Diffusive Growth and Retreat of Ground Ice on Mars.
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Introduction: Recent experimental and theoretical work on near-surface diffusion in current martian conditions shows that communication with the atmophere is sufficiently fast for many possible soils that an ice table is expected to respond quickly to climate cycles and reach its equilibrium position [1, 2]. In addition to diffusive loss and retreat, it is possible for a modern ice table below its equilibrium to advance upwards using atmospherically derived water vapor. Two complimentary experiments to investigate these processes are described and implications of the results to the understanding of ground ice on Mars are presented.

Ice Loss Experiments: Recent work has been done to determine diffusion coefficients, *D*, under Mars like surface conditions. The theoretical basis, experimental setup and methods, sample characteristics, and some experimental data are reported in [1]. These and some additional data are summarized in Figure 1. Note that most simulants cluster between 3–6 $cm^2\ s^{-1}$, notable exceptions being packed dust (1–3 µm particles), dust and glass bead (40–70 µm) mixtures, and salt crusts.

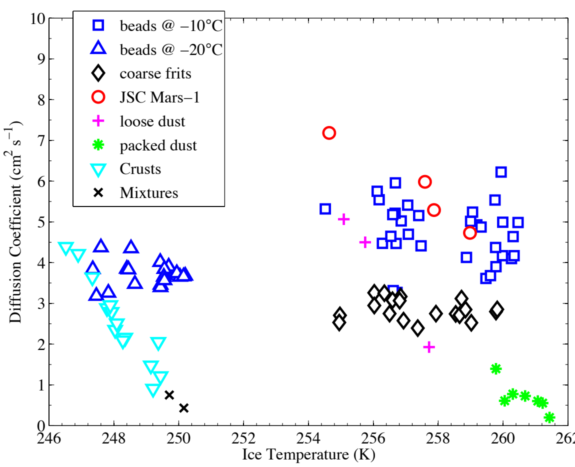

Figure 1. Diffusion coefficients measured for 8 different simulants types. Simulants are homogeneous except for $MgSO_4$ salt crusts and mixtures of glass beads and dust.

Mechanically packed dust data (✱) consistently fall below other homogeneous simulants. For mixtures (✕), the lower point is a simulant composed of glass beads and enough packed dust to fill the pore spaces between them. The upper point is a mixture with 10% as much dust. Crust data (▽) are glass beads mixed with $MgSO_4$, a salt shown to exist in the Mars regolith [3]. Salt content is negatively correlated with diffusion coefficient and varies from 0.5% to 2.5% by weight.

Subsurface Ice Retreat: The diffusivity of regolith overlying buried ice is a first-order control on the rate of subsurface ice migration. In extreme cases, low diffusivity barriers could act to protect buried ice from being lost during periods of dry climate as suggested by [4] and others. The experiments described above and in [1] suggest that a variety of unconsolidated media of varying particle size, shape, and mineralogy give very similar values of *D* in a range conducive to rapid adjustment of subsurface ice to changing equilibrium depths. Invoking a significant reduction of *D* to preserve ground ice requires specification of the processes forming the barrier (e.g. compaction of dust, emplacement of salts) in the context of other observations.

Ice Accumulation Experiments: A Mars-environment chamber in the Caltech Icelab simulates conditions under which water vapor on Mars would fill regolith pore spaces. To ensure Fickian diffusion and reduce experiment duration, a coarse sand (200-500 µm) with large pore cross sections is used.

Experimental procedure. A Neslab recirculating chiller maintains a cold plate in the chamber at 183 K. The plate is in conductive contact with the base of a soil column and is otherwise insulated to prevent condensation on exposed surfaces. An incandescent lamp mounted above the soil column uniformly heats the sample surface and allows the free flow of vapor. A PID controller modulates the duty cycle of the lamp to maintain a constant surface temperature (ideally 268 K), creating a linear temperature gradient between the ends of the column. Keeping temperatures below zero throughout prevents the occurrence of liquid water.

Temperature is monitored at regular depth intervals throughout the soil column and relative humidity and air temperature are logged at the sample surface. Dual inputs of CO_2 enter via Tylan mass flow controllers. One input is passed through a sparger and water bubbler to humidify the gas. This moist gas can then be mixed with dry CO_2 to create the desired chamber humidity. The current setup uses only the 'wet' CO_2 line, resulting in a relative humidity of 40-50%. Under such conditions, the saturation temperature where ice first forms is beneath the surface of the soil column.

After many hours the soil column is removed from the chamber and sliced into layers of ~ 0.7 cm thickness. Each layer is weighed on a precision balance, dried in an oven for 24 hours, and weighted again to determine gravimetric water content. At present we do not monitor ice content *in-situ*.

Experimental results. Initial experiments have successfully demonstrated substantial ice filling of pore spaces throughout the soil column via diffusion. The mass fraction achieved in tens of hours of exposure to a wet atmosphere varies up to nearly 30% by mass. Several experiments with temperature gradients in the range of 3–7 K/cm exhibit greater than 50% of pore space filled after 60 hours of exposure. By establishing gradients of up to 17 K/cm, similar experiments should exhibit greater degrees of filling, as per the quadratic dependence on temperature gradient (Equation 2), providing data on system behavior at high ice contents.

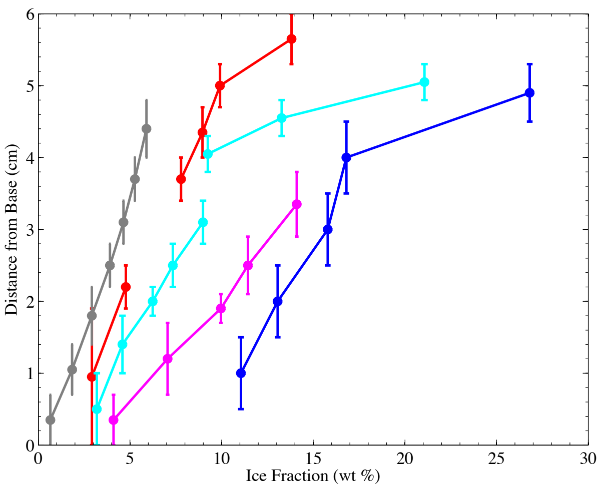

Figure 2. Ice content by mass in simulant columns for experiments of, from left to right, 12, 18, 42, 63, and 116 hours exposure to humid CO_2. The leftmost data are with 500 µm sand, all other data are for 40–70µm glass beads. Vertical lines through data points are thicknesses of analyzed layers; the uncertainty in water mass fraction is ~1-2%.

Subsurface Ice Growth: Neutron fluxes observed by Mars Odyseey indicate high water contents in the polar regions of mars. A two-layer model developed to explain the data results in an average water content poleward of 70°S of 55% by mass [5, 6]. If the pore spaces are ice filled, this is equivalent to 70–80% ice by volume for rock densities of 2–3 g cm^{-3}. Extremely vacuous near-surface terrestrial soils rarely reach 50% porous [7]. Thus the subsurface ice in these regions takes up more space than would be available in an unsupported soil. Two possible explanations are that relatively clean ice was emplaced at the surface during a favorable climate epoch and subsequently buried, or that it was derived from atmospheric moisture at conditions similar to present-day Mars.

Ice Growth Physics. The diffusive flux of ice in a porous soil is governed by the diffusion equation

$$\frac{\partial \sigma}{\partial t} = -\frac{\partial J}{\partial z} \approx D \frac{18}{RT} \frac{\partial^2 p}{\partial z^2}, \qquad (1)$$

where D is constant with depth, and where σ is the density of ice relative to total volume, J is the flux, z is depth, T is subsurface temperature, p is partial pressure of water vapor, and R is the universal gas constant. Using the Clausius-Clapeyron expression for vapor pressure, the pressure derivative becomes

$$\frac{\partial^2 p}{\partial z^2} \approx p\left(\frac{1}{T}\frac{\Delta T}{\Delta z}\right)^2 \frac{H}{RT}\left(\frac{H}{RT} - 2\right) \qquad (2)$$

for a linear temperature profile, where H is the latent heat of sublimation (H/R ≈ 6130 K). Initial filling of a dry soil proceeds rapidly. For example, with a 5 K/cm temperature gradient, air temperature T = 200K, 600 Pa pressure, and D = 3 cm^2/s [1], the rate of ice filling will be ~ 0.23 kg m^{-3} day^{-1}. A 50% porous soil can fill half of the available pore space in ~ 1000 days. As ice accumulates, the porosity ϕ will decrease, and with it the diffusion coefficient according to $D=(\phi/\tau)D_{12}$, where D_{12} is the free-gas diffusion coefficient ([1] and references therein), thereby reducing the rate of filling.

Ground Ice Observations: Observations of ground ice on Mars [5, 6] closely match theoretical predictions of ice distribution under the current climate, e.g. [5, 6, 8, 9]. This suggests rapid exchange between the atmosphere and regolith as supported by experiments [1] and that a shallow, sharp ice table exists at high latitudes. If experiments show that ice volumes greater than pore-filling can accumulate in the absence of a liquid phase, invoking climatic conditions significantly different from the present day to explain the observations is not necessary. If such quantities of ice cannot be emplaced via diffusion, the explanation may require direct deposition different climates coupled with diffusive restriction of vapor flux.

Terrestrial permafrost regions form lenses of pure ice through the action of seasonal melting and grain surface migration of water [10]. Annual temperature fluctuations could permit migration of water molecules via gaseous diffusion or quasi-liquid thin films and engender lens formation without a true liquid phase.

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