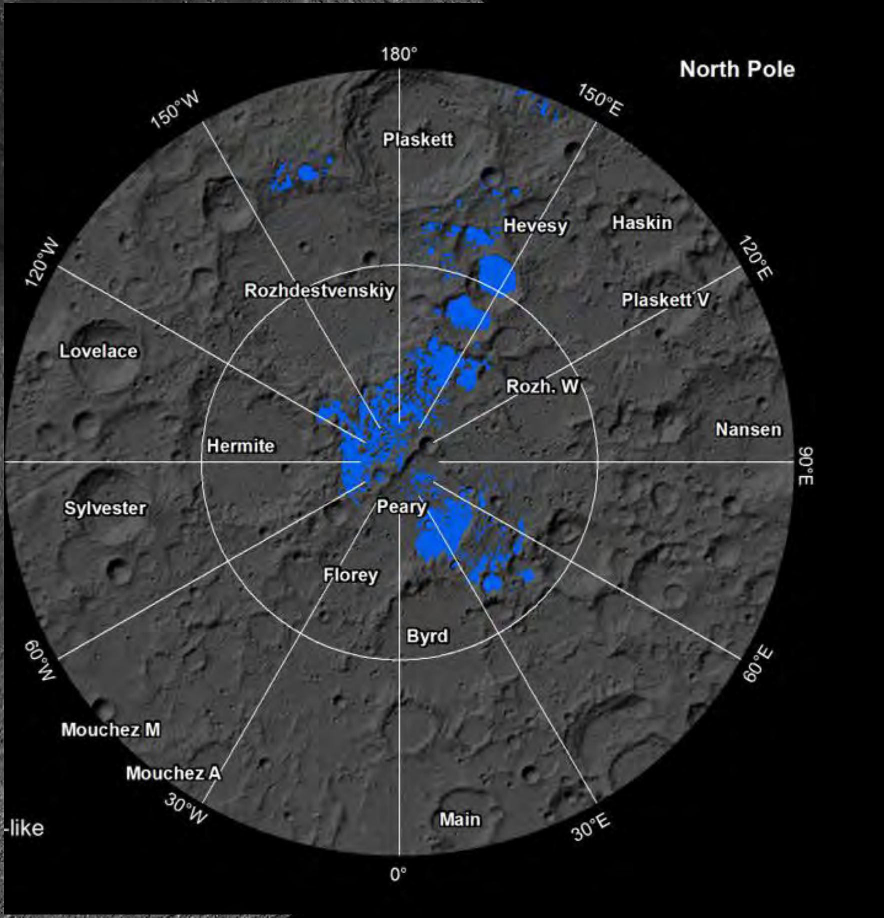
http://www.lpi.usra.edu/leag/reports/vsat_report_123114x.pdf

LEAG VOLATILES SPECIFIC ACTION TEAM (V-SAT) REPORT

North Pole

- Regions similar to LCROSS Cabeus site in H and annual average temperature.

Peary and the north rim of Hermite vicinities contain locations most similar to LCROSS site in H and temperature with Earth visibility



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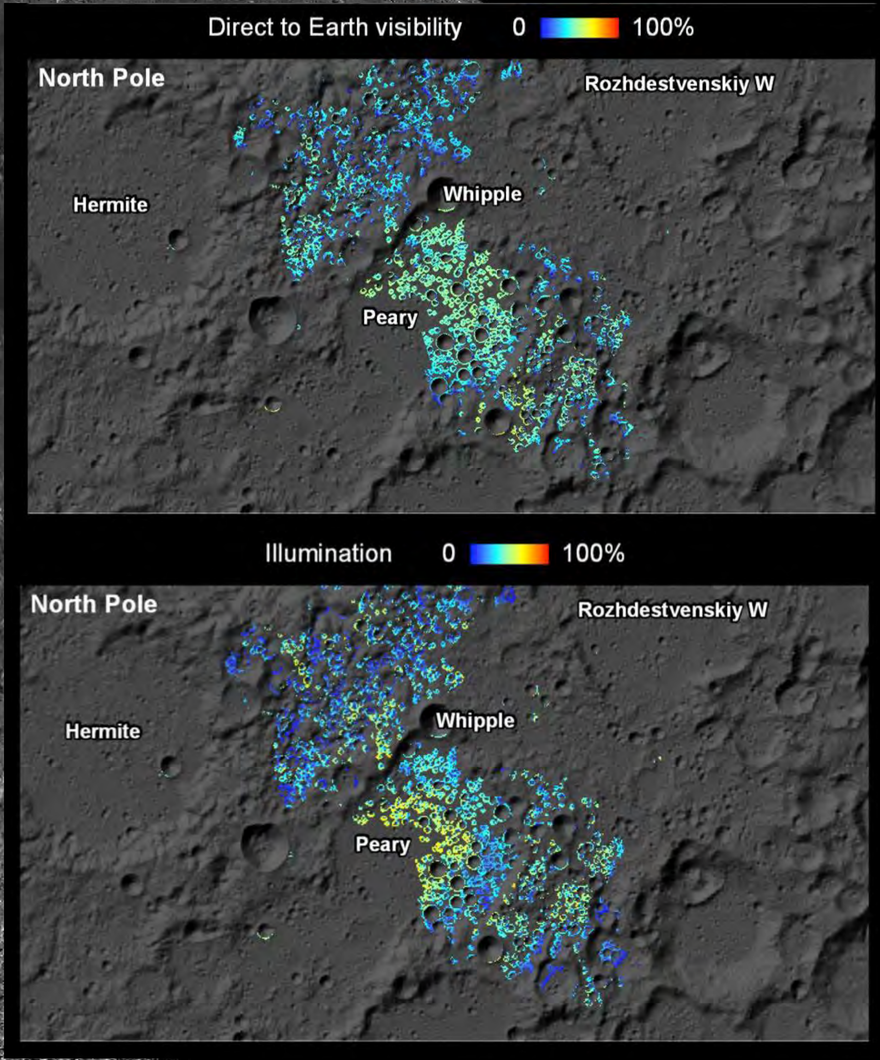
LEAG VOLATILES SPECIFIC ACTION TEAM (V-SAT) REPORT

North Pole

Direct to Earth Visibility: These areas meet the Hydrogen, Temperature, and Slope criteria, and are within 1 km of a Permanently Shadowed Region (PSR).

Proximity to Persistent Lighting: These areas meet the Hydrogen, Temperature, and Slope criteria, and are within 1 km of a PSR.
Availability of illumination in the Peary region is more favorable than the south polar site, or the farside north polar sites.



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

SUMMARY AND CONCLUSIONS

- Lunar resources have the potential to make human Solar System exploration sustainable while stimulating commercial industry and national economies.
- An important question to be answered is: “Are lunar resources actually reserves?”
- The next stage of Solar System exploration should involve prospecting rovers on the lunar surface to address this question.
- If successful, the data from the prospecting rovers can be used not only for science, but also to stimulate further exploration and the commercial sector.
    - International bodies, such as the International Space Exploration Coordination Group or ISECG), could be used to implement “commercial on-ramps” in the extraction and refinement of lunar resources.

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