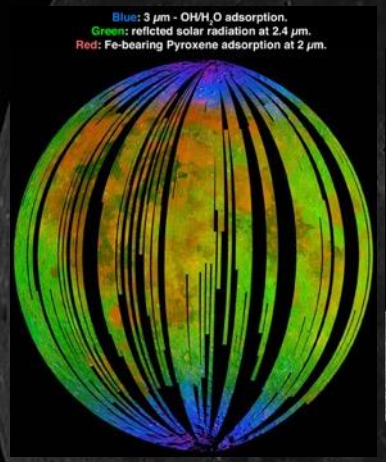
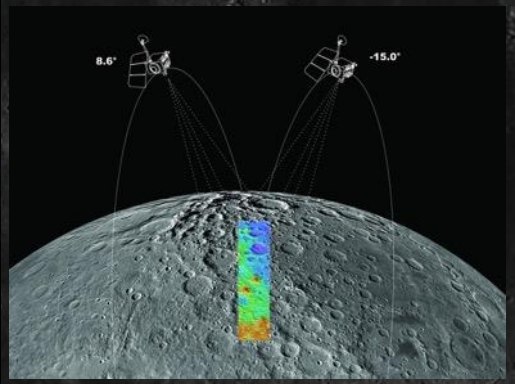
Orbital Capabilities for Lunar Science and Exploration



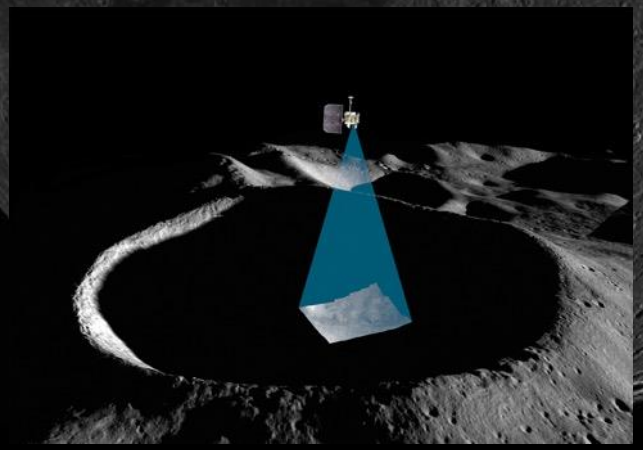


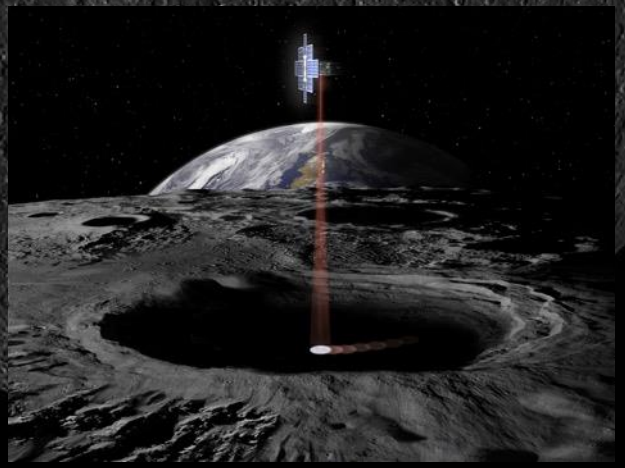
Clive R. Neal

University of Notre Dame

neal.1@nd.edu

@Prof_Clive_Neal

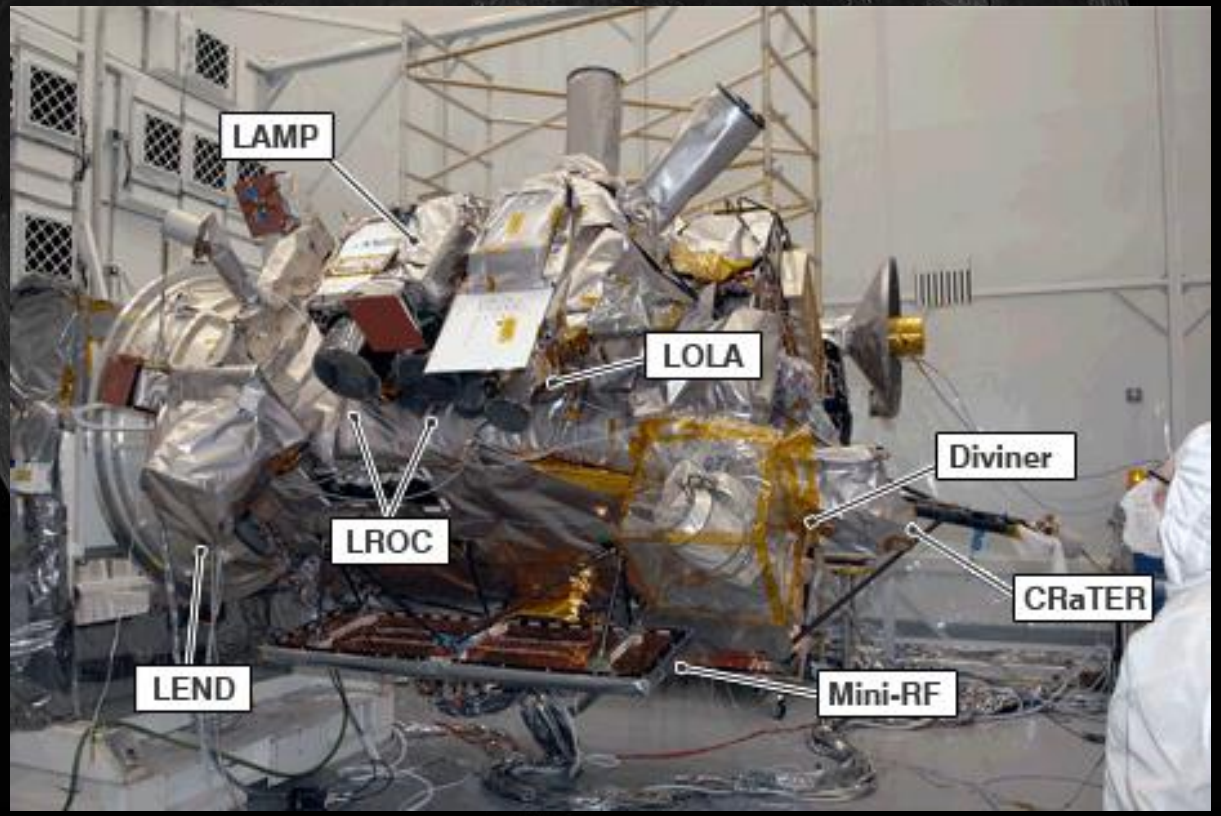




Why LRO Isn't Enough

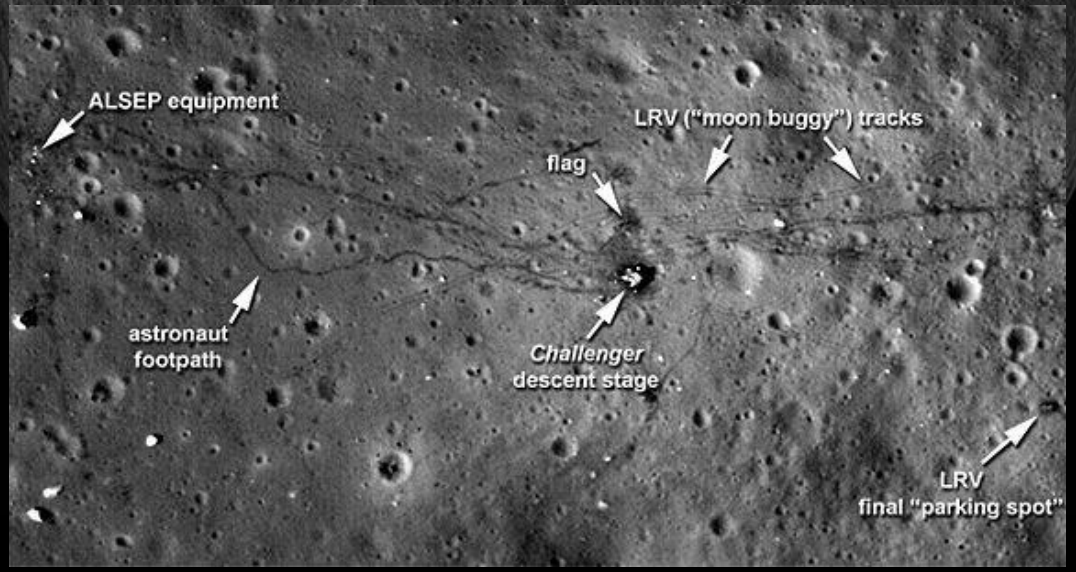
LRO Personifies an inter-directorate mission: so should any successor orbital capability.

1.3 Petabytes of data delivered to the PDS



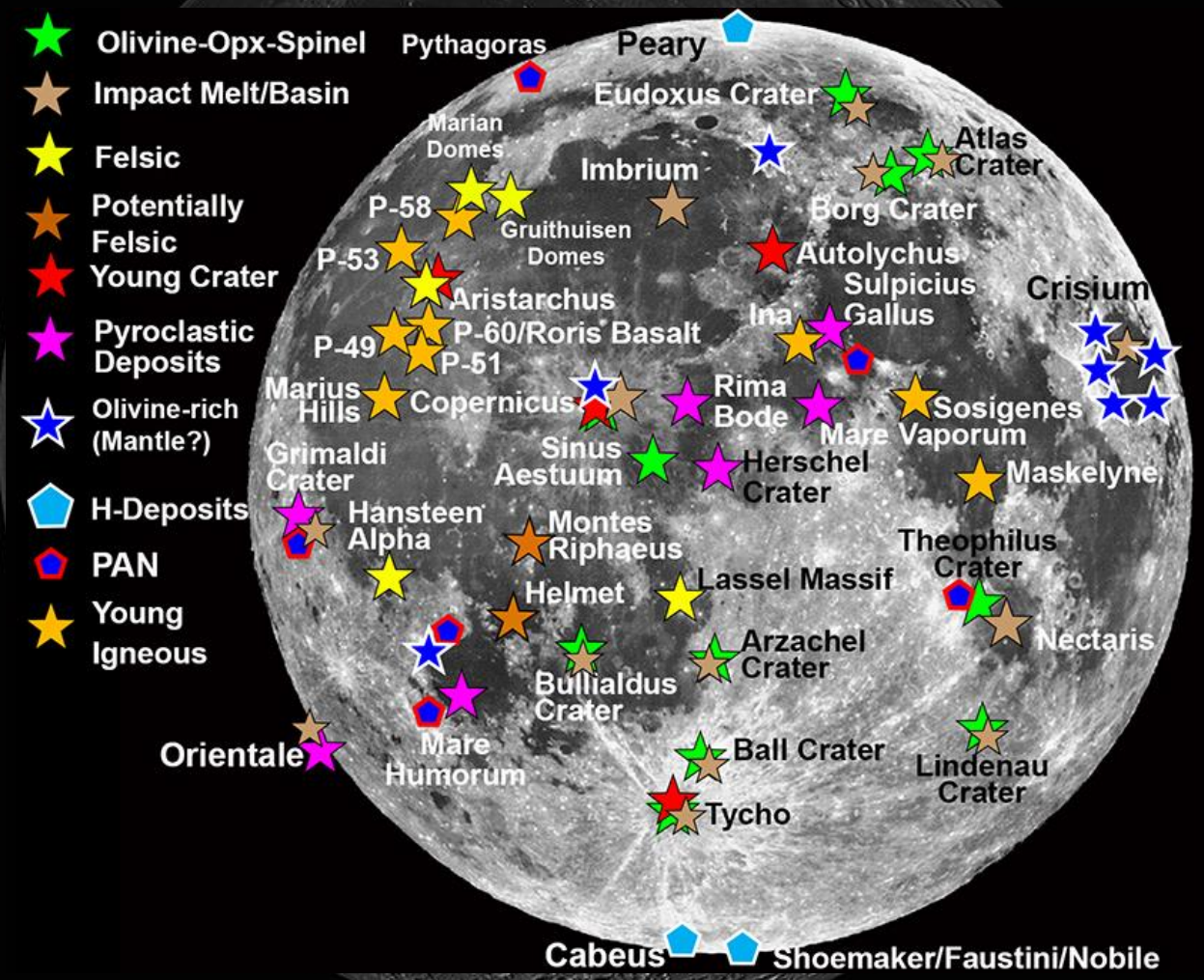
What can be done any better??

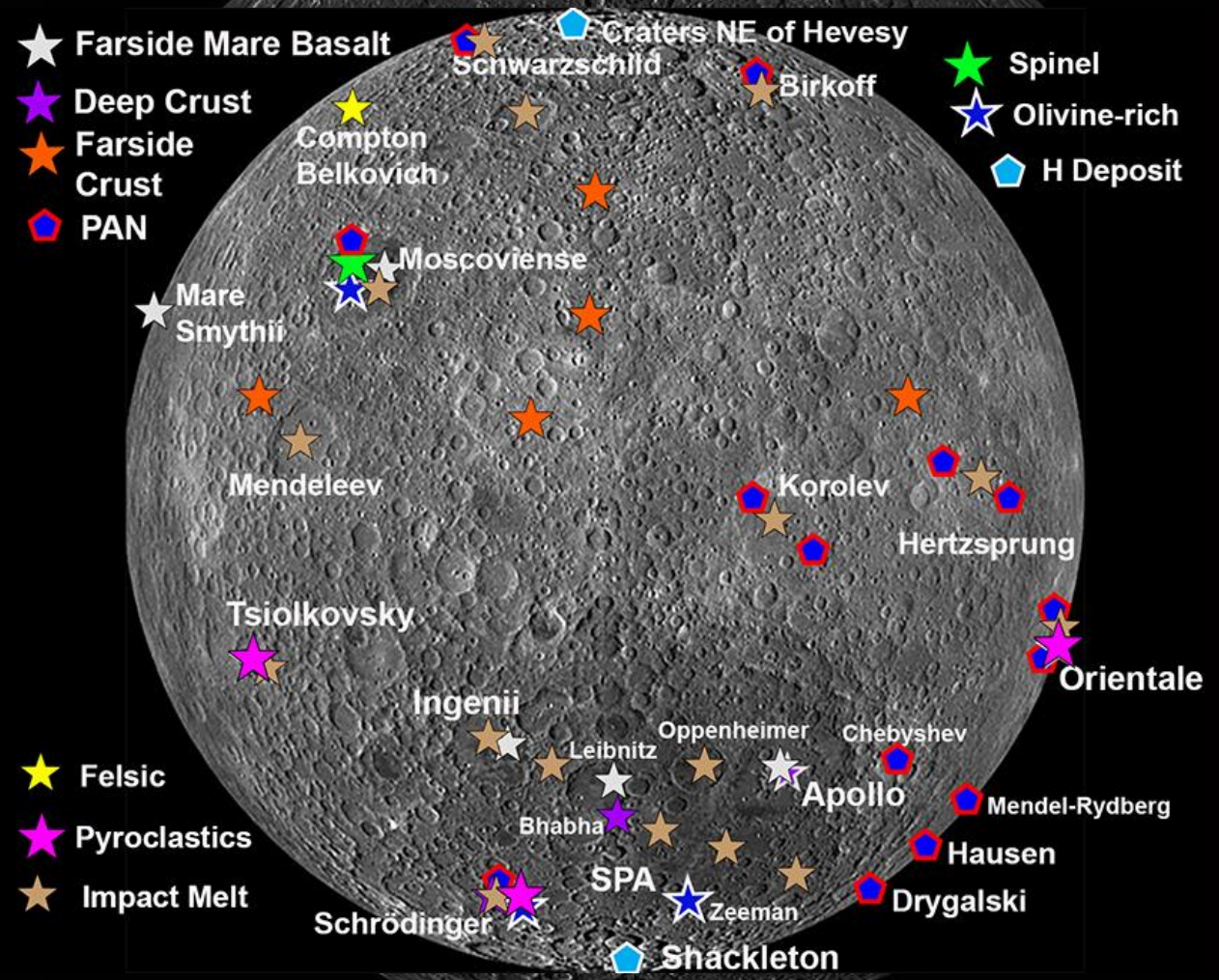
- Broad range reflectance spectrometer
- Better spatial resolution, especially neutrons
- Lunar environmental monitoring
- Magnetometer(?)
- What else?



Constraining Landing Sites

Sample Return Sites





Targets: Olivine, Opx, Spinel lithologies; Crater impact melts; Felsic lithologies; Young igneous; Far-side mare basalts; Pyroclastic deposits; Hydrogen/ice deposits; Deep crust/mantle; Farside crust; Pure anorthosite.

Science Objectives

- Objectives Sci-A-2 & FF-C-3: Development & implementation of sample return technologies & protocols
- Objectives Sci-A-2 & FF-C-4: Understand lunar/planetary differentiation
- Objective Sci-A-6: Understand volcanic processes
- Objective Sci-A-7: Understand the impact process
- Objective Sci-A-8: Determine the stratigraphy, structure, and geological history of the Moon
- Objective Sci-A-9: Understand formation of the Earth-Moon system
- Objective Sci-B-1: Impact history of the inner Solar System as recorded on the Moon
- Objective FF-C-1: Ability to operate on a geologic surface

- **All have robotic sample return as an early stage**
- **Development of SR technology has feed-forward implications to other destinations**

Potential Lunar Resources

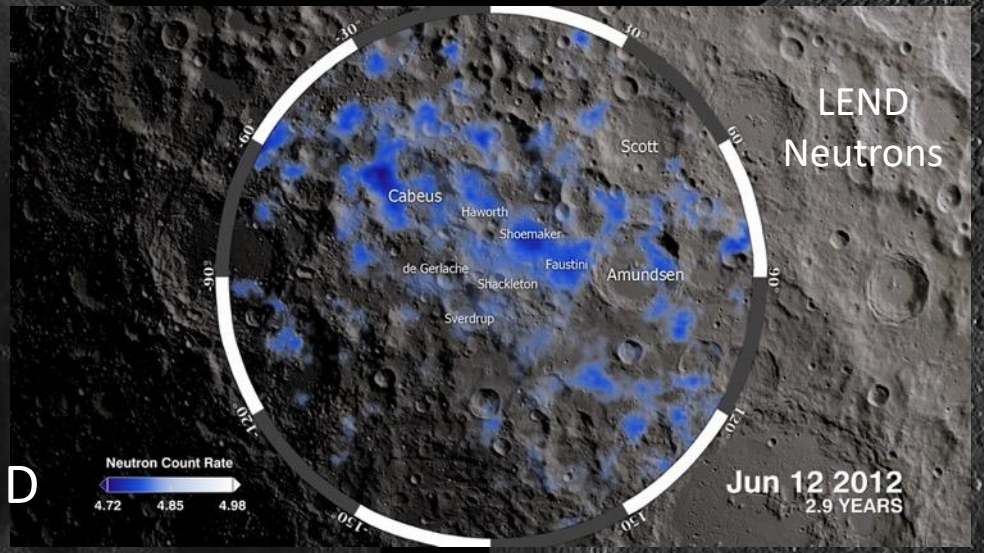
Polar Volatile Deposits

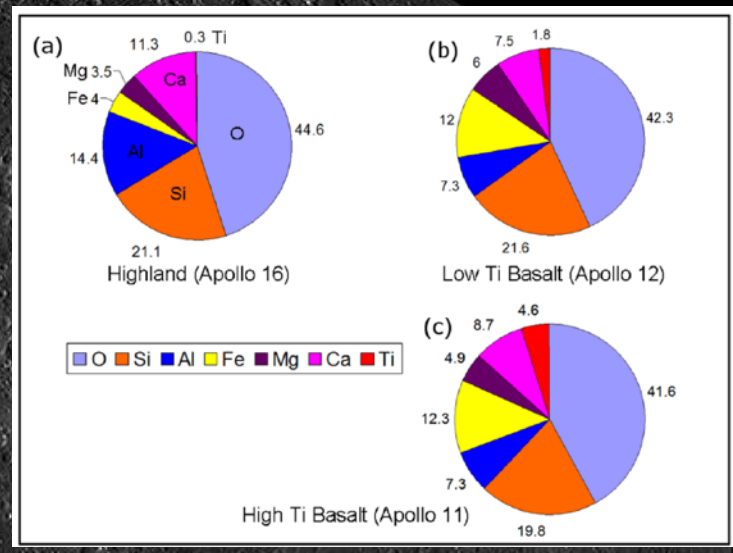
Pyroclastic Deposits

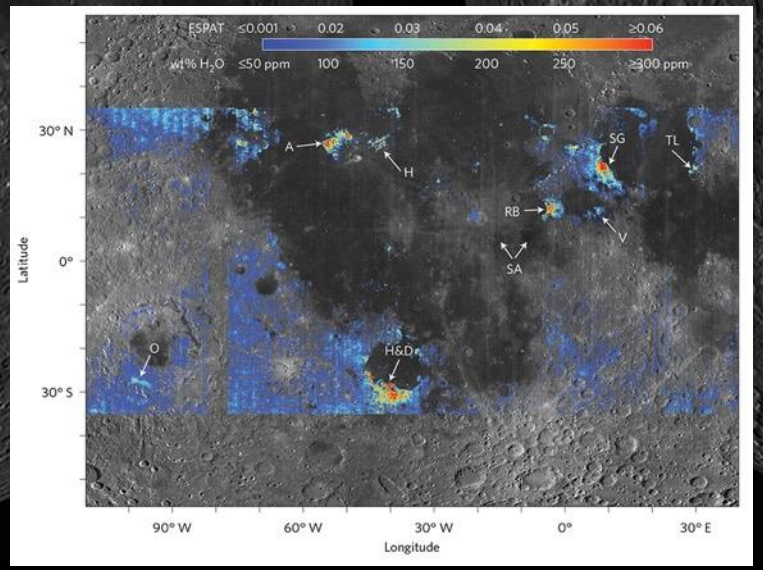
- Volatiles
- Metals

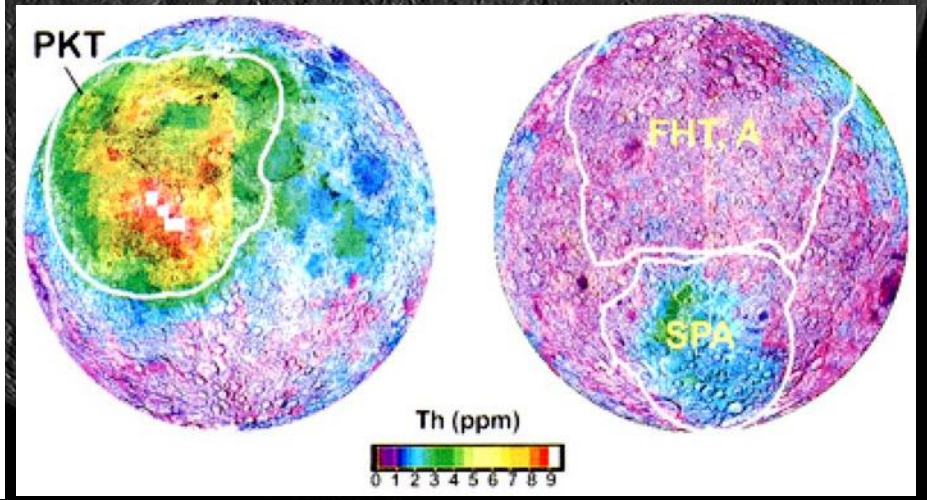
Regolith:

- Building materials (e.g., 3D printing)
- Metals
- Oxygen
- Solar wind implanted volatiles (H, He C, N, etc.)
- Platinum group metals
- Rare earth elements
- Th, U





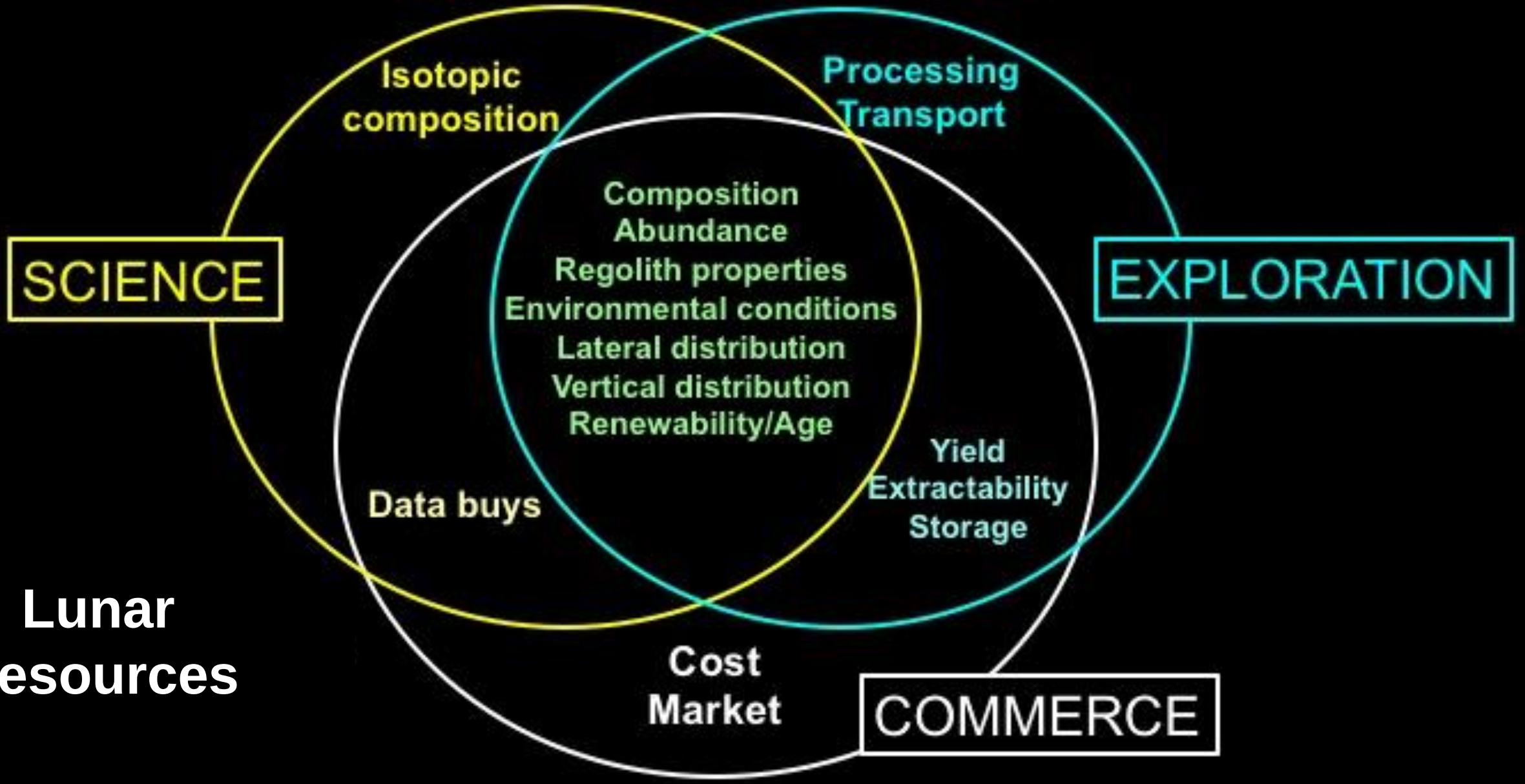




Milliken & Li (2017) *Nat. Geosci.* **10**, 561-565.

Jolliff et al. (2000) *JGR.* **105**, 4197-4216.

Science Enables Exploration & Exploration Enables Science. Both Enable Commerce.

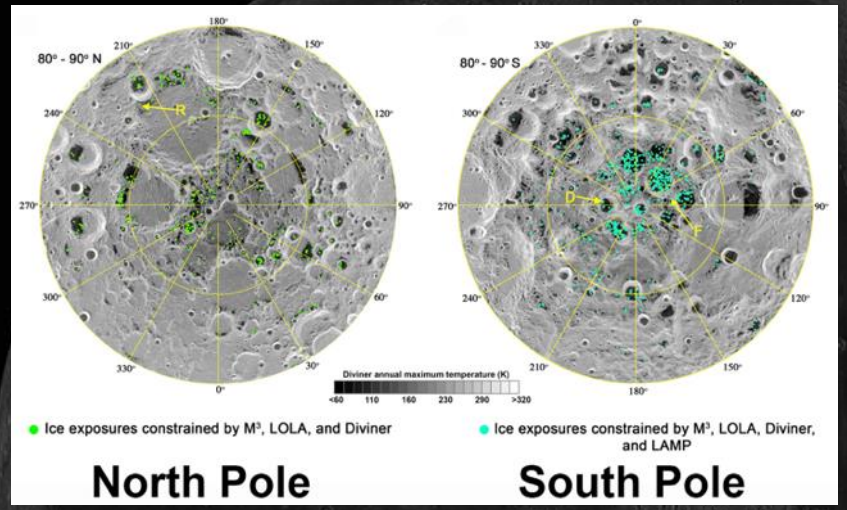


Lunar Resources

Sustainability Objectives

- Objective Sust-A-1: Establish policies and implementation of comprehensive, coordinated governmental and intergovernmental action to foster space commerce.
- Objective Sust-A-2: Preparation for Commerce I: Conduct a comprehensive resource and market assessment of commercial support for scientific and exploration activities on the Moon.
- Initiative Sust-A-2A: Identify linkages between lunar surface science goals and objectives and resources related to early exploitation for production of oxygen, water and other mission consumables.
- Initiative Sust-A-2B: Identify sites for detailed mapping, prospecting and assaying of resources and the feasibility of extraction options.
- Initiative Sust-A-2C: Develop standards for lunar surface mapping; prospecting and assaying that can realize savings in fleets of commercial robots.

Polar Volatile Resources

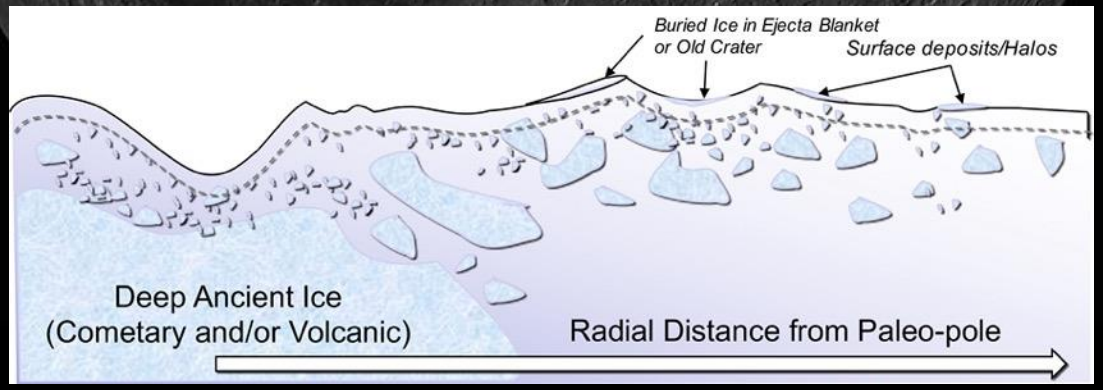


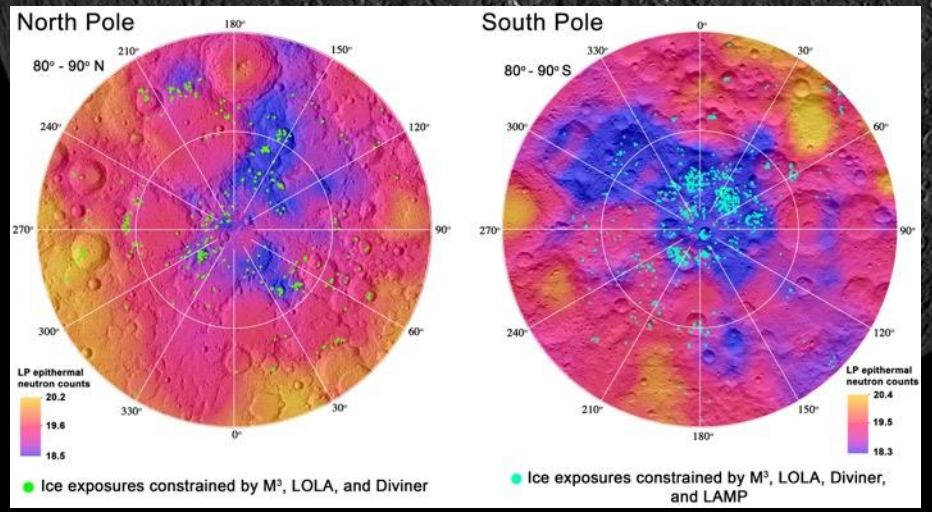
Intersection of datasets.

- Moon Mineralogy Mapper (M^3) data show direct evidence for water ice at the surface of some PSRs.
- Green and blue dots (280m x 280m) show results for surface water ice using M^3, Diviner, and LOLA data for the North pole, and M^3, Diviner, LOLA, and LAMP data for the South pole.
- Data points have maximum annual temperatures of <110 K) from Diviner data.
- Pixel size: 280 m x 280 m.
- Coincident with neutron suppression zones.

Modeling: up to 30 wt.% water ice is present at the surface.

Li et al. (2018) **Direct evidence of surface exposed water ice in the lunar polar regions.** Proc. National Acad. Sciences, https://doi.org/10.1073/pnas.1802345115

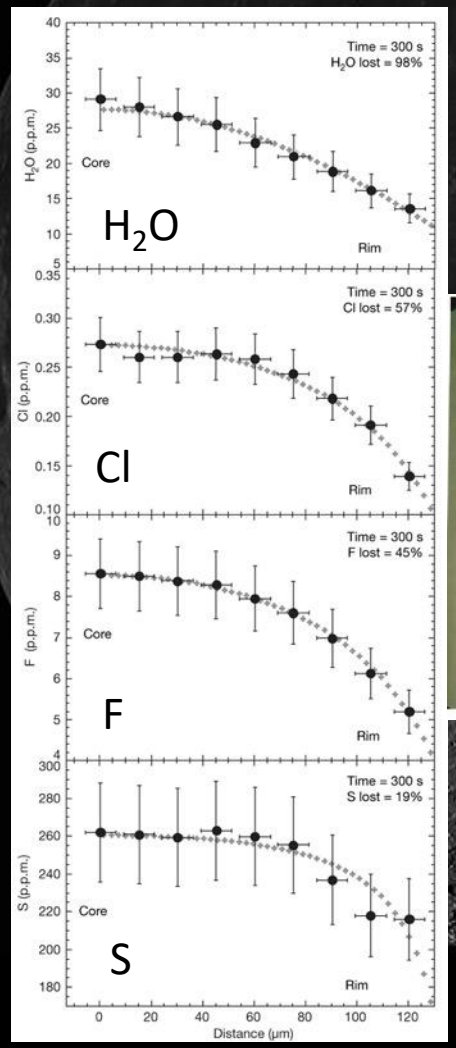




Thanks to Shuai Li & Rick Elphic

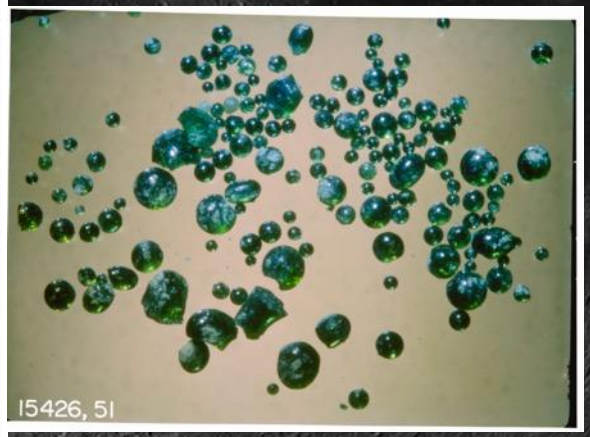
Pyroclastic Deposits

36 years after collection, volcanic glasses shown to contain water and other volatiles.

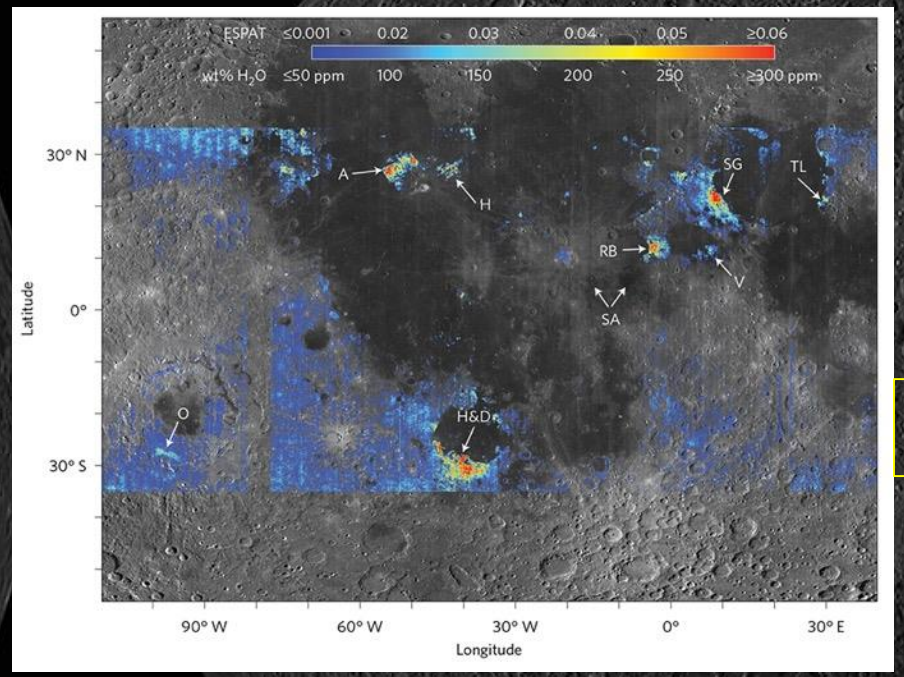


Water in the Glass Parent Magma: 260-745 ppm

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

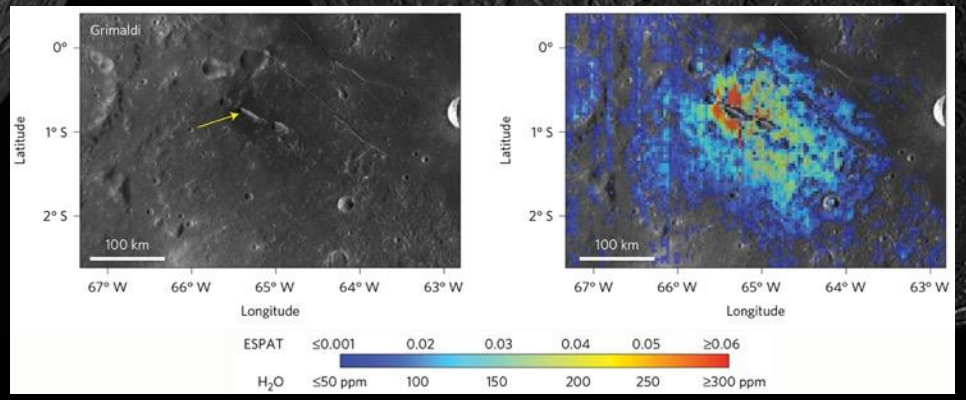


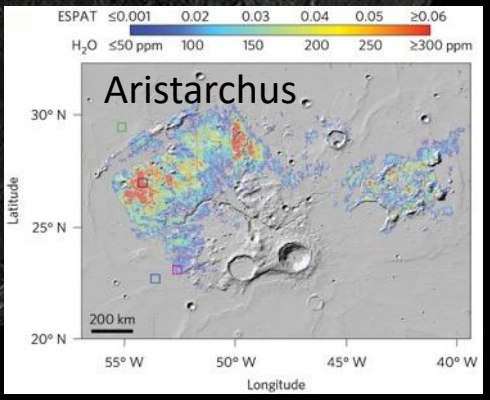
~30 μg/g H_2O in glasses



>300 μg/g H_2O

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

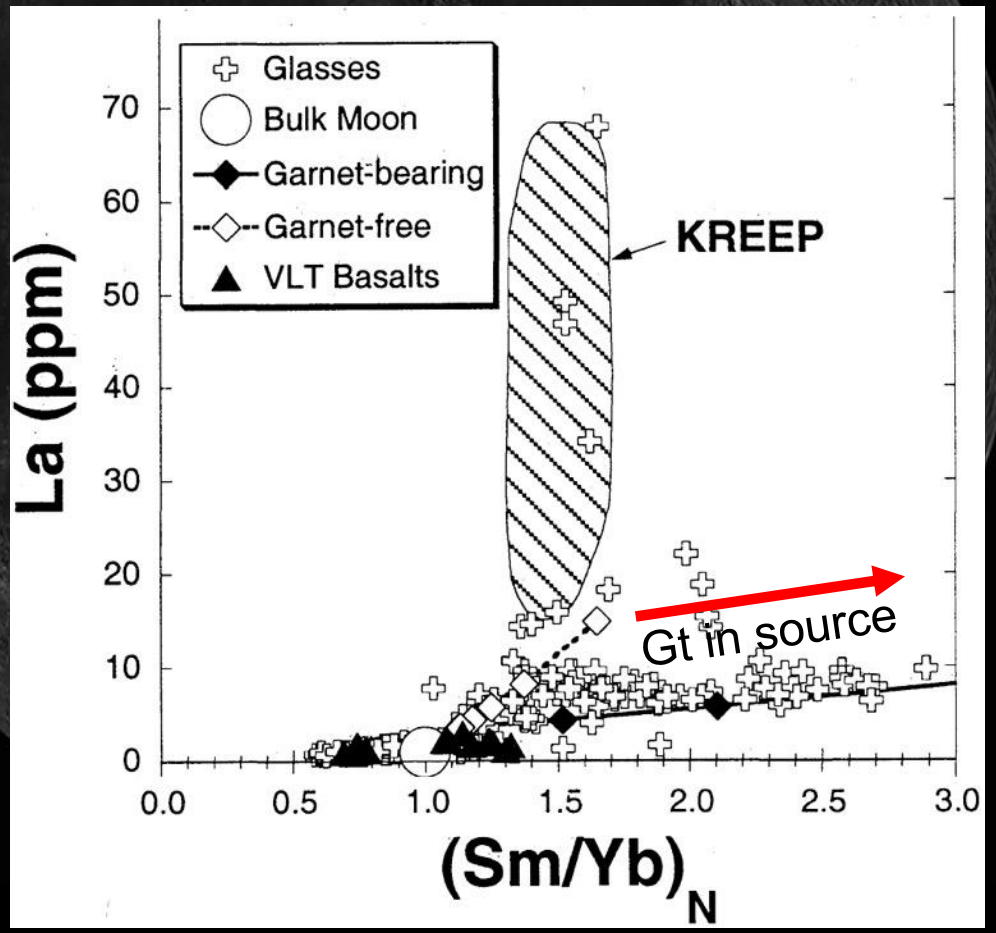


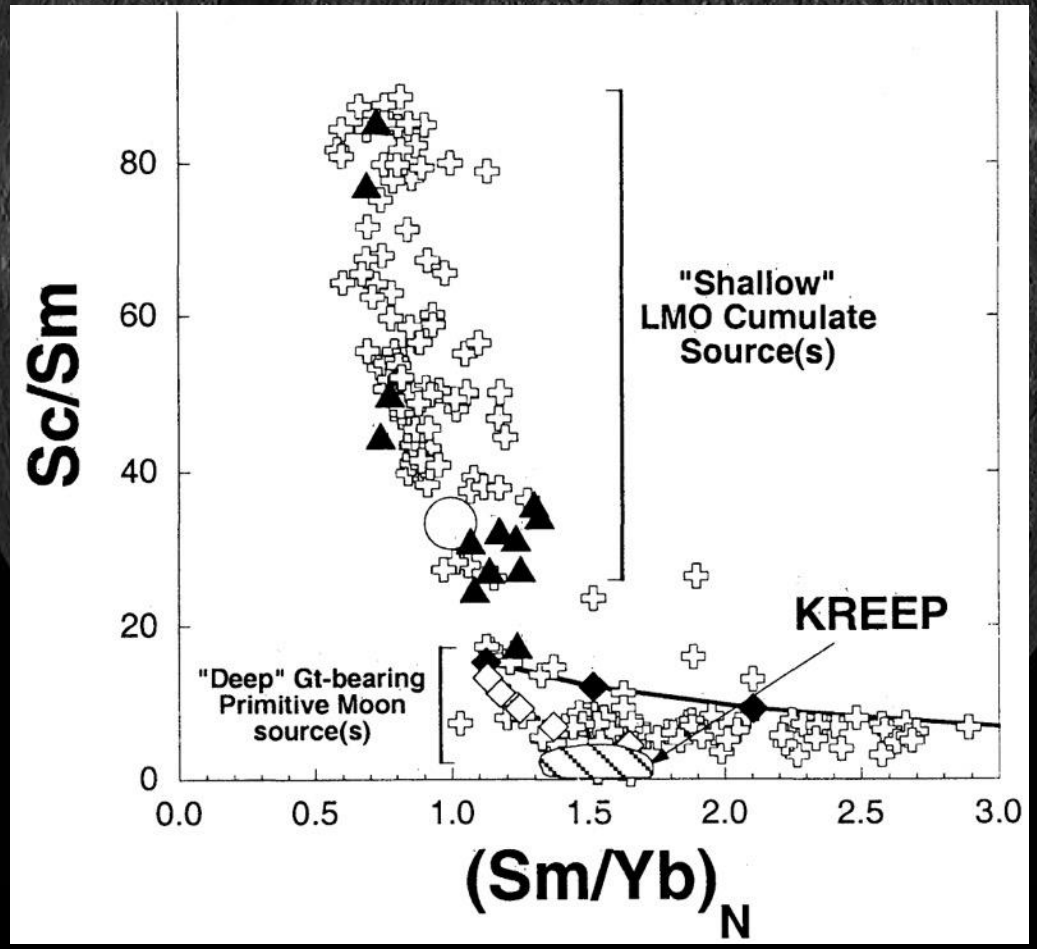


Pyroclastic Deposits

Pyroclastic glasses are derived from deeper levels of the lunar mantle, some from the garnet stability zone within the mantle

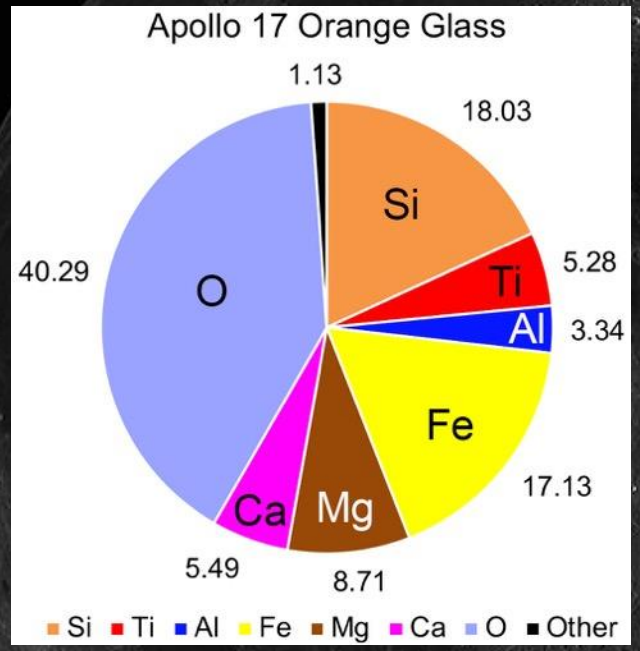
Longhi (1992) *GCA* **56**, 2235-2252; Neal (2001) JGR 106, 27,865-27,885

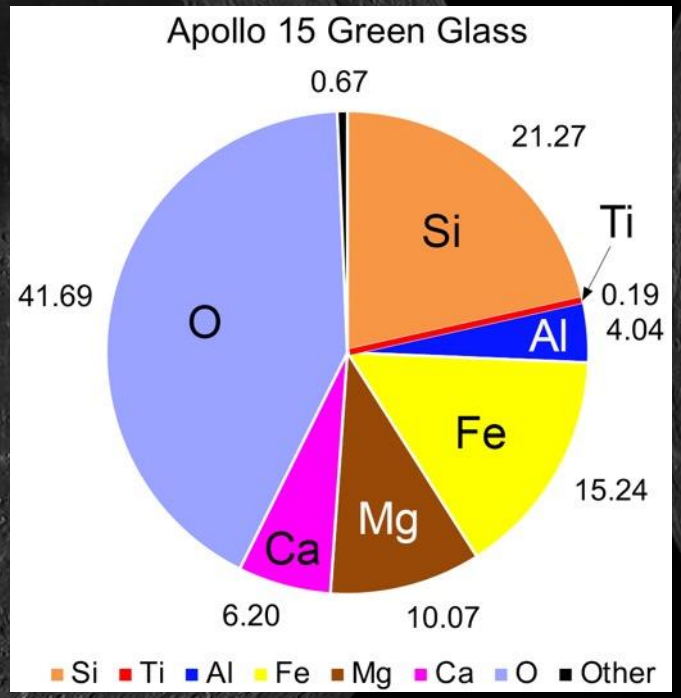


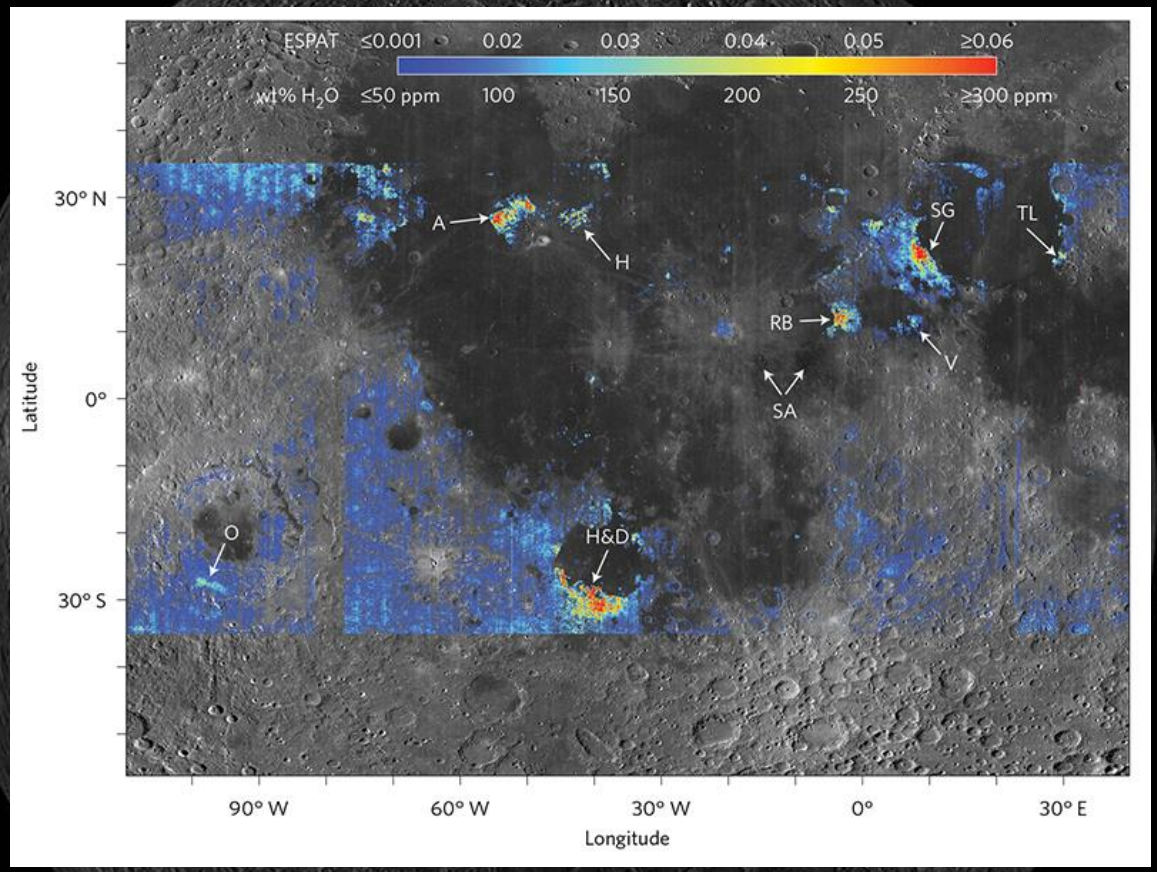


Pyroclastic Deposits

Pyroclastic glasses could be a resource







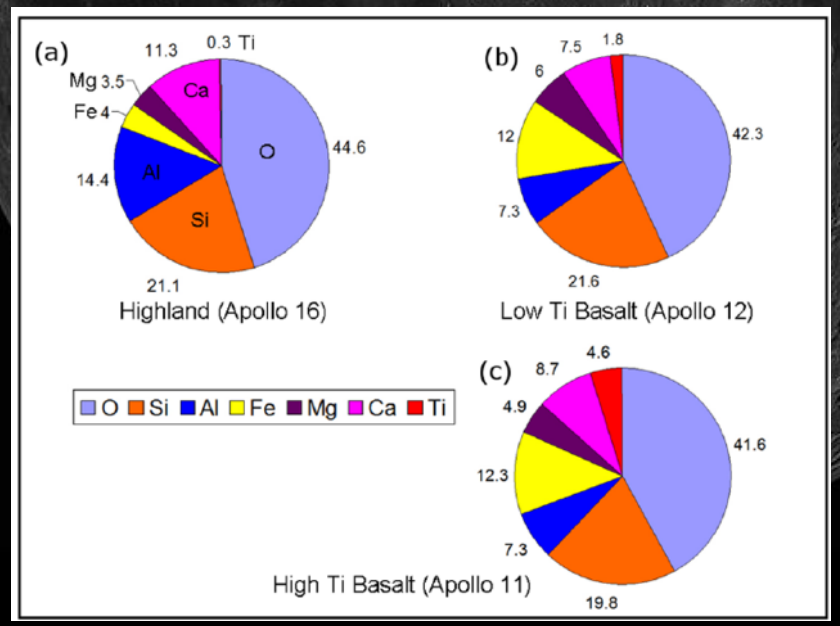
Milliken & Li (2017) *Nat. Geosci.* **10**, 561-565.

>300 µg/g H_2O, but 1 tonne of H_2O requires 3,333 tonnes of glass to be processed. But how variable is this amount? Better fidelity to guide surface exploration.

Regolith Resources

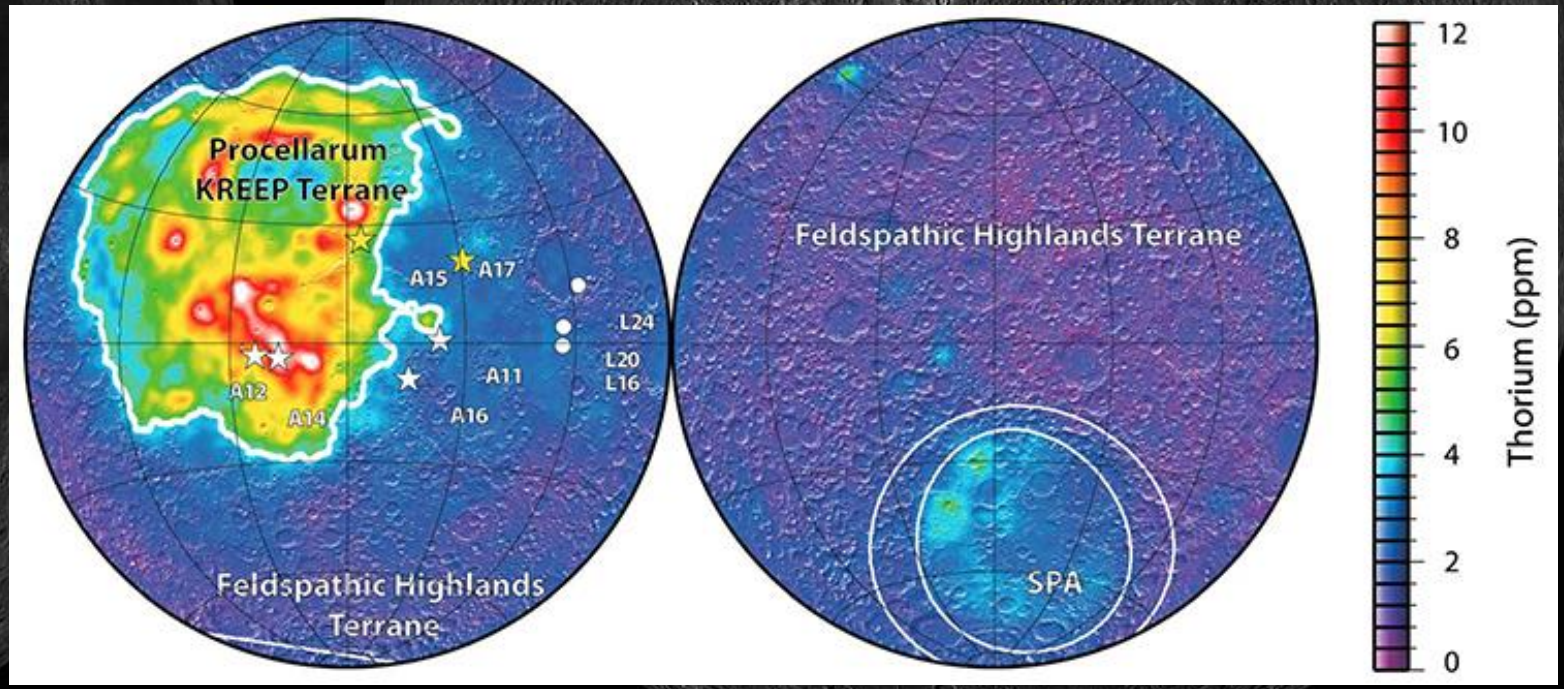
Regolith:

- Building (e.g., 3D printing)
- Metals (inc. PGE, REE)
- Oxygen
- Solar wind implanted volatiles (H, He C, N, etc.)
- Th, U



Rare Earth Elements

- Procellarum KREEP Terrane.
- Concentration of REE and other rare elements (e.g., U, Th).



Laneuville et al. (2018) *J. Geophys. Res. Planets* **123**, 3144-3166

Regolith Resources

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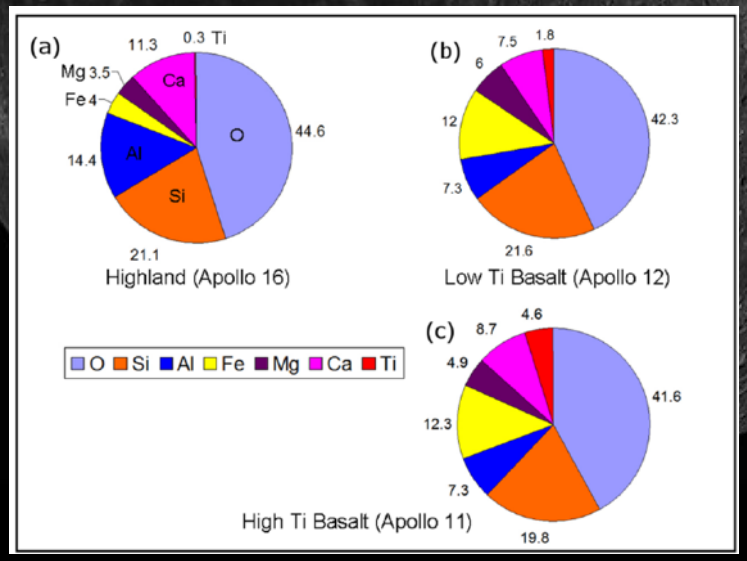
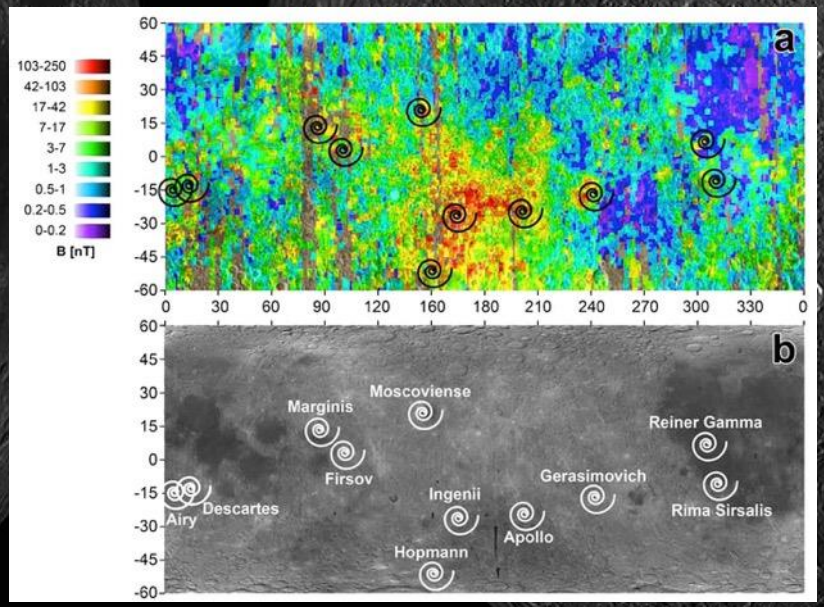


Platinum Group Metals

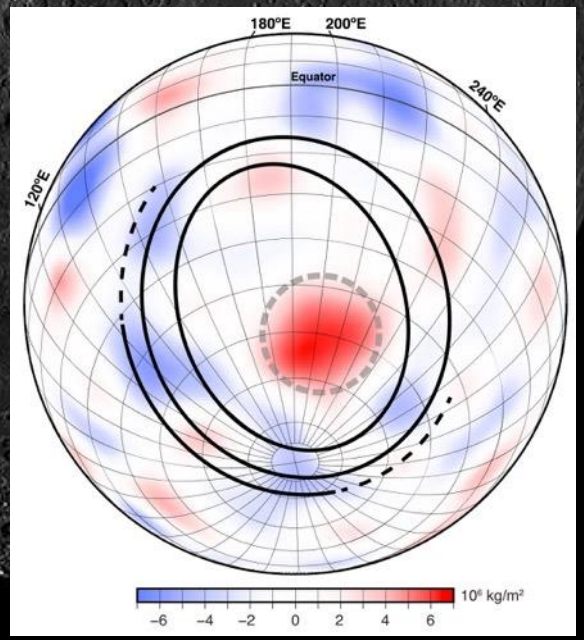
- Metal from meteoroids/asteroids within the regolith – lunar “swirls”?.
- Also embedded in the lunar interior? Too deep.



Magnetic swirls

Kramer et al. (2011) J. Geophys. Res. 116, E04008, doi:10.1029/2010JE003669

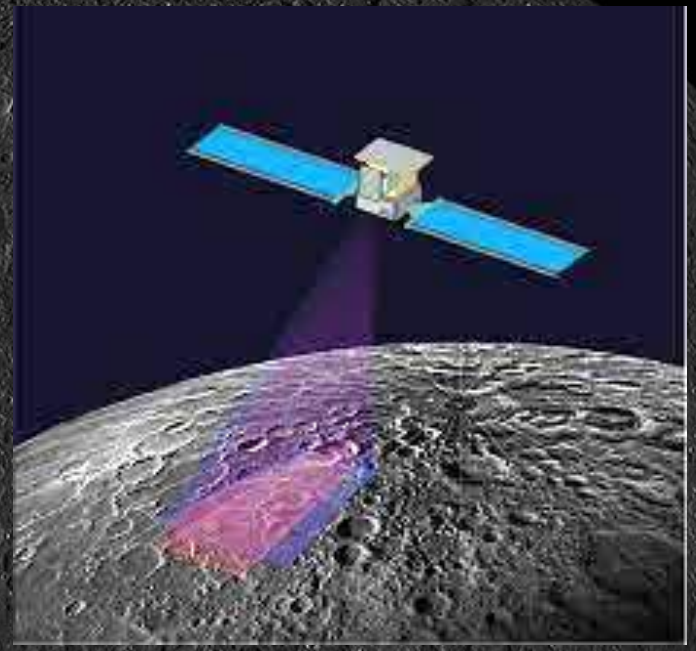
James et al. (2019) *Geophys. Res. Lett.* **46**, 5100-5106

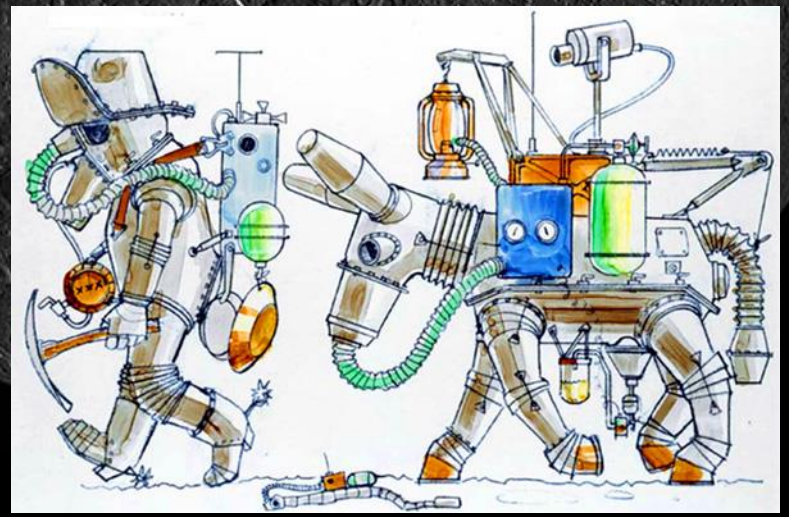


Polar Volatile Resources

We don’t know the following about lunar resources:

- 3D distribution;
- Form;
- Composition;
- Grade;
- Regolith geotechnical properties;
- Ease of extractability;
- Quantify the refining process for and transport and storage of products.





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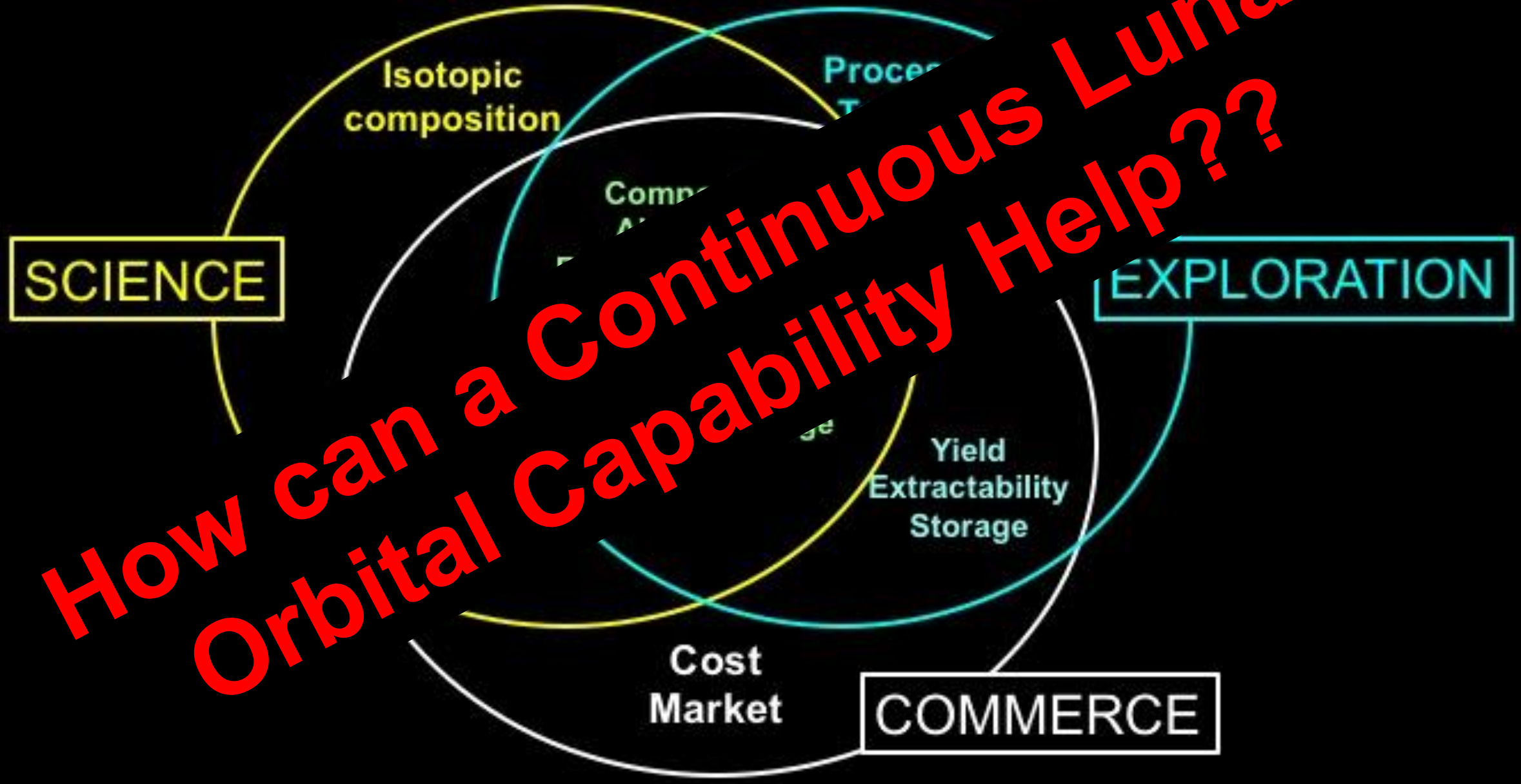

How can a Continuous Lunar Orbital Capability Help??