Calculated Thicknesses of Volcanically Derived Water Ice Deposits at the Lunar Poles

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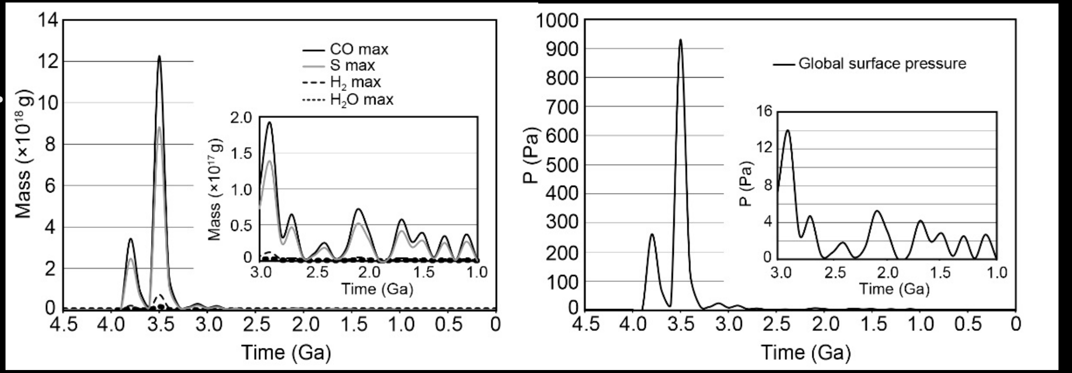
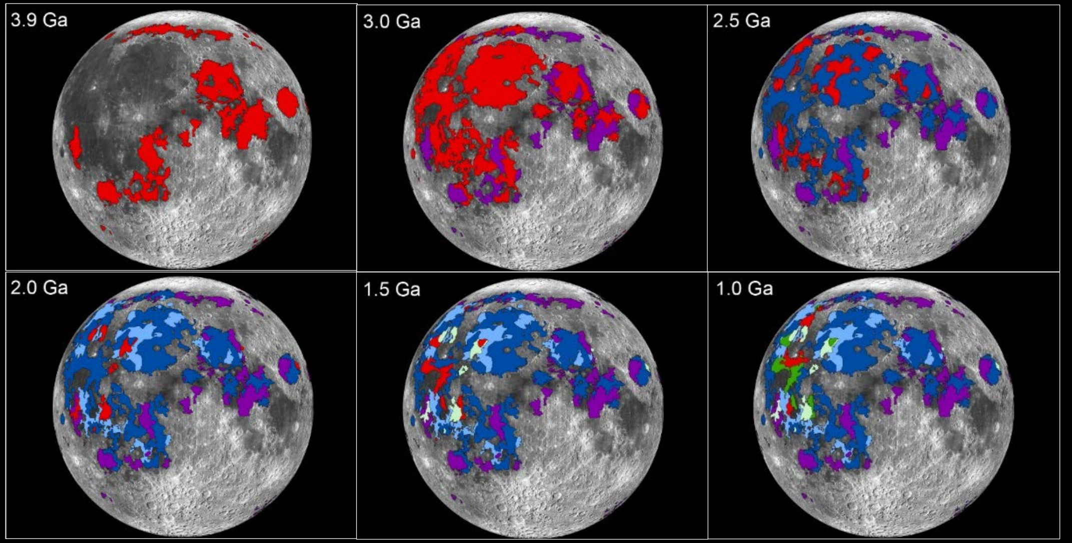
Overview

- What we know:
  - Volcanically derived volatiles.
  - Timing of volatile release.
  - Current observations of lunar polar volatiles.
- How volatiles migrated on the Moon.
- Thickness of resulting deposits.
- Implications for the current distribution of lunar volatiles.

Volcanic Volatiles Released from the Moon

- Apollo mare basalt samples: CO, H, OH, H_2O, and S volatiles.
  - e.g., Housley, 1978; Robinson and Taylor, 2014; McCubbin et al., 2010; Shearer et al., 2006
- Volcanic activity peaked 3.8 Ga and 3.5 Ga.
  - 60% of all volcanically derived volatiles were released 3.5 Ga.
  - 20% released 3.8 Ga; remaining 20% released during all other mare eruptions.
- Peak volatile release may have resulted in the formation of a transient lunar atmosphere.
  - Some volatiles lost to space, others settled to the surface as atmosphere dissipated.

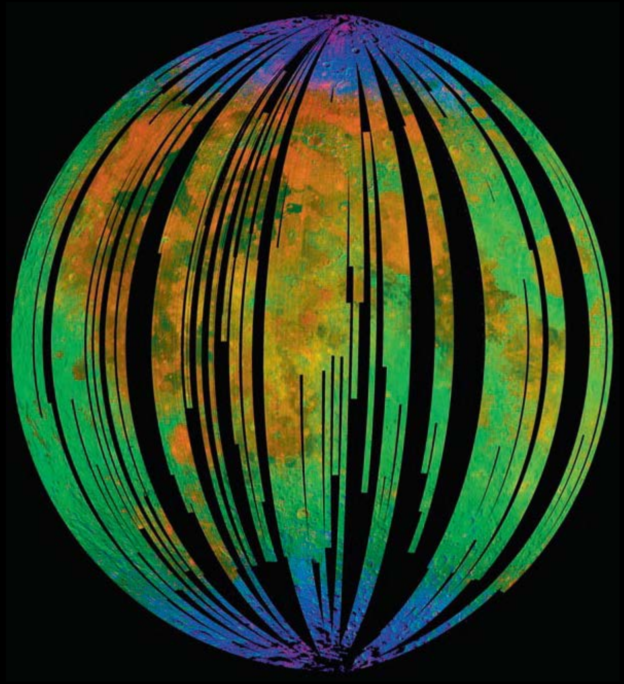




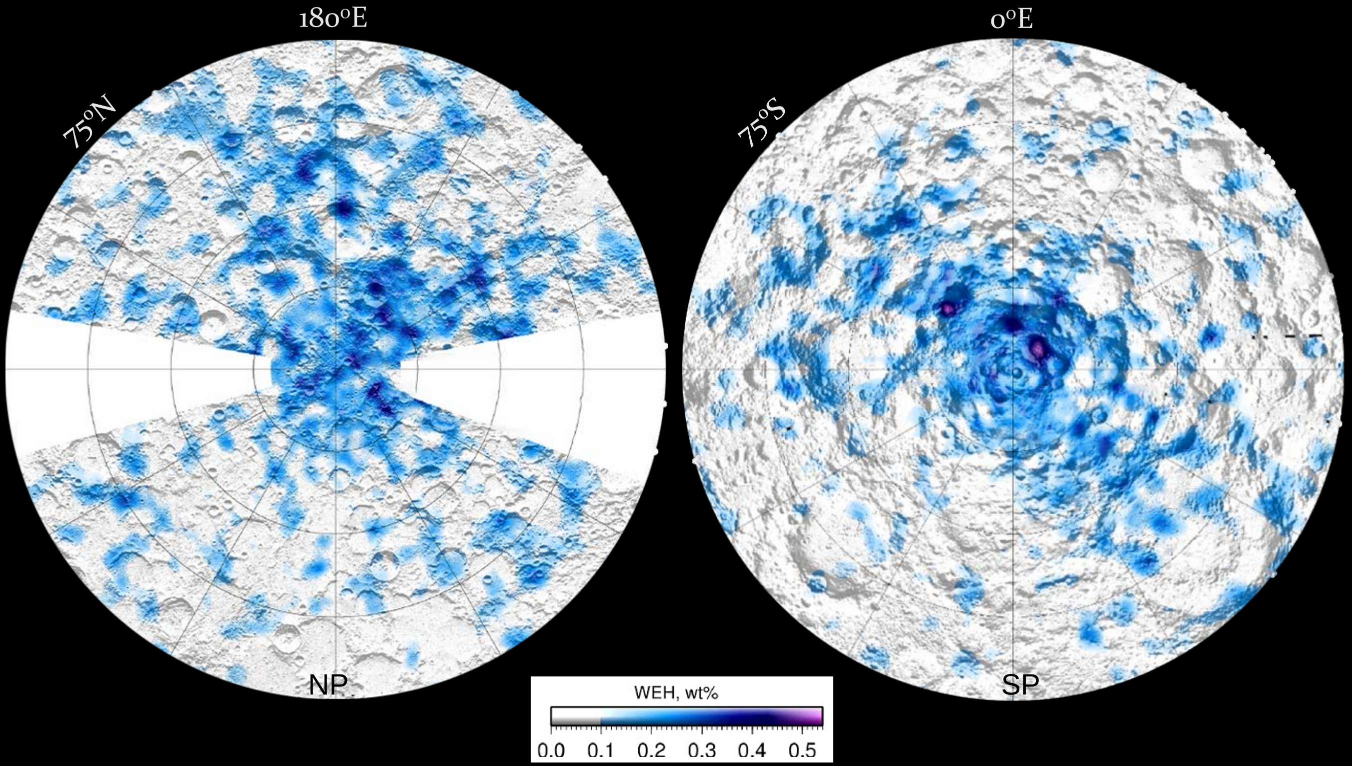
Based on data presented in Hiesinger et al., 2011; Whitten et al., 2011

Needham and Kring, 2017, *EPSL*.

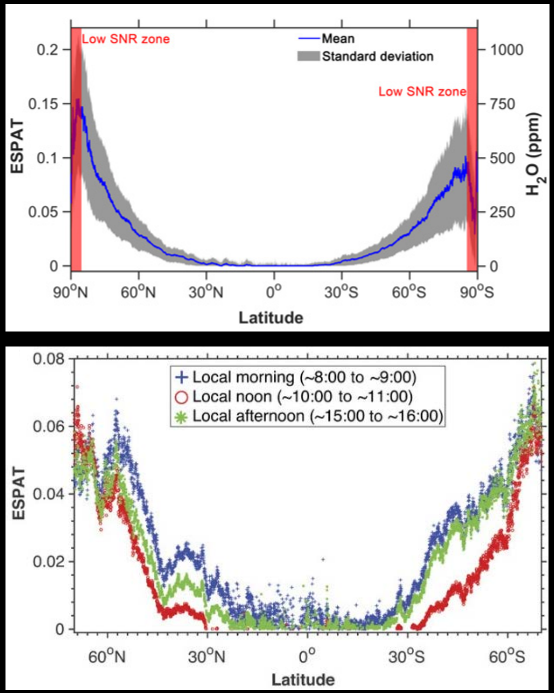
Recent Polar H-Bearing Material Detections from Orbit



Moon Mineralogy Mapper surface detection of OH/H_2O at lunar poles (blue/purple); Pieters et al., 2009



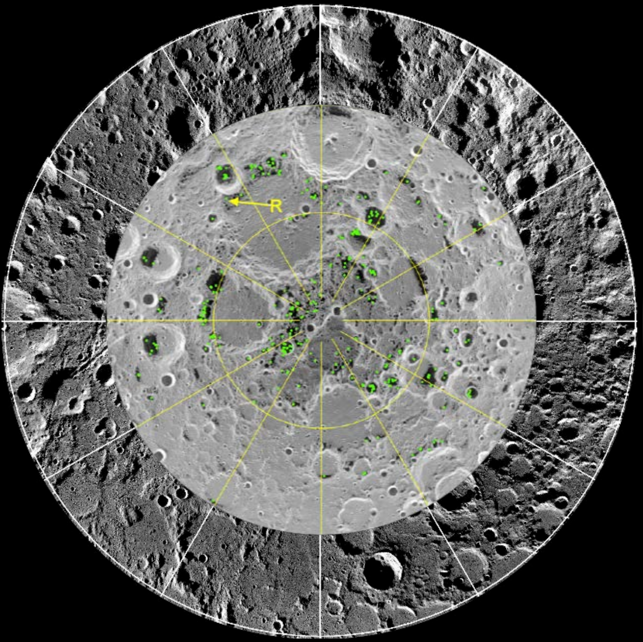
LEND detection of water equivalent H (1 m depth) via neutron suppression at lunar poles; Sanin et al., 2017



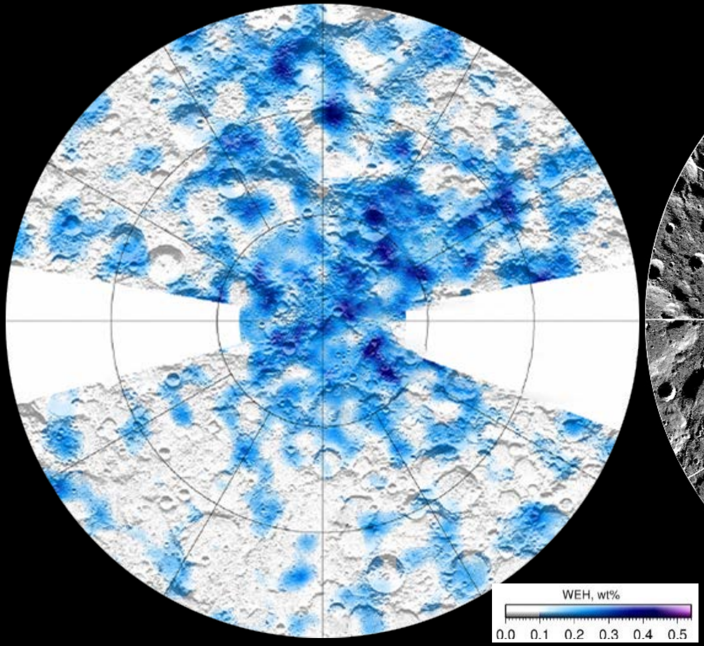
OH/H_2O variability by latitude and day from M^3; Li and Milliken, 2017

Where Lunar Volatiles are Now: North Pole

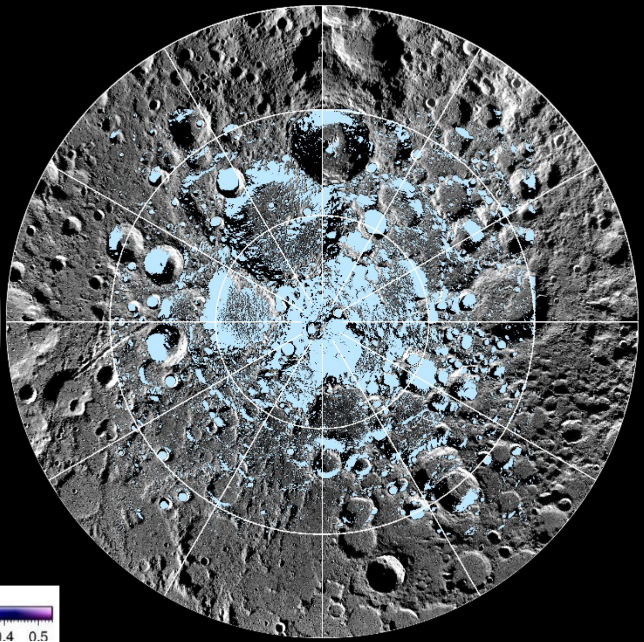
- Water at surface: Centered about North Pole.
  - Modern accumulations?
- Water at 1 m depth: Offset to 90°E – 180°E.
  - Ancient accumulations? (e.g., Siegler et al., 2016)



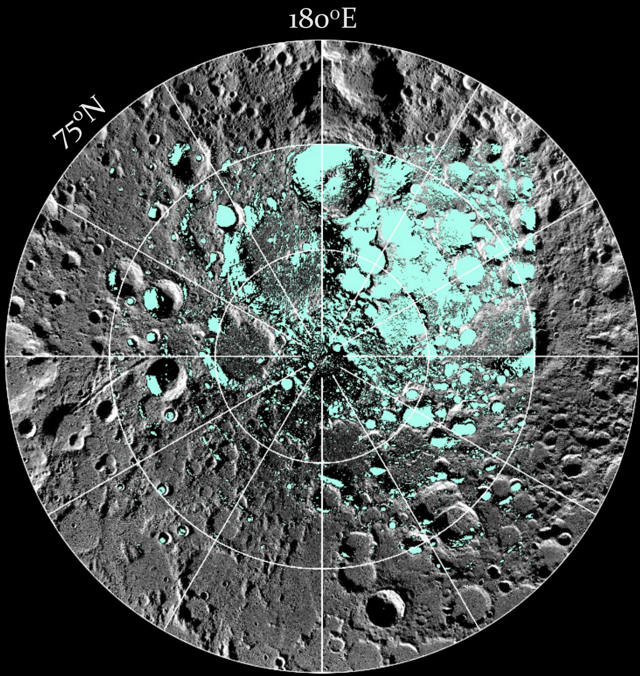
Current M^3 H_20 Ice Detection (surface)
Li et al., 2018



LEND Water Equivalent H (1 m depth)
Sanin et al., 2017



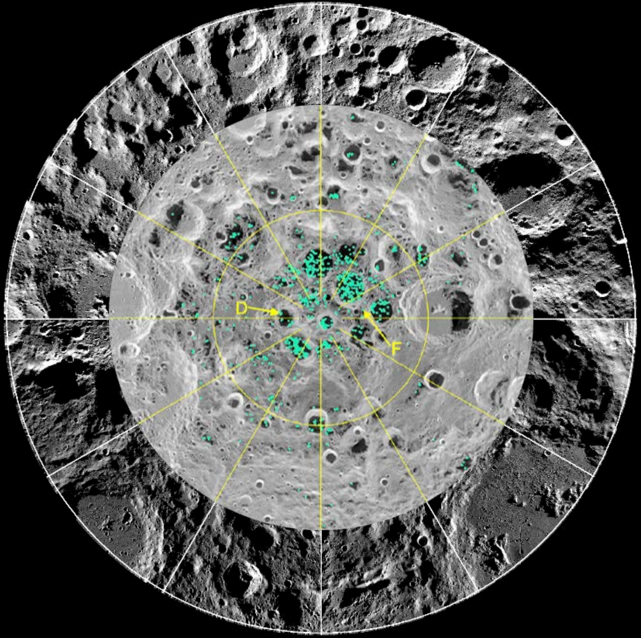
Current Ice Stability Zones (2.5 m depth)
Siegler et al., 2016



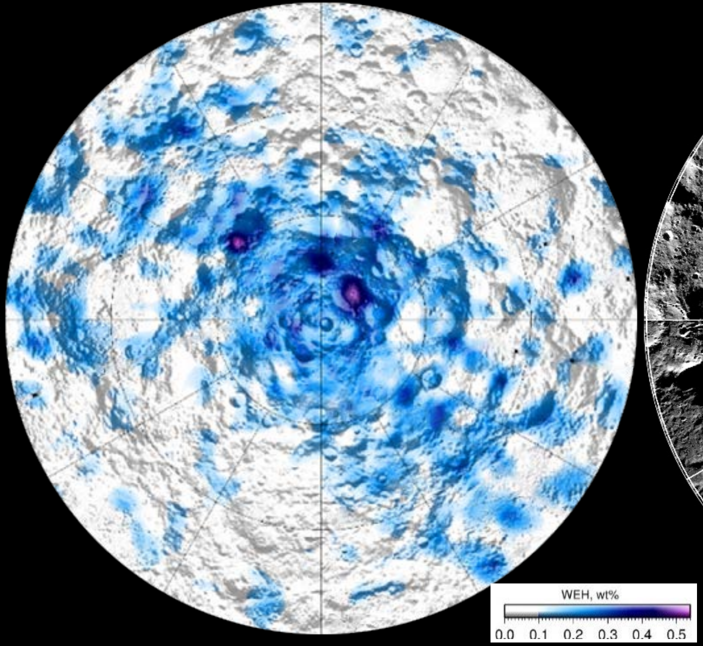
Past Ice Stability Zones (2.5 m depth)
Siegler et al., 2016

Where Lunar Volatiles are Now: South Pole

- Water at surface: Centered about South Pole.
  - Modern accumulations?
- Water at 1 m depth: Offset to 270°E – 0°E. (?)
  - Ancient accumulations? (e.g., Siegler et al., 2016)



Current M3 H_2O Ice Detection (surface)
Li et al., 2018



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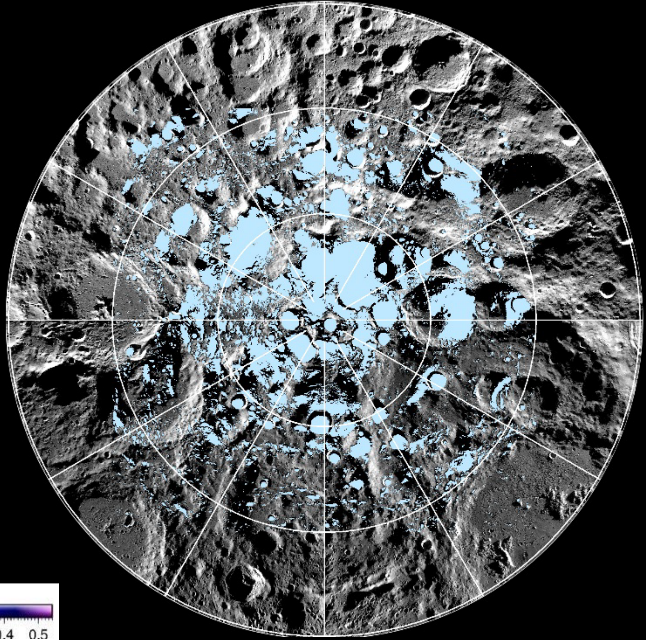

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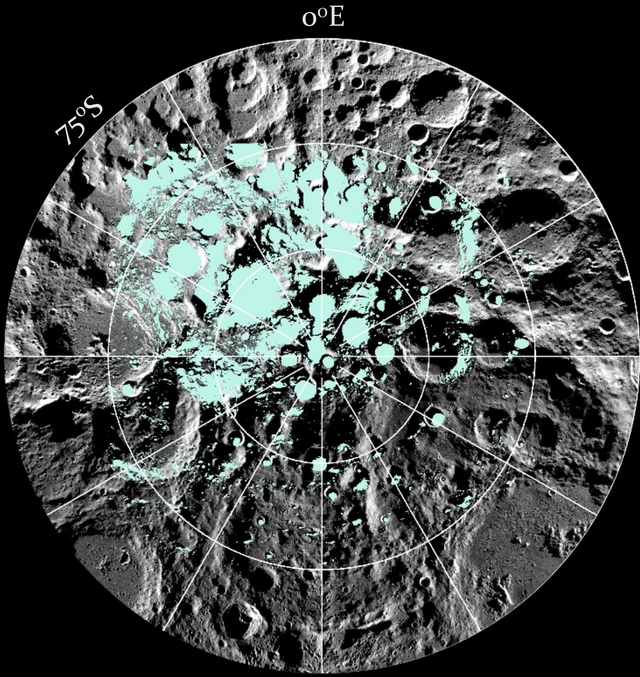

Past Ice Stability Zones (2.5 m depth)
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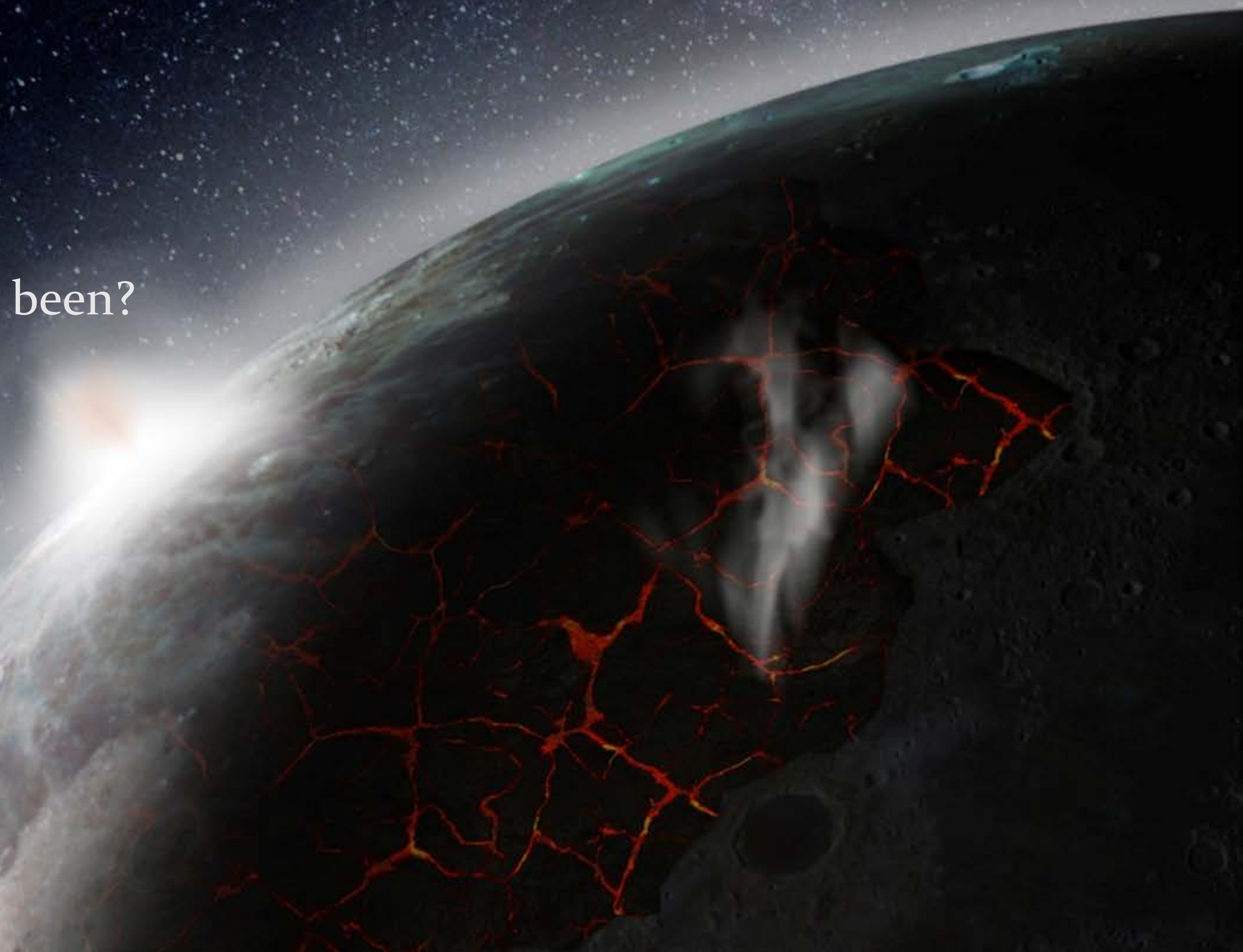
Volcanic Volatiles Released from the Moon

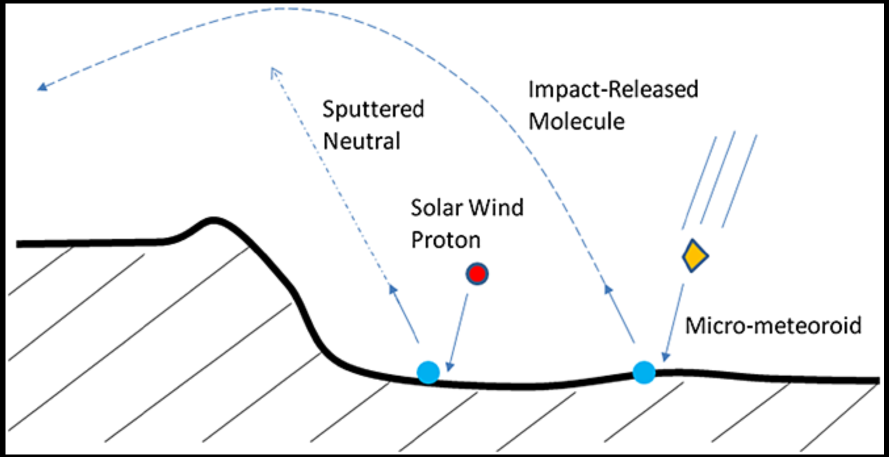
- Questions:
  - Where did the volatiles settle on the Moon?
  - How thick would the resulting deposits have been?

- Results have implications for the current distribution of lunar volatiles.

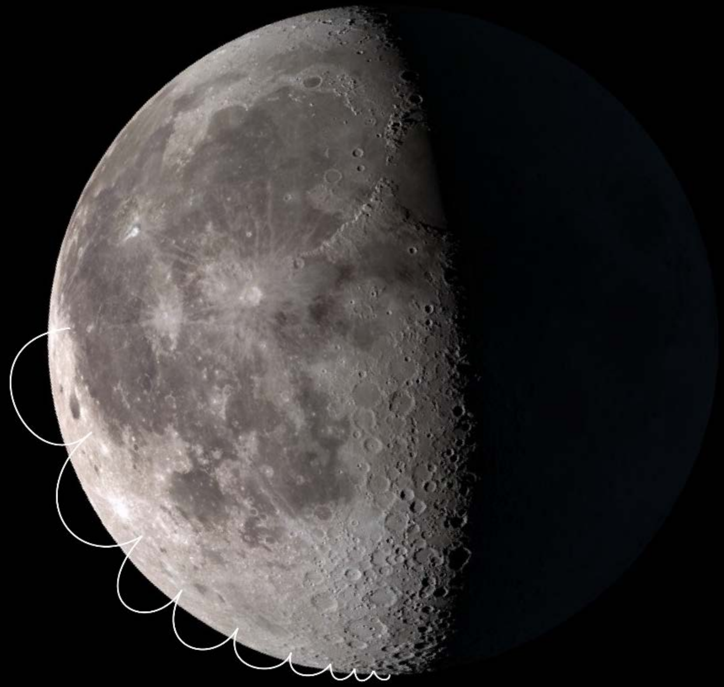


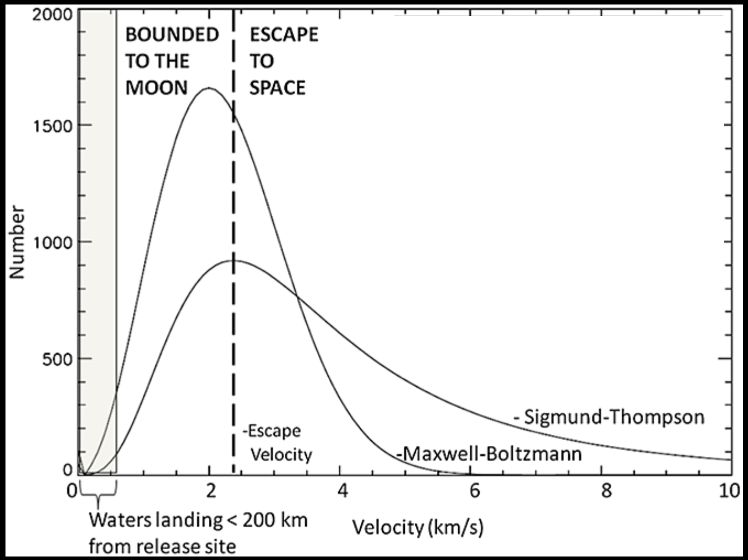
Migration of Lunar Volcanically Derived Volatiles

- In the absence of a lunar atmosphere:
  - Volatiles 'hop' based on energy gradient, traveling towards lower energy (to the poles).
  - Assume erupted volatiles migrated to nearest pole – dependent on eruption location.



Releasing volatiles via sputtering and impact vaporization processes; Farrell et al., 2015.





Released volatiles lost to space vs. bounded to the Moon; Farrell et al., 2015.

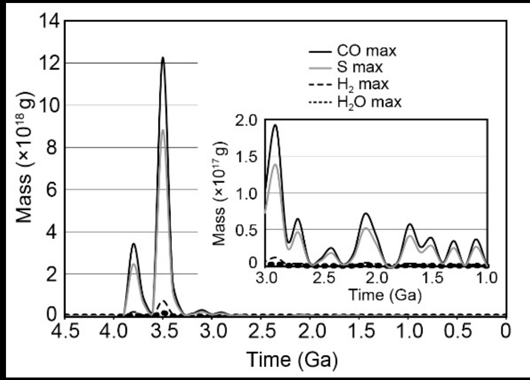
Migration of Lunar Volcanically Derived Volatiles

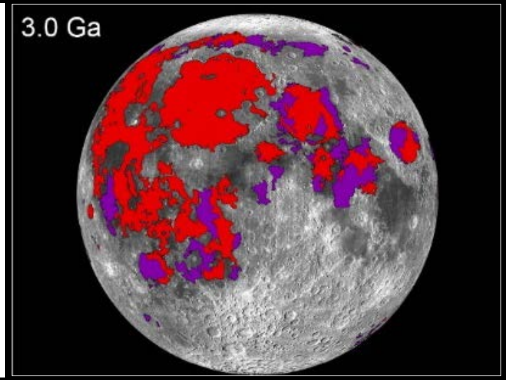
- In the presence of a lunar atmosphere:
  - Volatiles entrained in globally distributed atmosphere.
  - Equatorial and mid-latitude volatiles likely to migrate to the poles (e.g., Soto et al., 2018)
  - Assume erupted volatiles deposit evenly at each pole as the atmosphere dissipates – 50% erupted volatiles to each pole.
- Volatiles trapped in areas of stability.

Max Equivalent Thickness of H-Bearing Volcanic Volatile Deposits

- Assumptions:
  - Volatiles released 3.5 Ga and 3.8 Ga (~80%) split between poles.
  - All other volatiles migrated to nearest pole (mostly north pole).
  - Assume no H_2O loss (2.4×10^{14} kg) – max deposit thickness.
    - H_2O/OH only; assume H is lost to space
  - Know areas of expected volatile preservation (NP/SP):

Region	NP Area (km²)	SP Area (km²)	Reference
Current PSRs	12866	16055	Mazarico et al., 2011
Currently Stable 2.5 m	94565	90884	Siegler et al., 2016
Past Stable 2.5 m	86285	82772	Siegler et al., 2016
Observed Surface Water	35	115	Li et al., 2018

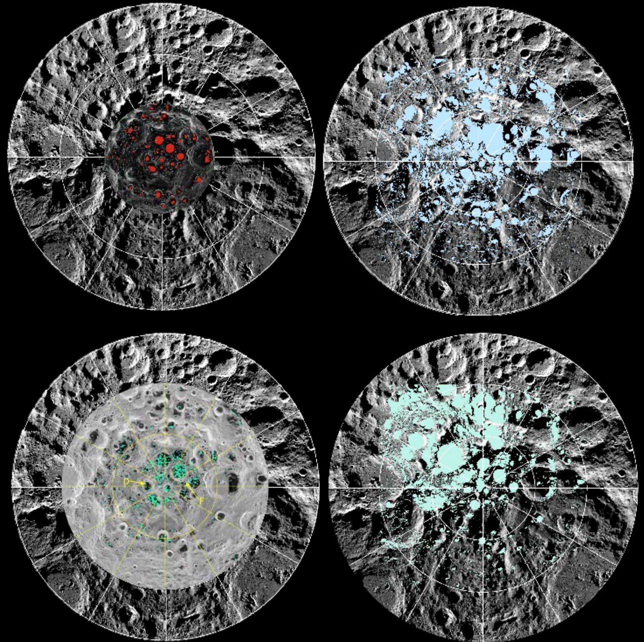




Needham and Kring, 2017, *EPSL*.

SP PSRs Mazarico et al., 2011

SP Currently Stable (2.5 m) Siegler et al., 2016



SP Current Surface Ice Li et al., 2018

SP Past Stable (2.5 m) Siegler et al., 2016

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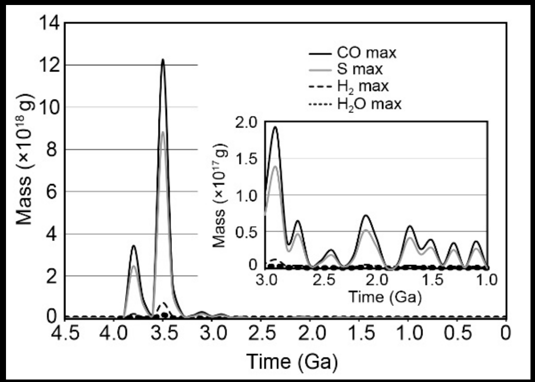

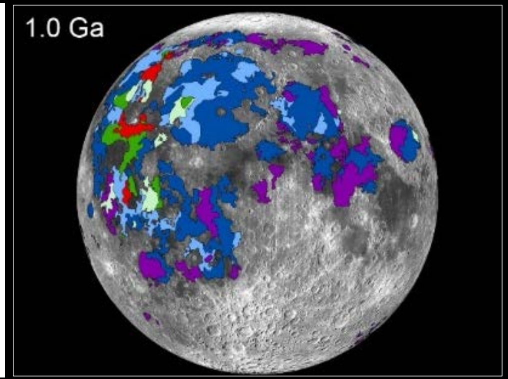

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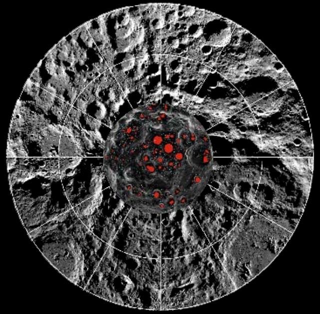
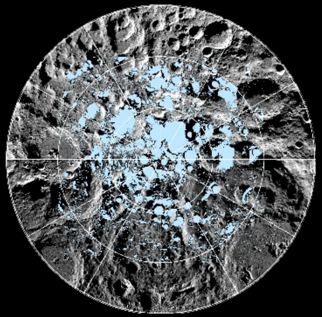
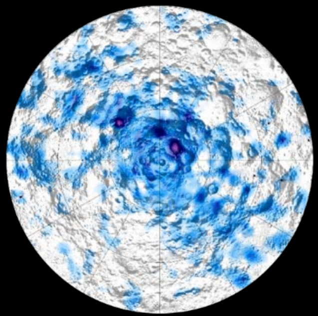
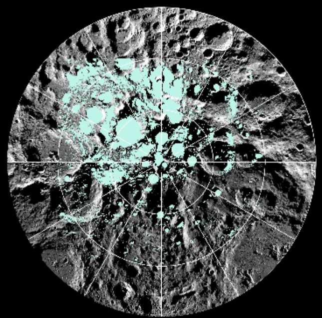




SP Currently Stable (2.5 m) Siegler et al., 2016

SP Current H Distribution Sanin et al., 2017



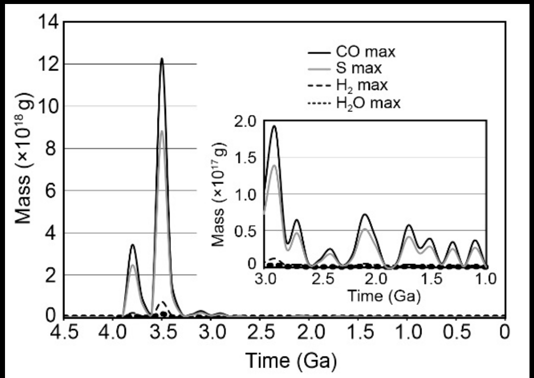


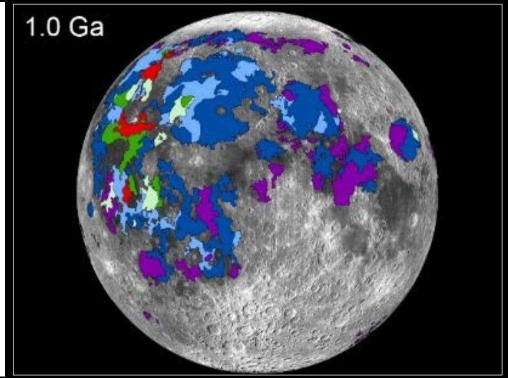
SP Past Stable (2.5 m) Siegler et al., 2016

Max Equivalent Thickness of H-Bearing Volcanic Volatile Deposits

- South Pole Results:

Region	Area (km^2)	Area Reference	Equiv. Thickness (m)
Current PSRs	16055	Mazarico et al., 2011	7.18
Polar Wander Present Stable to 2.5 m	90884	Siegler et al., 2016	1.39
Polar Wander Past Stable to 2.5 m	82772	Siegler et al., 2016	1.27





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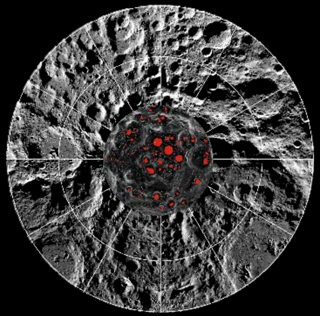
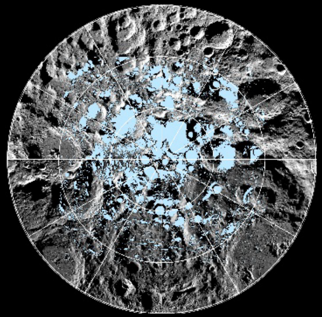
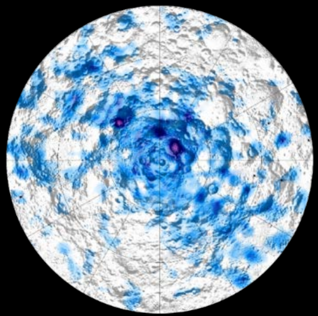
SP PSRs Mazarico et al., 2011

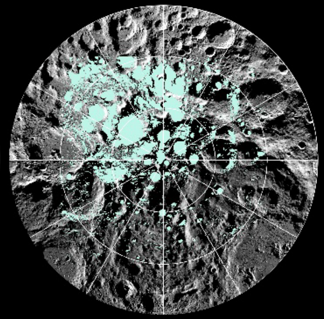




SP Currently Stable (2.5 m) Siegler et al., 2016

SP Current H Distribution Sanin et al., 2017



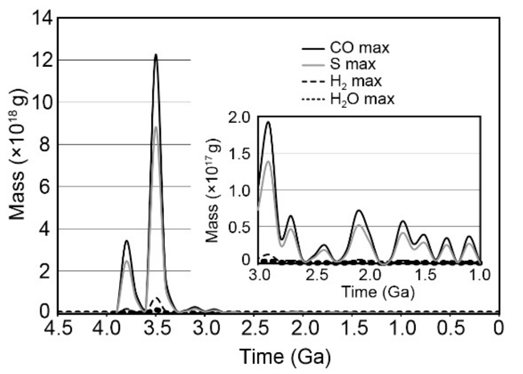


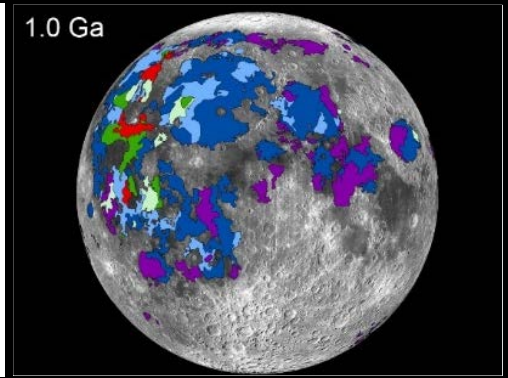
SP Past Stable (2.5 m) Siegler et al., 2016

Maximum Thickness of H-Bearing Volcanic Volatile Deposits

- North Pole Results:

Region	Area (km²)	Area Reference	Equiv. Thickness (m)
Current PSRs	12866	Mazarico et al., 2011	9.70
Polar Wander Present Stable to 2.5 m	94565	Siegler et al., 2016	1.45
Polar Wander Past Stable to 2.5 m	86285	Siegler et al., 2016	1.32





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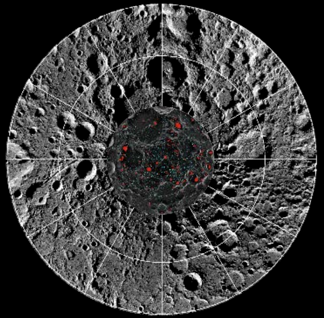
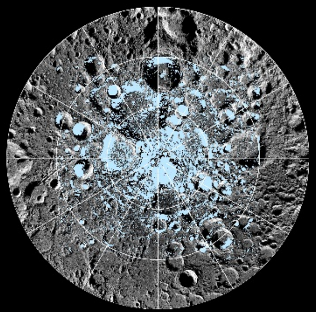
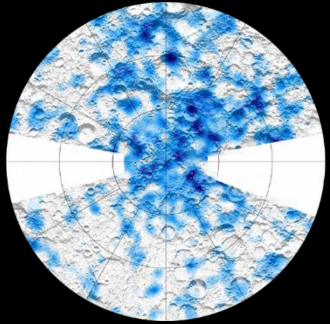
NP PSRs Mazarico et al., 2011

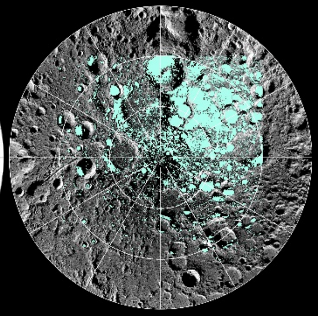




NP Currently Stable (2.5 m) Siegler et al., 2016

NP Current H Distribution Sanin et al., 2017



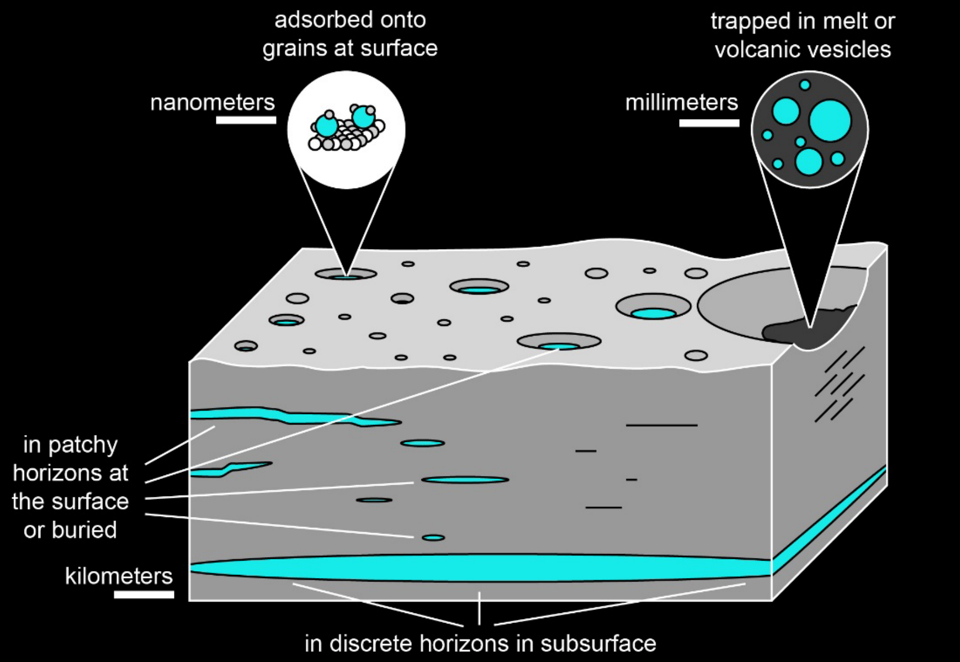


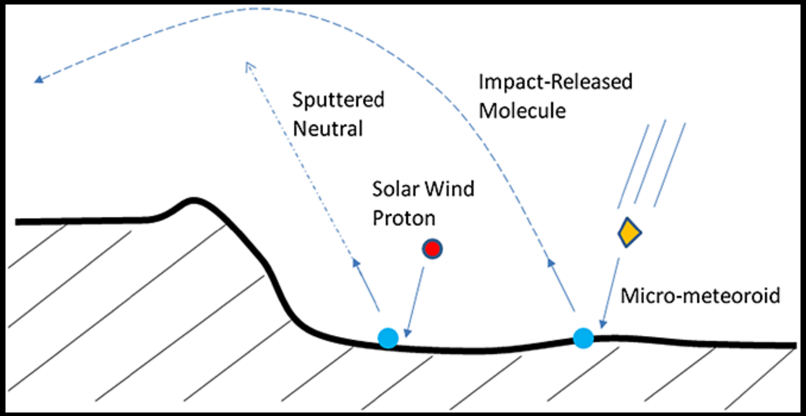
NP Past Stable (2.5 m) Siegler et al., 2016

Implications for Distribution of Polar Lunar Volatiles

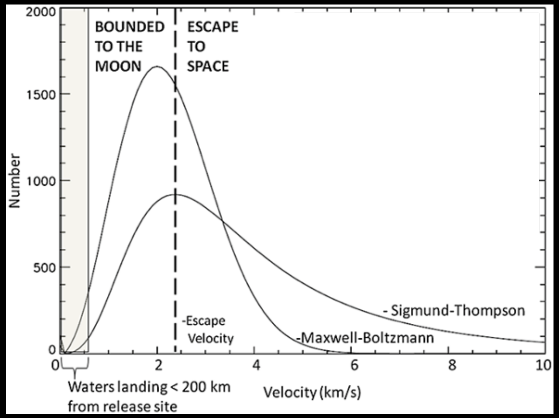
- Ice ~1.5 m thick deposited in stable regions at each lunar pole.
  - Subsequently covered by ejecta, vaporized, and gardened by subsequent impacts.
  - May have 6-10 m ice-bearing regolith above thinner subsurface ice horizon.

(Fa and Jin, 2010; Kobayashi et al., 2010)





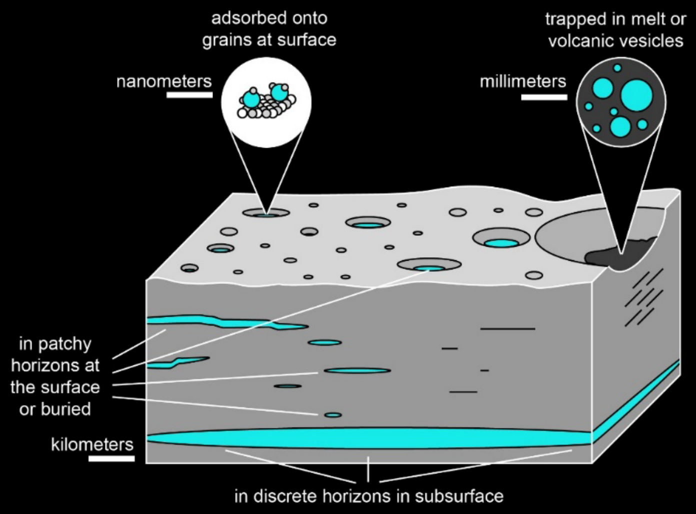
Releasing volatiles via sputtering and impact vaporization processes; Farrell et al., 2015.

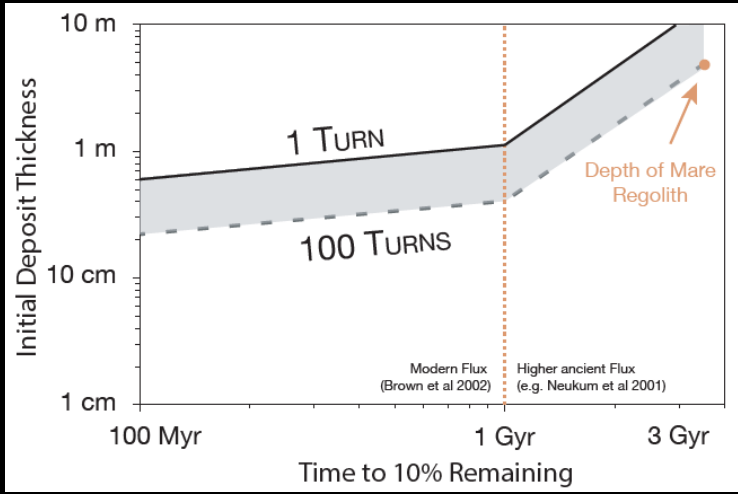


Released volatiles lost to space vs. bounded to the Moon; Farrell et al., 2015.

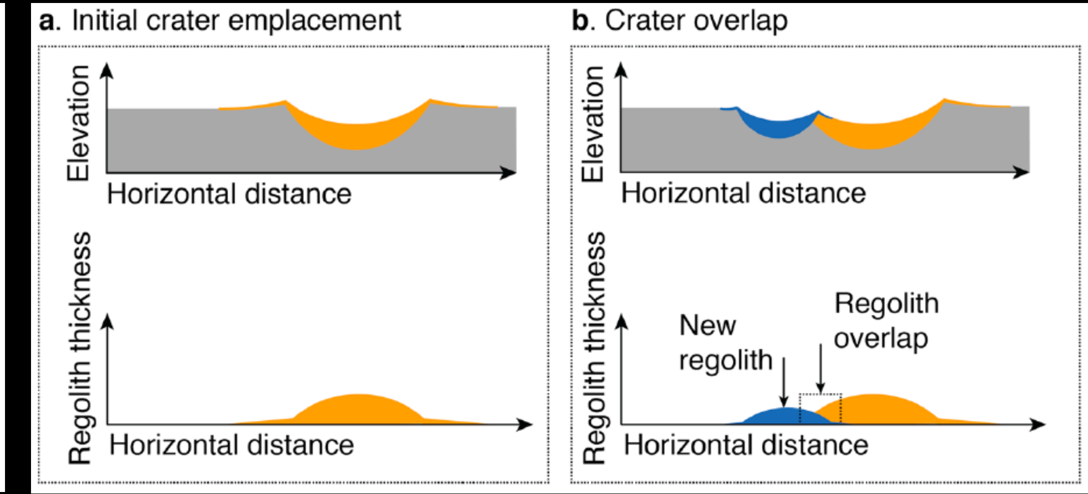
Implications for Distribution of Polar Lunar Volatiles

- Would ~1.5 m thick layer of ice survive 3.5 Ga?
  - Based on “turns” of regolith based on impact gardening rates, no. To survive 3.5 Ga, 5-10 m thick layer required. (Costello et al., 2019)
  - Beginning to look at this with another model based on the generation of small, simple craters, to confirm. (Hirabayashi et al., 2018)





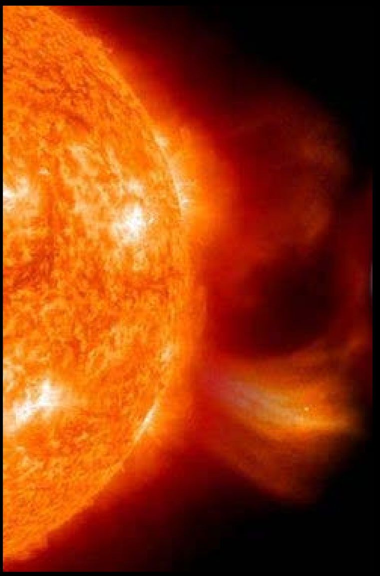
Mare regolith is ~ 5m thick. If 100 turns pulverizes rock into regolith, then to produce the present patchiness, ice that was deposited 3.5 Gyrs ago would have initially been 5 - 10 m thick.
Costello et al., 2019



Schematic indicating how the analytical model deals with crater overlapping. (Top) Elevation along the horizontal direction. (Bottom) Regolith thickness along the horizontal direction. Orange region is regolith produced by initial crater, blue region is regolith region developed by a new crater’s formation.
Hirabayashi et al., 2018

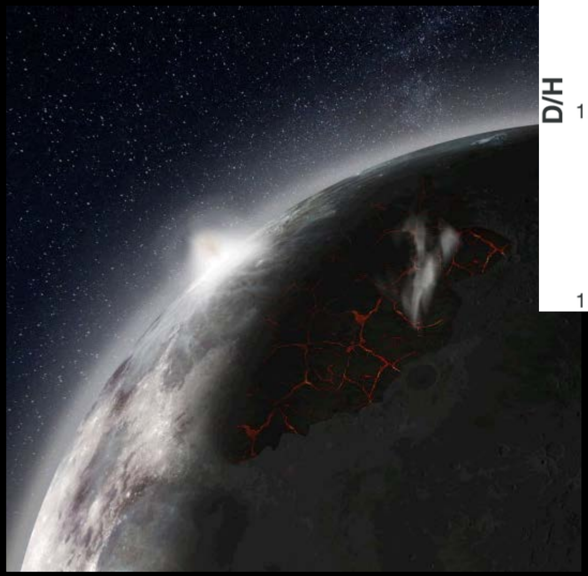
Implications for a Mission Prospecting for Lunar Volatiles

- The source of volatiles can affect the composition of these volatile deposits.
  - H, O isotopes
  - Alteration minerals like hematite! (Li et al., this meeting)

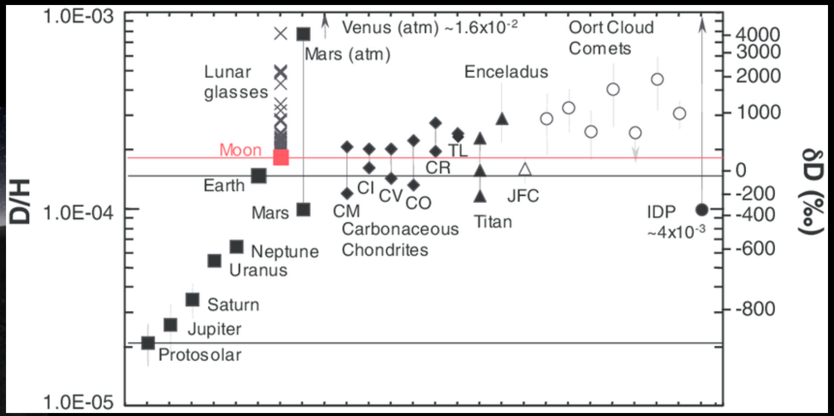


Solar wind-delivered hydrogen trapped in the Moon's PSRs.

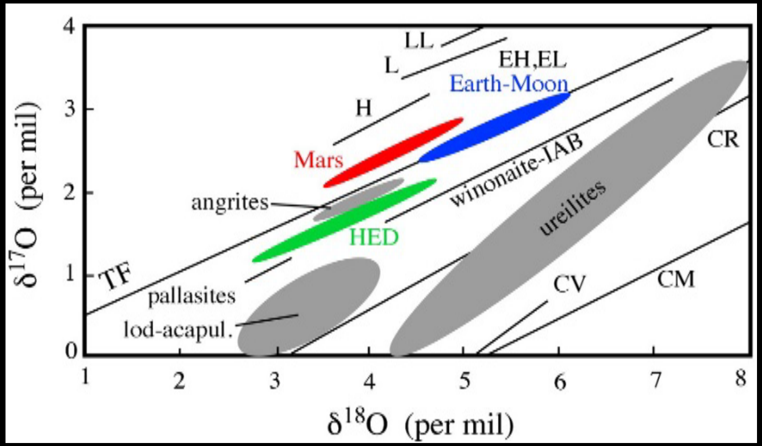
Water delivered by asteroid and comet impacts on the Moon.



Water-building components erupted during volcanic eruptions.



D/H isotopes across the Solar System, from Saal et al., 2013 and references therein.



Oxygen isotopes across the Solar System from Righter and O'Brien, 2007 and refs. therein.

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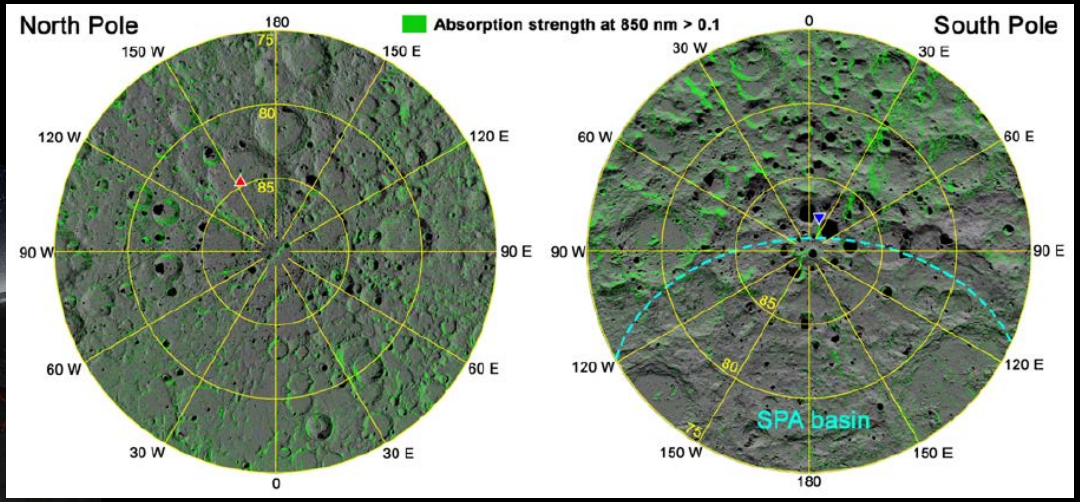

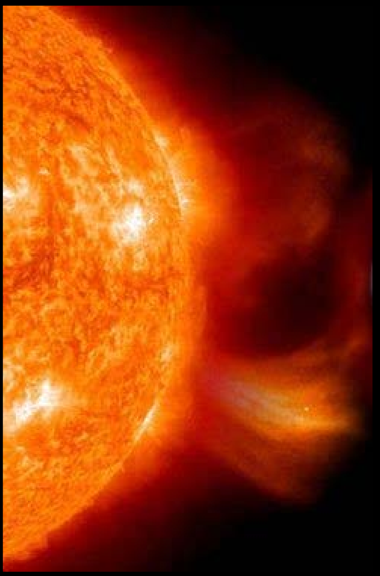
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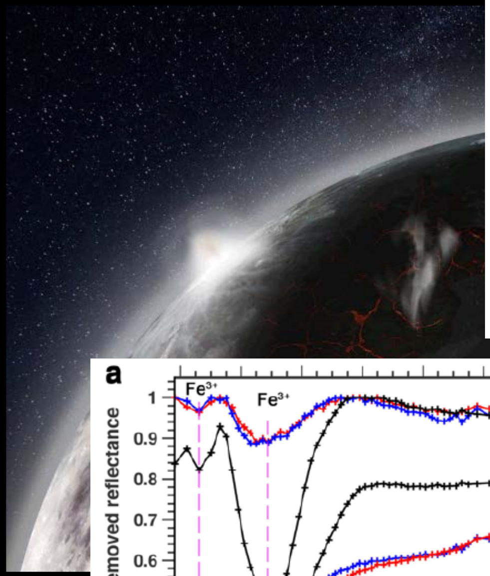
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