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, H₂O, 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/H₂O 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/H₂O variability by latitude and day from M³; 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 M³ H₂O 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 H₂O 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 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 \( \text{H}_2\text{O} \) loss \( (2.4 \times 10^{14} \text{ kg}) \) – max deposit thickness.
    • \( \text{H}_2\text{O}/\text{OH} \) only; assume \( \text{H} \) is lost to space
  • Know areas of expected volatile preservation (NP/SP):

<table>
<thead>
<tr>
<th>Region</th>
<th>NP Area (km(^2))</th>
<th>SP Area (km(^2))</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>Current PSRs</td>
<td>12866</td>
<td>16055</td>
<td>Mazarico et al., 2011</td>
</tr>
<tr>
<td>Currently Stable 2.5 m</td>
<td>94565</td>
<td>90884</td>
<td>Siegler et al., 2016</td>
</tr>
<tr>
<td>Past Stable 2.5 m</td>
<td>86285</td>
<td>82772</td>
<td>Siegler et al., 2016</td>
</tr>
<tr>
<td>Observed Surface Water</td>
<td>35</td>
<td>115</td>
<td>Li et al., 2018</td>
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Needham and Kring, 2017, EPSL.
Max Equivalent Thickness of H-Bearing Volcanic Volatile Deposits

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Max Equivalent Thickness of H-Bearing Volcanic Volatile Deposits

- South Pole Results:

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<tr>
<td>Current PSRs</td>
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<td>Mazarico et al., 2011</td>
<td>7.18</td>
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<tr>
<td>Polar Wander Present Stable to 2.5 m</td>
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<td>Siegler et al., 2016</td>
<td>1.39</td>
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<td>Polar Wander Past Stable to 2.5 m</td>
<td>82772</td>
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Maximum Thickness of H-Bearing Volcanic Volatile Deposits

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<td>Current PSRs</td>
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<td>Mazarico et al., 2011</td>
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<td>Siegler et al., 2016</td>
<td>1.45</td>
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<td>86285</td>
<td>Siegler et al., 2016</td>
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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.
- Expected to 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 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)

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

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