LIQUID VEIN NETWORKS AS HABITATS IN MARTIAN & ANTARCTIC ICE-CEMENTED GROUND.

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Introduction: The search for life in the Solar System is a major driver of Mars science. In this context there has been a particular focus on water, and by extension, ground ice, which constitutes a major reservoir of H_2O accessible to spacecraft. Analog studies of ground ice and overlying sediments in the Antarctic Dry Valleys of Earth are commonly used to place constraints on the potential habitability of Martian ground ice, despite the ~50° C average temperature difference between these two environments. Here, we build on recent work by [1] to model the freezing behavior of example "Martian" and "Antarctic" soils and characterize residual liquid vein networks as microbial habitats in both locations.

Background: Jakosky et al. [2] and Zent [3] carried out theoretical studies evaluating the habitability of Martian ground ice. Both studies explicitly assumed that habitability was contingent on the presence of a network of liquid films or veins in the ice-soil matrix at temperatures well below bulk freezing. Both studies shared the implicit assumption that the volume and *connectedness* of liquid vein networks were potentially limiting for microbial survival. The liquid vein network must be well connected to allow transport of nutrients and wastes; maximum vein diameter should also exceed the size of approximately micron-scale cellular organisms.

Methods: Theoretical understanding of soil freezing has progressed significantly in the past ~15 years. There have been corresponding advances in Mars climate and ice stability models [e.g., 4].

Monte Carlo simulations of soil freezing. Soil freezing curves (SFCs) describe the residual liquid fraction, S_l, in the pores of H_2O-saturated soil at temperatures below 0° C. We have combined laboratory data and numerical simulations of soil freezing to produce best-approximation SFCs for soils with the grain size distribution and porosity observed at the Phoenix landing site and in Beacon Valley, Antarctica. Our methods build on the combined empirical-algebraic approach of [5], the Monte Carlo modeling techniques of [6], and the laboratory NMR measurements of [7]. We developed synthetic soil packing geometries based on in situ microscopic imaging of the Phoenix soil [8] and laboratory characterization of Beacon Valley soil samples [9]. We applied the Monte Carlo model of [6] to build SFCs for these two soils with and without salt doping. We considered two salt species, NaCl and $Mg(ClO_4)_2$, as endmember examples of salts that weakly and strongly reduce the freezing temperature, respectively. NaCl is present in Beacon Valley soils; both species occur on Mars. We also used Monte Carlo freezing models to calculate the dependence of maximum liquid vein diameter (refugia diameter, d_r) on pore liquid fraction for each soil.

Dynamic simulations of permafrost liquid fraction. We combined the dynamic frost heave model of [5] with the improved historical ice-stability model of [1,4] and the newly developed Phoenix and Beacon SFCs to self-consistently model four habitability parameters in ice-rich permafrost: temperature, *T*, water activity, a_{H2O}, pore-space liquid fraction, S_l, and maximum liquid vein diameter, d_r. We modeled summertime diurnal variability of all parameters under recent climate conditions identified as favorable to life [1].

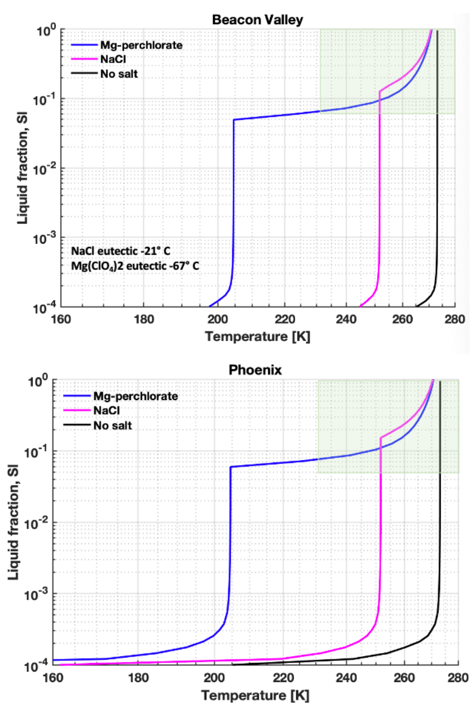

Fig. 1. SFCs for Beacon Valley and Phoenix soils. Green box indicates the Mellon et al. 2024 "extreme metabolic limit" temperature threshold of -40° C.

Results:

Soil freezing curves and liquid vein diameter. Fig. 1 shows the "Phoenix" (sandy silt) and "Beacon" (sand) SFCs developed for the NaCl, $Mg(ClO_4)_2$, and salt-free cases. The Beacon and Phoenix SFCs are broadly similar with minor differences arising from the Phoenix soil's broader grain-size distribution and larger fine-fraction. For both soils above the eutectic, the addition of salts shifts the freezing curve to substantially lower temperatures. Below the eutectic, the curves revert to approximately the salt-free case and liquid availability is negligible. The key difference in the model SFCs for Martian applications arises from the difference in the eutectic temperatures of the selected salts.

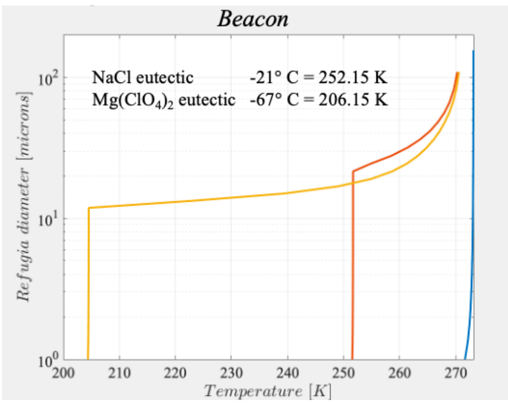

Fig. 2. $d_r(T)$ in "Beacon" for no-salt (blue), NaCl (red), $Mg(ClO_4)_2$ (orange). Phoenix results are similar.

Fig. 2 shows maximum liquid vein diameter, d_r, as a function of temperature in the Beacon soil. For a given temperature above the eutectic, both salts increase the total liquid fraction and the maximum vein diameter in both soils substantially; below the eutectic maximum vein diameter drops to < 1 micron regardless of soil particle geometry, precluding the complete immersion of micron-scale cells. For salt-free scenarios, this limit occurs at $T > 270$ K. For salty scenarios and temperatures above the eutectic, both soil geometries produce maximum vein diameters of several to 10s of microns, more than adequate to immerse cells.

Dynamic simulations of T, a_{H2O}, S_l, d_r. We employed our combined climate and liquid fraction model to calculate maximum values of all four habitability conditions (T, a_w, S_l, and d_r) over 2.5 Ma of Mars climate history and latitudes from 30°-70°N. We used the thin film model to predict summertime diurnal variability of all parameters under recent climate conditions previously identified as favorable to life (i.e., 70° N, 630 ka before present, obliquity = 34.7°, see Mellon et al. 2024) and under present-day climate conditions at the same latitude, which are generally considered unfavorable to life. In these diurnal simulations we investigated salt-free and 1 dry wt. % magnesium perchlorate doping scenarios for both soil types (Fig. 3).

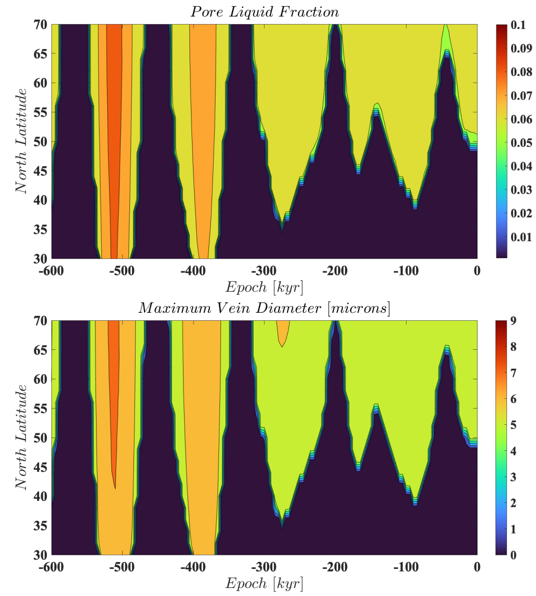

Fig.3. Maximum values of S_l (top) and d_r (bottom) in the Phoenix soil with 1 dry wt. % $Mg(ClO_4)_2$ over the past 600 thousand Martian years poleward of 30°N. Note that habitability criteria are met repeatedly during this time period due to high-obliquity excursions; earlier, higher obliquity excursions produced higher values of S_l and d_r for longer time periods.

We also calculated a_w, S_l, and d_r for ice-cemented ground in University Valley, Antarctica directly from ice temperature data measured over a full seasonal cycle by Marinova et al. (2022). The Dry Valleys of Antarctica have been studied extensively as analogs to the Martian northern plains, due to the presence of dry permafrost (ground that never warms above 0 °C and has negligible ice content) occurring above ice-cemented soil. University Valley and adjoined Beacon Valley have received particular attention, as their high-elevation, inland location produces the coldest and driest Antarctic conditions most analogous to Mars (e.g., McKay et al., 1998; Kounaves, et al., 2010; Tamppari, et al., 2012; Marinova et al., 2013; 2022). University Valley is a small hanging valley adjacent to the larger, and nominally lower-elevation Beacon Valley. The Antarctic soil samples on which we based our Monte Carlo soil-freezing simulations were collected in Beacon Valley (Sizemore & Mellon, 2008), but are also typical of University Valley soils and the unconsolidated soils of the Dry Valleys region more generally. As such, we refer to the soil freezing curves generated from the Beacon samples as "Antarctic" or "Beacon" SFCs, interchangeably. In calculating habitability parameters for an Antarctic environment, we specifically used environmental data from University Valley as representative of "Antarctic" climate conditions. We intentionally neglected lower altitude, more coastal valleys in which temperatures can seasonally exceed 0 °C, bulk melting periodically occurs, and temperature is not a dominant restriction for life. We applied only the Beacon SFCs and refugia data to our investigation of the Antarctic environment. We considered salt-free, NaCl-doped, and $Mg(ClO_4)_2$-doped cases, to capture endmember and intermediate behavior. Many other soluble salts are common in the Dry Valleys and on Mars (e.g., chlorides and nitrates).

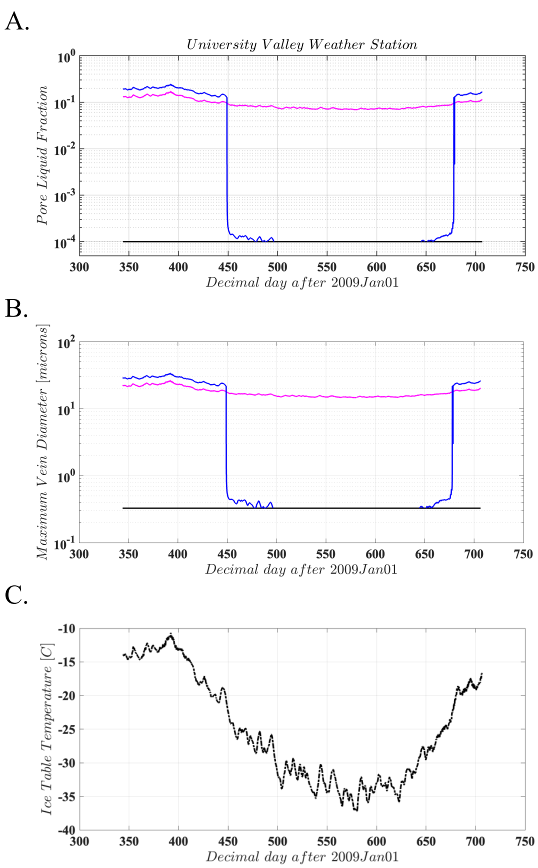

Fig. 4 S_l (a) and d_r (b) at the ice table in University Valley calculated for the Beacon Valley soil with no salt (black), 1 dry wt. % NaCl (blue), and 1 dry wt. % $Mg(ClO_4)_2$ (cyan), based on one seasonal cycle of temperatures measured in situ (c). Note that the salt-free scenario never meets either habitability criterion (S_l > 5%, d_r > 1 μm), despite temperatures that perennially exceed the extreme metabolic limit defined by Mellon et al. (2024), -40 °C.

Summary & Conclusions:

We have found that:

Environmentally available solutes are likely to be the dominant factor controlling low-temperature liquid availability in the icy permafrost of Mars and in the highest altitude Antarctic Dry Valleys where ground ice does not experience excursions above the bulk melting temperature 0 °C.

Soil geometry (particle and pore-size distributions) play a secondary but still important role in determining whether S_l and d_r meet habitability thresholds under a given set of environmental conditions. The synthetic soil packings we built are applicable to both the Antarctic and Martian environments, despite their basis in *in situ* data from different planetary settings.

Without salts, neither of the examined soil geometries produce habitable values of S_l or d_r below ~-3 °C based on pore-confinement effects alone. The addition of 1 dry wt. % NaCl extends the occurrence of habitable values of S_l and d_r to the eutectic temperature of -21 °C; the addition of 1 dry wt. % $Mg(ClO_4)_2$ extends the occurrence of habitable values of S_l and d_r to the magnesium perchlorate eutectic temperature of -64 °C, well below the previously defined extreme metabolic limit of T = -40 °C. This finding leads us to conclude that meeting the requirement of d_r > 1 μm and S_l > 5% is surprisingly easy for silty to sandy soils with plausible salt doping in the Martian and Antarctic environments.

In the University Valley environment, localized solute deficits may preclude habitable S_l and d_r even in the "warm" austral summer when conventional T and a_w thresholds for metabolism are met. However, we generally expect available chlorides and nitrates to produce habitable values of T, a_w, S_l, and d_r simultaneously in the summer months in University Valley. On Mars, local deficits in perchlorate and nitrate concentrations may prevent S_l and d_r from reaching habitable values even under idealized summertime, high obliquity conditions, but in general, we expect abundant perchlorates in the unconsolidated regolith to produce habitable values of S_l and d_r below T and a_w habitability thresholds. Thus, there is an Antarctic scenario in which S_l is the most restrictive habitability criterion (i.e., lack of residual water precludes habitability at warm temperatures), and a Martian scenario in which T, but not S_l or d_r, is the most restrictive criterion (i.e., extreme cold precludes habitability despite the existence of a well-connected liquid vein network).

For a Phoenix-like soil containing 1 dry wt. % magnesium perchlorate on Mars, high-obliquity "relatively-clement" periods can produce summertime S_l > 5% and d_r > 1 μm for periods of 10s of kyrs repeatedly over the past 2.5 Ma for all latitudes poleward of 30°N (e.g., Fig. 7). These periods of habitable conditions last longer and both parameters achieve higher values at higher latitudes. Furthermore, our simulations show that for Phoenix-like soils poleward of 50°N, 1 wt. % $Mg(ClO_4)_2$ produces S_l ~ 6 % and d_r > 5 μm *in the current climate*, whereas ground ice itself is predicted to be currently stable poleward of ~47°N (Mellon et al., 2024). However, the coarser-grained Beacon soil with magnesium perchlorate doping does not meet habitability thresholds for both parameters in the current Martian climate, indicating that the independent effects of grain-size distribution on pore confinement and thermal inertia can locally or regionally tip the balance for liquid availability and habitability. In our simulations of Martian permafrost with magnesium perchlorate, S_l and d_r were never the dominant limitations to habitability. This result raises the possibility that temperature thresholds for life based on terrestrial organisms in terrestrial environments should be considered more holistically for Mars.

In University Valley, Antarctica, a deficit of perchlorates relative to Mars likely restricts habitable S_l and d_r to the summer months, when temperatures are above the eutectic of NaCl and other chlorides. Observed vertical and regional variation in the concentrations of soluble ion species raises the possibility that ice in some parts of University Valley never reaches habitability thresholds despite warm temperatures due to local, extremely low concentrations of a wide range of salt species. Thus, solute availability may be the dominant habitability restriction in "warm" Antarctic Dry Valley conditions. New surveys of soluble ion concentrations in University and Beacon Valleys, as well as targeted development of SFCs for specific Dry Valley weather-station and bore-hole locations could substantially expand our understanding of temporal and spatial variability of conditions supporting metabolism.

Our simulations provide landing site selection guidance for a Mars life-detection mission broadly similar to Mellon et al. (2024). We recommend landing sites poleward of 49°N, which provide confidence in access to ice that has periodically experienced "habitable" conditions as defined by all four parameters (T, a_w, S_l, and d_r). Equatorward of 47° - 49° N, there is risk of failing to encounter ice. Poleward of 49° N, higher-latitude landing sites offer progressively greater opportunities to compare ice across stratigraphic layers defined by distinct ages and habitability histories. Between ~47° and 50° N ice is too deep to have met the extreme metabolic limit of T = -40 °C in the past few Myr; additionally, d_r and S_l do not reach "habitable" values during current summertime conditions. Between 50° and 59° N ice has periodically met all four habitability thresholds, but the soil column has also been periodically desiccated to depths of 1-2 m in the last several hundred thousand years. Poleward of 59° ice has been continuously present in the upper 1-2 meter and younger, shallower ice has been periodically habitable. Poleward of 61° ice has been continuously present for Myr and some of this ancient ice has also met all four habitability criteria (T, a_w, S_l, and d_r). Everywhere poleward of 50° N 1 wt. % $Mg(ClO_4)_2$ can produce S_l > 5 % and d_r > 1 μm in a Phoenix-like soil under current summer-time conditions. Landing sites poleward of 61° N offer the best opportunities to sample and compare ice of different ages and distinct habitability histories.

Our results also indicate that massive ice is a less desirable target than pore-filling ice at all latitudes. Absent confinement effects of the soil pore space, clean low-temperature ice will have a lower liquid fraction, lower permeability, and lower effective diffusion coefficients for ion transport than adjacent soil-ice mixtures, restricting S_l and d_r, and thus habitability.

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References: [1] Mellon et al., *Icarus, 408*, 2024; [2] Jakosky et al., *Astrobiology, 3,* 2003; [3] Zent, *Icarus, 196,* 2008; [4] Mellon & Sizemore, *Icarus, 371,* 2022; [5] Sizemore et al., *Icarus, 251,* 2015; [6] Chen et al., *J. Advs. In Modeling Earth Sys.,12,* 2020; [7] Lei et al., *Cold Reg. Sci. & Tech., 199,* 2022; [8] Pike et al., *Geophys. Res. Let., 38,* 2011; [9] Sizemore & Mellon, *Icarus, 197,* 2008; [10] Laskar et al., *Icarus, 170,* 2004.