A review of processes influencing the form and morphology of ice on the Moon

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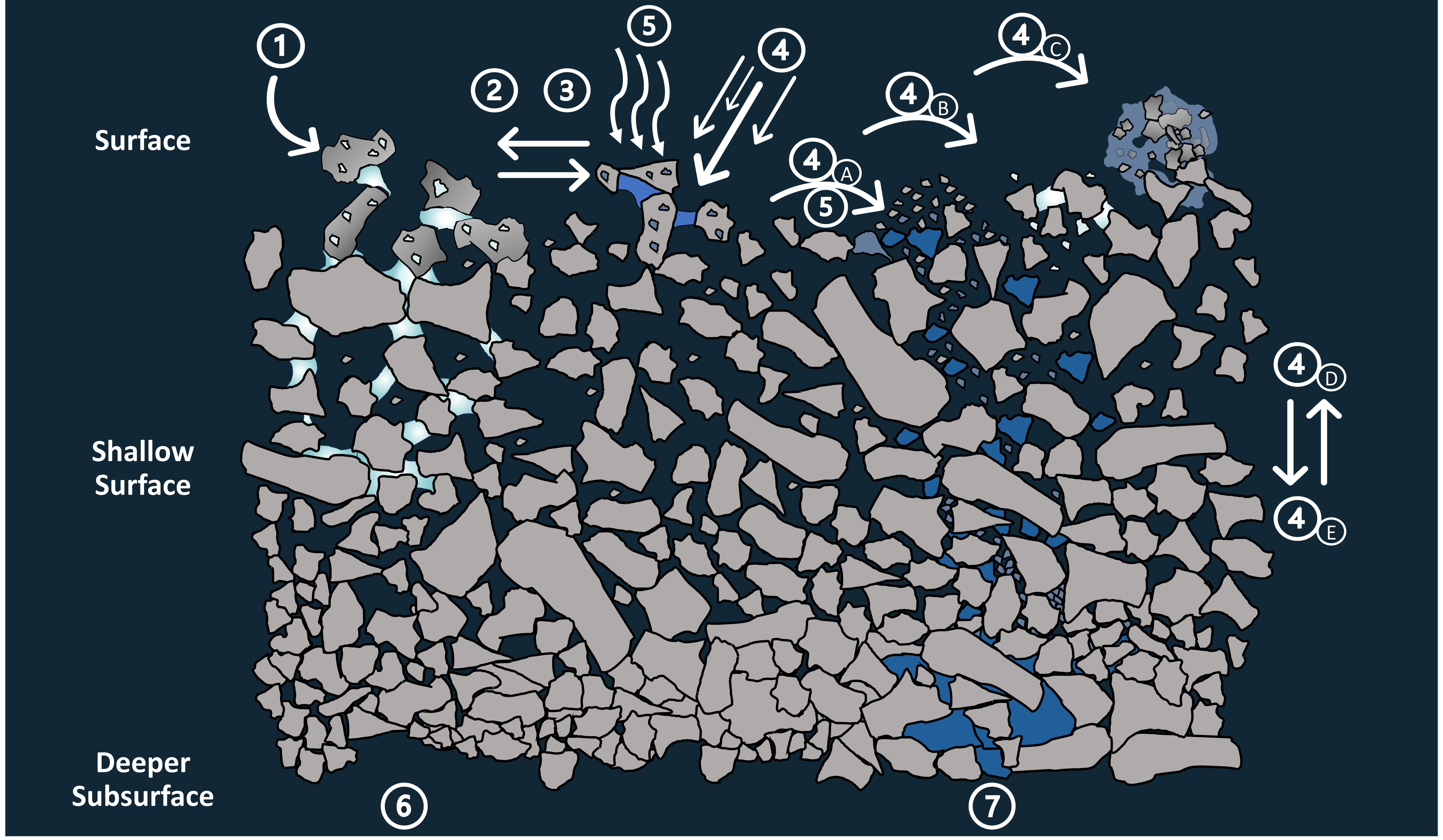
Background

- Water-ice (H_2O) has been observed in lunar Persistently Shadowed Regions (PSRs).[1,2]
- Interests to utilize these frozen deposits[3] require knowledge of its lateral and vertical distribution, which limited resolution.[4,5,6]
- Several space weathering processes within PSRs are proposed in the literature, which may influence the formation and geological evolution of ice on the Moon, and have significant implications for *In-Situ* Resource Utilization activities like excavation or extraction.
- For lunar PSR conditions, the microstructure of ice or its presence as crystalline or amorphous polymorphs may result in mechanical strengths varying by several orders of magnitude[7,8,9], its bulk density varying from 0.12 to 1.06 g/cm^3 [10,11] and its vapor pressure or thermal conductivity varying up to 2 to 6 times, sublimating at lower temperatures[12,13,14]

Conceptual model of ice formation and weathering processes on the Moon



Polymorphic Water-Ice

- **Amorphous Solid Water (ASW)** forms via vapor-deposition below 140 K[12] can be highly microporous, annealing above 90K [11]
- **Cubic Crystalline ice (I_c)** forms via vapor-deposition above 130[15] and coexists with/anneals to **hexagonal crystalline ice (I_h)** as **Stacking Disordered ice (I_{SD})** between 160 to 240 K[16,17]
- **Orthorhombic crystalline ice (I_{XI})** is a metastable proton-ordered equilibrium structure of I_h and may be ferroelectric, which may effect behavior of icy-dust[18,19]
- **Medium Density Amorphous ice (MDA)** is a highly sheared glassy polymorph of I_h [10]

Morphology of icy lunar regolith

- A variety of physical textures are proposed to describe the morphology of icy lunar regolith[20,21,22,23] - to better explain these morphologies we describe processes that may occur in lunar PSRs to produce these textures.
- Initial ice deposition will be **discontinuous** across a grains' surface as ice nucleation will occur in small defects or regions of inward curvature where there is both a thermal and Gibbs free-energy advantage[24]
- Existing ice acts a preferential sites for subsequent growth forming **continuous rinds** across a grains' surface which grow outwards to connect nearby grains forming **ice-necks** or forming larger segregated **massive** lenses[24]
- Micrometeorites serve an ambivalent role in production and destruction of lunar cryogenic sedimentary fabrics
  - Existing ice deposits are fragmented into fine-grained angular debris (**unfused granular ice**)[25]
  - Burial and compaction of ice will lithify to **pressure-sintered granular ice** or **breccia** depending on grain size[23]
  - Vaporized ice and rock may redeposit as **iceglutinates,** or conversely lead to excessive sublimation and loss

Conclusion

Multiple complex processes influence the formation and evolution of lunar ice. We find temperature primarily controls which processes occur and to what extent. *In-situ* observation of ice in PSRs is required to validate hypothesed processes.

Space Weathering

1. **Vapor deposition** of ASW on cold trap (<110K) surfaces[26,27] as continuous or discontinuous ice rinds as ice-necks
2. **Thermal crystallization** of ASW → I_c or I_h above approximately 120 K[15]
3. **Irradiation amorphization** of I_c or I_h → ASW below approximately 70 K[28,29]
4. **Meteorite Impacts**
   A. **Comminution** of existing ice into smaller, angular discrete fragments[25].
   B. **Physical amorphization** of I_c or I_h → MDA below approximately 80 K [10]
   C. **Iceglutinate formation** via vaporized and re-deposited H_2O – similar to glass-welded agglutinate formation [23,30]
   D. **Burial and compaction** under ejecta
   E. **Upheaval** and increase of porosity
5. **Dielectric breakdown** of ice and regolith to finer-grained material with elevated porosity ('fairy castle structure') and reduced albedo [31,32]
6. **Subsurface diffusion** along water vapor density gradients via thermal pumps oscillating between 100 to 120 K[33] - limited to diurnal skin depths of less than 1 m[34] and temperatures above 100 K[35]
7. **Lithification** of ice via diffusion (sintering) and recrystallization (dislocation creep) at temperatures above 80K.[23,36,37] Ice may crystallize at depth due to elevated temperatures with geotherm

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