WATER ACTIVITY OF PREMELTED FILMS IN HIGH LATITUDE MARTIAN GROUND ICE.

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Introduction & motivation:

Shallowly buried ground ice is nearly ubiquitous on Mars at high latitudes poleward of ~50° in both hemispheres. In the current climate, this ice is perennially cold, e.g., ~190 K on annual average at ~70° N. Despite low temperatures, thin "premelted" films of unfrozen water can exist in the shallow subsurface due to interfacial and Gibbs-Thomson pre-melting at soil-ice interfaces [1]. The presence of salts can further depress the freezing point, increasing the volume of unfrozen pore water [1, 2]. There has been long-term interest in ground ice as a potential microbial habitat on Mars [3], supported in part by the occurrence of viable bacteria in liquid vein networks of Antarctic glacial ice [4].

The chemical availability of liquid water for biological processes can be expressed in terms of its activity (a_{H2O}). Most terrestrial organisms cannot grow in solutions with $a_{H2O} < 0.9$; a few extremophiles can tolerate $a_{H2O} = 0.75$-0.85, and a single fungus has been shown to tolerate $a_{H2O} = 0.61$ [5]. For solutions in contact with ice, a_{H2O} is a simple function of temperature (see below). Here, we have employed numerical simulations of subsurface temperature and unfrozen water content to calculate water activity in thin films in ice-cemented ground on Mars and constrain their habitability over the past 10 Ma.

Water activity calculation:

Water activity is defined as the equilibrium fugacity of water vapor over a solution relative to the fugacity of water vapor over pure water. At low pressures, fugacities are well approximated by partial vapor pressures [6]. Thus, the water activity of ice and liquid solutions in equilibrium with ice can be calculated as:

$$a_{H_2O} = \frac{p_{sat,ice}}{p_{sat,liq}}$$

where $p_{sat,ice}$ is the saturation vapor pressure over ice and $p_{sat,liq}$ is the saturation vapor pressure over liquid water at standard conditions [5], both known functions of temperature [7, 8]. We used the Murphy & Koop [8] formulation.

Numerical models and parameter space:

We used the set of numerical models employed by Sizemore et al. [1] in their investigation of martian frost heave to simultaneously calculate temperature, T, unfrozen volume fraction, $S_l = 1\text{-}S_i$, and a_{H2O} in the upper meter of ice-cemented ground poleward of 55° N. Below, we briefly describe these models, their major assumptions, inputs and outputs.

Climate model. We use the climate model described by Zent [3] to simulate the evolution of temperature and ice-table depth, z_i, at latitudes north of 55° over the past 10 Ma. The model tracks temperatures in the upper 30 m of regolith based on Laskar et al. [9] orbits, and defines z_i assuming diffusive equilibrium with the atmosphere. Because atmospheric water vapor density at high latitude is buffered by the polar cap, ice-table depths and ice temperatures predicted by the model are very sensitive to assumptions about the fate of the residual cap at high obliquity. We assume that the cap remains a source of H_2O vapor at all times. We use results from the Ames GCM to guide our assumptions about meridional vapor transport. Temperature profiles and ice-table depths produced by the climate model provide the initial and boundary conditions for the thin film model.

Thin film model. We use the thin film model described by Sizemore et al. [1] to track temperatures and phase partitioning in a soil that is fully ice and water saturated. The premelting physics employed in this model is based on mass and energy conservation equations developed by Rempel [10] and modified for martian conditions [1]. For computational simplicity, the soil-water-ice system is assumed to be gas and solute free in the majority of our simulations.

Soil parametrization. We define the thermal conductivity and heat capacity of soils in both numerical models based on published values for silt and clay minerals [11, 12] and analysis of the soil at the Phoenix landing site [13]. In the thin film model, we define additional soil characteristics using four empirical parameters, two of which are relevant to the current discussion:

1) $\Delta T_f = T_m - T_f$ is the freezing point depression caused by inter-molecular forces at grain-water boundaries;

2) β describes ice saturation as a function of temperature ($S_i = 1 - \theta^{\beta}$, where $\Theta = \frac{T_m - T}{\Delta T_f}$).

We focused our numerical experiments on three soils, Chena Silt, Inuvik Clay and Tomokomai Clay, with the goal of spanning the parameter space of freezing properties in heave-susceptible materials on Earth [1,14]. Additionally, we use β corresponding to Chena Silt as a best solute-free approximation of soil at the Phoenix landing site. We use a parametric expression for $S_i(\theta)$ that combines empirical soil freezing data and

FREZCHEM liquidus curves to estimate the effects of perchlorate salts on film volume in the Phoenix soil [1].

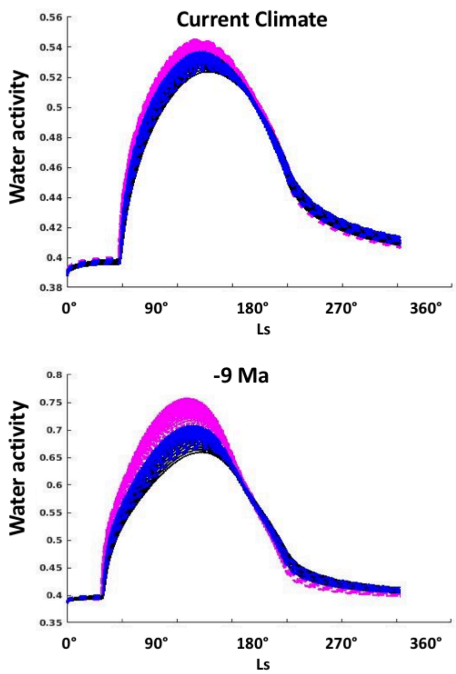

Fig. 1. Seasonal variation in a_{H2O} for three soils (pink, Chena silt; blue, Tomokomai clay, black, Inuvik clay) for the current climate at 70° N (a, top) and model climate conditions at 9 Ma (b, bottom). For each soil, a_{H2O} values are plotted at 10 depths ranging from the ice table to ~1 m below the surface.

Results and discussion:

Our simulations indicate that unfrozen water in martian ground ice rarely meets minimum thresholds for habitability by terrestrial organisms. In the current climate, a_{H2O} ranges from 0.39 to 0.54 seasonally at the Phoenix landing site in the upper ~1 m of ice (Fig. 1a). Toner et al. [15] previously suggested that a_{H2O} might exceed the 0.61 (T=220.65 K) threshold for ~100 sols seasonally at the Phoenix site; however, their calculations were based on surface temperature measurements. Due to the low thermal conductivity of the ~4 cm of dry soil overlying the ice, the ice and thin films themselves never experience temperatures at or above 220.65 K in the current climate.

The thermal and mechanical properties of the dry overburden have competing effects in terms of the habitability of the underlying ice. At a given temperature, a fine-grained soil (e.g., clay) will retain a larger volume fraction of unfrozen water than a more coarse-grained soil (silt, sand). However, under equivalent climate conditions, a fine-grained soil (low thermal inertia) will be colder on average and host thermally stable ice at shallower depth than a coarse-grained soil (high thermal inertia). Thus, our simulations indicate that – for salt-free systems -- the highest water activities occur in the soils with the lowest unfrozen water fraction and vice versa; a catch-22 for potential martian organisms. In our model, the addition of perchlorates can substantially increase the film volume in silt (but not clays), without changing a_{H2O}. Laboratory validation of our parameterization of S_l for salty systems is in the early stages [2].

Over the past 10 Ma, we do find orbital conditions under which mid-summer values of a_{H2O} exceed the 0.61 threshold for all soils, and even reach the 0.75 threshold at shallow depths in silts. Fig. 1b shows an example at 9 Ma. Notably, most of these "habitable" periods occur at or before 4 Ma, a timeframe in which there are major uncertainties in the atmospheric vapor density boundary condition, the orbital configuration, and the occurrence of precipitation. Episodes of habitability are also brief and rare – persisting for 100-200 sols/year during isolated ~10^5 year windows.

Our results indicate that the most realistic soil scenario for the Phoenix landing site – a silt with 0.5-1 wt. % perchlorate doping – is also the most likely to be habitable in terms of both water activity and film volume during windows of opportunity. The presence of perchlorate at the Phoenix site also offers the advantage of protecting cells from ice crystal damage during low-temperature periods [15]. However, substantial laboratory work remains to be done to understand the volume, ion concentration, viscosity, etc. of perchlorate brines at martian temperatures, in both icy and ice-free settings [2, 6].

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