INITIATION AND GROWTH OF MARTIAN ICE LENSES.

H. G. Sizemore[1], A. P. Zent[2], and A. W. Rempel[3]. [1]Montani Consulting (HC 64 Box 176 Hillsboro WV, hgsizemore@gmail.com), [2]NASA Ames Research Center (Moffett Field CA, aaron.p.zent@nasa.gov), [3]Univeristy of Oregon (Department of Geological Sciences, University of Oregon, Eugene OR, rempel@uoregon.edu).

Introduction: Excess ground ice, or ice that exceeds the pore volume 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^o) 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^o N), trenching activities 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. Here, we employ numerical simulations of climate and soil-ice interactions to place quantitative constraints on the growth of segregated ice lenses throughout the northern latitudes. We discuss where and how ice lenses may contribute to observations of excess ice.

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 latitudes north of 55^o 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 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. Here, 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 conditions for simulating ice segregation.

Lens initiation and growth model. We have developed a numerical model that tracks temperatures, phase partitioning, and pressures at grain-grain contacts in a soil that is fully ice and water saturated. We assume that premelted films at the ice-mineral boundaries grow and shrink in place under diurnal and seasonal forcing when no lens is present. We rigorously test for lens initiation, and make order-of-magnitude estimates of subsequent lens-growth rates. The premelting physics employed in this model is based on mass and energy conservation equations developed by Rempel [7]. For computational simplicity, the soil-water-ice system is assumed to be gas and solute free in the majority of our simulations. However, we have parameterized some effects of dissolved perchlorate salts in to make a preliminary assessment of their effect on Martian frost heave.

Soil paramartization. We define the thermal conductivity and heat capacity of soils in both numerical models based on published values for silt and clay minerals [8, 9] and analysis of the soil at the Phoenix landing site [10]. In the lens initiation model, we define additional soil characteristics using four empirical parameters:

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 $\Theta = \dfrac{T_m - T}{\Delta T_f}$);

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

Andersland and Ladanyi [11] compiled measurements of these parameters in 33 terrestrial soils. We have focused our numerical experiments on three of these, Chena Silt, Inuvik Clay and Tomokomai Clay, with the goal of spanning the parameter space of freezing properties in heave-susceptible materials on Earth. Additionally, we use values of k_o, β, and α corresponding to Chena Silt as a best solute-free approximation of soil at the Phoenix landing site. We develop a new parametric expression for $S_i(\theta)$ to account for the effects of varying concentrations of perchlorate salts in the Phoenix soil.

Results and Discussion: Our simulations have produced four 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 nearly ubiquitous in our simulations and occurs at depths ranging from a few to 35 cm, at temperatures as low as 245 K at all latitudes poleward of 55^o. 2) Some degree of lens growth is also ubiquitous in our simulations. Soil properties play a major role in controlling the rate of lens growth. In typical clays, ΔT_f is large (>0.1 ^{o}C), α is small (< 2), and macroscopic lens growth (mm to cm over several sols) is possible. In silts, ΔT_f is small (<0.02 ^{o}C), α is large (> 2), and opportunities for macroscopic growth are infrequent, unless unique Martian soil chemistry increases water availability over a broad range of temperatures. 3) The maximum growth rate for Martian ice lenses is limited by the available reservoir of potentially mobile water, which lies between the depth of lens initiation and the ice table. 4) In the majority of soils investigated, the development of macroscopic ice lenses requires long-term accumulation of ice over many mid-summer growing seasons.

Implications for GRS. If the majority of Martian soils produce freezing point depressions of $\Delta T_f \geq 0.1$ K, *in situ* segregation could be a globally significant process in the late Amazonian. Soil inflation and progressive accumulation of ice lenses could contribute to high volumetric ice contents inferred from GRS data throughout much of both Martian hemispheres. The GRS instrument is sensitive to the upper ~50 cm of regolith; our simulations indicate lenses could accumulate in the upper portion of this region. A persistent challenge in understanding the origin of excess ice inferred from GRS data is analysis of the characteristic length scale of periglacial polygons. Visco-elastic modeling and statistical analysis of polygon size indicate that the rheology of the subsurface is *only* consistent with pore-filling ice to depths of a few to several meters [3]. In other words, the excess ice detected by GRS may only be a decimeters-thick “icing” on otherwise pore-filling ice. Our simulations indicate that ice lens formation is a mechanism that could produce high volumetric ice contents in the shallow region where GRS is sensitive without affecting soil rheology at greater depth.

Implications for mid-latitude craters. Our results indicate excess ice observed on the floors of fresh mid-latitude craters is unlikely to be exposed segregation ice formed in a manner analogous to terrestrial ice lenses, because this ice occurs at pre-excavation of depths > 40 cm, beyond the maximum depth at which we see lens initiation. However, at the majority of fresh crater sites that have been studied in detail, ice exposures are seen only on crater walls and ejecta. This suggests complete excavation through a layer of excess ice [2], which is not inconsistent with our results. Further, the excess ice exposed in fresh craters occurs exclusively under surfaces that are dominated by clay-sized particles – i.e. in the soils that we would expect the most vigorous lens growth.

Implications for Phoenix. Our theoretical results support the interpretation of excess ice observed at the Phoenix landing site as a segregated ice body. Both the burial depth (~4 cm) and the estimated thickness (mm to cm) are consistent with initiation depths and growth rates predicted by our simulations at 70^{o} N [3]. Solutes are not required to produce this degree of segregation. The white ice in the Dodo-Goldilocks trench was located at the ice table, consistent with lens formation in a previous climate regime when the ice table was marginally shallower. The only persistent challenge to interpreting the Dodo-Goldilocks ice as a segregated ice body is the texture of the ice, which is porous and friable.

Generally speaking, the particular properties of Martian soils will determine if ice lenses play a major or minor role in the stratigraphy of the ice-rich regolith. If some characteristic of the Martian soil (e.g., grain size or solute content) depresses the bulking melting temperature by > 0.1 ^{o}C *without substantially changing the premelting physics*, then it is easy to envision a scenario in which diffusive equilibrium with the atmosphere buffers the source region on timescales of years or more and single or multiple ice lenses contribute to long-term inflation of the soil. In this scenario, accumulation of centimeters of excess ice at depths of a few to 10s of cm would be possible in a few thousand years or less. Depressing the bulk melting temperature by 0.1 ^{o}C is a modest requirement in soils with concentrations of magnesium perchlorate of order 1 wt%; ΔT_f in an equivalent concentration $Mg(ClO_4)_2$ solution is ~ 2.5K. Thus, there is a fundamental ambiguity in interpreting our results that points to a need for 1) an extension of the mass and energy conservations equations on which this work is based to account for the full effects of deliquescent salts, and 2) targeted laboratory studies of soil freezing at temperatures appropriate to Mars, with and without salts.

References:

[1] Boynton W. V. *et al.* (2002) *Science, **297**,* 81-85,. [2] Byrne S. *et al.* (2009) *Science, **325**,* 1674-1676. [3] Mellon M. T. *et al.* (2009) *JGR, **114**,* E00E07. [4] Zent A. P. (2008) *Icarus, **196***, 385-408. [5] Laskar J. *et al.* (2004) *Icarus, **170***, 343-364. [6] Rempel A. W. *et al.* (2004) *J. Fluid Mech., **498**,* 227-244. [7] Rempel A. W. (2007) *JGR, **112***, F02821. [8] Wechsler and Glaser, *Icarus*, **4**, 335–352 (1965). [9] Grønvold and Westrum, *J. Am. Chem. Soc.*, **81**, 1780–1783 (1959). [10] Zent A. P. *et al.* (2010) *J. Geophys. Res., **115***, E00E14. [11] Andersland, O. B., and B. Ladanyi (2004), *An Introduction to Frozen Ground Engineering*, 363 pp., CRC Press, Boca Raton, FL.