ICE LENS FORMATION AND UNFROZEN WATER AT THE PHOENIX LANDING SITE.
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Introduction: Excess ground ice, or ice that exceeds the pore voume of its host soil, has been observed at several locations on Mars. Data from the Mars Odyssey Gamma Ray Spectrometer (GRS) indicates that ice occupies >90% of the regolith by volume over large regions of the high latitudes (>50°) in both hemispheres [1]. Thermal and optical observations of fresh impact craters also indicate the presence of relatively pure sub-surface ice at mid-latitudes [2]. At the Phoenix landing site (68° N), trenching activies primarily revealed ice that was pore-filling. However, excess ice (98-99% water by volume) was found in the Dodo/Goldilocks trench complex [3].

The origin of excess ice at its various locations is not well understood. Excess ice cannot be cold-trapped from atmospheric water vapor. Its presence implies either bulk deposition or *in situ* segregation of pre-existing pore ice. Mellon et al. [3] examined the properties of the Dodo/Goldilocks ice and discussed evidence supporting several formation hypotheses. They concluded that *in situ* segregation was the most likely formation mechanism at that location. The possibility of *in situ* ice segregation on Mars is of major interest from both a physical and an astrobiological stand point. Here, we employ numerical simulations of climate and soil-ice interactions to place quantitative constraints on the growth of segregated ice lenses at the Phoenix landing site.

Numerical Models:

Climate model. We use the climate model described by Zent [4] to simulate the evolution of temperature and ice-table depth, z_i, at the Phoenix landing site over the past 10 Ma. The model tracks temperatures in the upper 30 m of regolith based on Laskar et al. [5] orbits, and defines z_i assuming diffusive equilibrium with the atmosphere. Because atmospheric water vapor density at the Phoenix landing site 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 use results from the Ames GCM to guide our assumptions about the cap. Temperature profiles and ice-table depths produced by the climate model provide the initial conditions for simulating ice segregation.

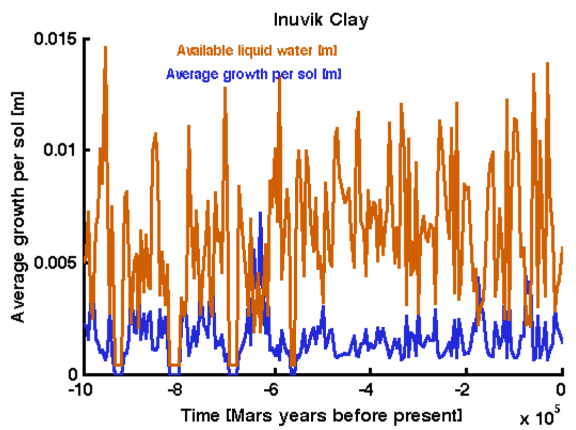

Figure 1. Comparison of calculated mid-summer lens-growth rates to available mobile water in the overlying soil column during the past 1 Ma.

Lens initiation and growth model. Water remains only partially frozen in a porous medium at temperatures below 0°C owing to two effects: the depression of the freezing temperature at curved phase boundaries and interfacial premelting caused by long-range intermolecular forces [6]. The latter effect can produce strong repulsive forces between pore ice and soil grains across premelted films. At any horizon in the soil, the resultant net thermomolecular force must be balanced by gravity and by the effective overburden pressure. When the net thermomolecular force becomes large, soil grains can separate and water can flow through thin films to form a lens or lenses of pure ice.

We have developed a numerical model that applies empirical parameters to track phase partitioning in soil pores and uses pre-melting physics to test for conditions under which ice lenses could initiate on Mars. The model distinguishes between initiation of an ice lens and the subsequent growth of the lens, which is directly limited by the rate of unfrozen H_2O migration. We rigorously test for lens initiation, and make order-of-magnitude estimates of subsequent lens-growth rates. Throughout, we assume that the soil-ice-water system below the ice table is solute free.

We have focused our lens-initiation simulations on the Martian mid-summer (L_s = 90°), when ice temperatures and unfrozen water fraction are at their maximum. A typical simulation runs 3-4 sols, and tests for lens initiation on the second sol. After lens initiation, we track lens growth-rate continuously, but we do not include the effects of advected heat in the subsequent thermal evolution of the subsurface. We calculate an average growth rate over the course of the simulation, which then represents the expected peak growth rate for a given set of orbital elements.

Soil paramartization. We define the thermal conductivity and heat capacity of soils in both numerical models based on analysis of the soil at the Phoenix landing site [7]. In the lens initiation model, we define additional soil characteristics using four empirical parameters, which can be measured in Mars-analog soils:

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

2) k_o is the ice-free soil permeability;

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

4) and α describes the reduction of permeability with reduced temperature ($k = k_o \theta^{-\alpha}$).

Andersland and Ladanyi [8] compiled measurements of these parameters in many soils. We have focused on two of these soils, Chena Silt and Inuvik Clay (*c.f.* [4]).

Results and Discussion: To date, our simulations have produced three primary results: 1) Lens initiation – the unloading of particle-particle contacts by thermomolecular forces at a given soil horizon – may be a common process in the shallow Martian regolith. It is ubiquitous in our simulations and occurs at depths ranging from a few to 20 cm, at temperatures as low as 245 K. 2) In at least one soil, Inuvik Clay, macroscopic lens growth (mm/sol) is possible at the Phoenix landing site in the past 10^4 years (Fig. 1). However, growth rates calculated for Chena Silt are vanishingly small throughout the past 1 Ma. 3) If and when they grow, Martian ice lenses have a distinct geometry from their terrestrial counterparts. On Earth, growing lenses draw liquid water upward from underlying pore spaces. In our simulations, growing lenses draw unfrozen water downward from pore spaces closer to the ice table and the ground surface.

Other considerations: Salts, lens re-activation, extrapolating empirical data. Taken together, our results broadly support the interpretation of excess ice in the Dodo/Goldilocks trench as a segregated ice body produced by thermal cycling in the geologically recent past. Notably, we can produce mm-scale lenses in the past 10^4 years without invoking the effects of salts.

Interfacial premelting is extremely sensitive to the presence of impurities. Effects of salts on lens growth are not straight forward; the presence of solutes would allow larger volumes of mobile water to persist at low temperature than we observe in the current salt-free simulations (Fig. 2). However, electrolyte solutions are non-ideal and become less ideal as temperature decreases. In the presense of salts, lenses might initiate sooner, but grow more slowly due to higher viscosities in the mobile brines. These effects are likely larger in coarse-grained soils than in fine-grained soils. Thus the inclusion of perchlorates (observed at the Phoenix site) might bring the results of our Chena Silt simulations more closely in line with the Inuvik Clay results.

More speculatively, our results may have relevance to the excess ice observed throughout the high latitude regions of Mars by GRS. Once initiated, a martian proto-lens might continue its incremental growth from year to year, and slow, multi-annual accumulation of segregated ice might change the character of extended regions of ground ice.

Our results and interpretation should be viewed with caution, however, because they hinge on the extrapolation of empirical soil-freezing data to Martian temperatures. Targeted laboratory studies of soil freezing are needed to improve the theoretical understanding of *in situ* ice segregation processes on Mars.

References:

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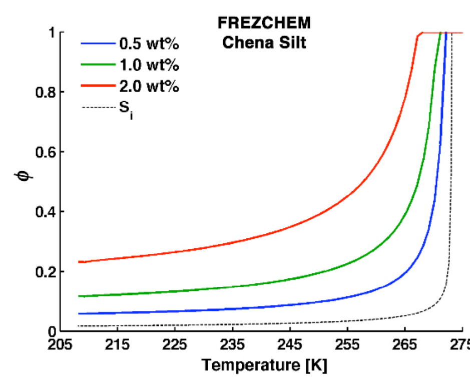

Figure 2. Effects of perchlorate on liquid fraction, ϕ, with temperature.