STABILITY OF SHALLOW BURIED ICE ON MARS. M.H. Hecht[1], J. W. Head[2]. [1]Jet Propulsion Laboratory, California Institute of Technology (michael.h.hecht@jpl.nasa.gov), [2]Brown University, Department of Geological Sciences, Providence RI 02912.

Background: One objective of the 2008 Phoenix Lander mission was to resolve a long-standing debate about the nature of the subsurface ice that underlies vast mid-latitude zones on Mars. One school of thought suggests that the icy deposits detected by the GRS suite [1] and predicted from stability arguments as early as 1966 [2] were simply the result of vapor diffusion from the atmosphere. This process would result in a relatively thin deposit constrained above by diurnal temperature fluctuations, and below by the geothermal gradient [3]. Another school of thought suggested the presence of a latitude-dependent mantle of bulk ice with some dust [4], deposited in previous climate extrema, and presumably similar in composition to the polar layer deposits (PLD). It was recently shown that the evolution of such a layer is consistent with the time scales of ice ages, and that the signature of such a process would be a thin layer of pore ice (on the order of a few centimeters) overlying a thick ice sheet [5]. Stability arguments alone do not discriminate these hypotheses.

Here we discuss experimental results from Phoenix and models inspired by those results in support of the latitude dependent mantle (LDM) hypothesis, demonstrating consistency between recent measurements of the vertical atmospheric water column, observations of mid-latitude ice, and a simple coupled surface-atmosphere water transport model.

Observational evidence from Phoenix: Direct observations of ice by Phoenix were ambiguous. The primary excavation sites were chosen within the boundaries of one of the polygons that typify the northern plains. Underlying a few centimeters of what was termed "dark soil" in the MER taxonomy [6] was a layer of permafrost that was clearly pore-filled, as indicated both by spectroscopy and by observation of darkening resulting from sublimation [7]. In hindsight, a surface "skin" of vapor-deposited ice was a predictable result of recent climate patterns [5,8], and Phoenix lacked the capability to penetrate this layer to observe any underlying structure.

At one anomalous site at the south-facing shoulder of a trough separating polygons, Dodo-Goldilocks (D-G), the thermal blanket of soil protecting the ice was excessively thin [7], suggesting a previous mass-wasting event. Restoration of equilibrium would require retreat of the ice surface by sublimation, and it can therefore be inferred that this singular location offered a view of ice older than that found within the polygon. Ice exposed at D-G was found to be friable and nearly pure, consistent with the LDM hypothesis and with the expectation that a thin layer of ground ice would overlay such an ice sheet [5].

Direct surface humidity measurements complemented the visual observations from Phoenix [9]. The measured vapor pressure was dominated by "breathing" of the subsurface ice layer, characterized by a plateau of constant vapor pressure for most of the day and reduced vapor pressure at night corresponding to 100% relative humidity. This behavior is expected if the thin soil layer forms a negligible diffusion barrier, true for all reasonable values of the diffusion constant unless adsorption dominates. The rapid equilibration to the daytime plateau suggests that soil transport is not adsorption-limited, and that water vapor diffuses readily through the soil. The plateau can therefore be attributed to the saturation vapor pressure of the subsurface ice, corresponding to a temperature of ~215K.

Other observations: Relevant to the Phoenix observations are recent reports pertaining to the latitudinal extent of shallow ice, the vertical distribution of atmospheric water vapor, and evidence from the size distribution of the polygons.

Byrne et al. recently reported fresh impacts in the northern plains [10]. HiRise and CRISM data indicated that the exposed ice was relatively pure (consistent with the D-G sample). Significantly, the icy deposits were reported well equatorward of of 45°N, below the latitude that was previously considered the ice stability limit, but within the region mapped as the latitude dependent mantle [4].

In studying the vapor column with the Mars Express Planetary Fourier Spectrometer (PFS) Tschimmel [11] concluded that most of the humidity is confined to a planetary boundary layer 2-3 km above the surface rather than being uniformly distributed through the 10 km atmospheric scale height, attributing the observed confinement to the role of the surface as a source or sink of H_2O. With this assumption, the mid-day humidity plateau of 0.017 kg/m^3 measured by Phoenix is not only consistent with the modeled subsurface ice temperature, but also with the column humidity levels observed from Viking [12] through MGS [13].

Mellon et al [14] pointed out that the surface expression of the polygons themselves could provide an indication of the underlying ice composition. Using a rheological model, they argued that polygons overlying pure ice would be significantly larger than the observed size distribution as a result of the greater tendency of particle-free ice to relieve stress through flow. However, this model assumed identical fracture strength of both types of ice, whereas Phoenix observations explicitly demonstrated that the ice-rich samples from D-G were easily fractured compared to the particle-laden samples in the polygon interiors. In addition, the error budget of the rheological model can be expected to be large due to its extreme sensitivity to the details of the temperature cycles to which the material is exposed.

Reconciling the observations: A common uncertainty in all models of subsurface ice dynamics is poor knowledge of the bounding vapor density at the surface, a parameter that uniquely determines the overall ice stability [15]. To explore the influence of various vertical water distributions as well as atmospheric diffusion rates, a simple one-dimensional Crank-Nicholson diffusion model was developed to treat thermal and vapor transport in a column consisting of ice, surface soil, and atmosphere, thereby modeling the breathing of the surface as well as the long-term evolution of the ice. Energy balance was imposed at the surface, including insolation, radiation, downwelling infrared, conduction, and latent heat of CO_2 deposition where appropriate. A Dirichlet boundary condition was imposed at a height of 1 km above the surface, intentionally chosen to be small relative to the overall atmospheric scale height. The number of samples in a diurnal cycle, the number of sols sampled per year, and the number of years explicity calculated were optimized to minimize the calculation time (<1 minute per scenario on a desktop computer) without significantly affecting the result. Options were included to model orbital-axial climate variation or simply to iterate the current-day scenario in order to establish an equilibrium rate of ice retreat or advance. In either case, the model is allowed to run through at least 100,000 martian years to establish initial equilibrium.

As a criterion of ice stability at a depth measurable by microcrater observation, the net retreat/advance of the ice interface was determined at a fixed depth of 1 meter below the surface. Fig 1 shows results when the *upper* boundary condition of the atmosphere is set to a value consistent with the measured column abundance confined to 2.5 km. It can be seen that ice is stable at this depth *down to a latitude of 40°*. This result does not contradict previous work; rather it is a consequence of using a surface vapor density consistent with recent findings.

The model was also used to explore the influence of atmospheric diffusion rates on the rate of retreat of subsurface ice. Not surprisingly, it was found that ice stability improves as the seasonal diffusion length becomes small compared to the total extent of the water column. For example, at 45° latitude, values of D on the scale of free-gas diffusion can reduce the retreat rate to 10 cm per million years.

Conclusions: We argue that the weight of observational evidence from Phoenix and from recent craters supports the concept of a latitude-dependent mantle of deposited [4] rather than vapor-diffused ice [3]. Measured column water abundances, when combined with measured vertical distribution of the column, are shown to be consistent with humidity values measured by Phoenix, calculated subsurface ice temperature at the Phoenix site, and a 40° latitudinal limit of ice stability that is consistent with observations in fresh microcraters.

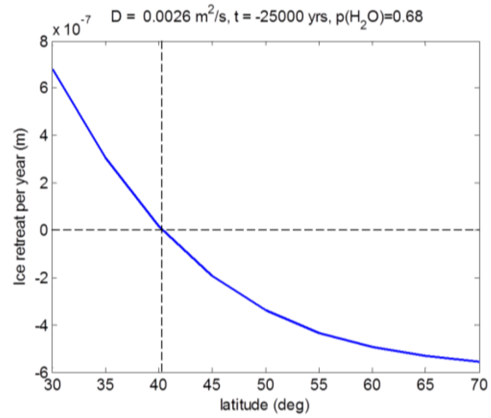

Fig. 1: Using a bounding partial pressure of H_2O consistent with column density measurements compressed into the lower 2.5 km of the atmosphere, it is seen that subsurface ice will be stable at 1 meter depth down to 40° latitude.

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