MARS: THE EFFECT OF STRATIGRAPHIC VARIATIONS IN REGOLITH DIFFUSIVE PROPERTIES ON THE EVOLUTION AND VERTICAL DISTRIBUTION OF EQUATORIAL GROUND ICE. S. M. Clifford, Lunar and Planetary Institute, 3600 Bay Area Blvd, Houston, TX 77058, clifford@lpi.jsc.nasa.gov.

As evident from the stratigraphy of a Martian canyon wall, lunar or terrestrial soil profile, or a deep drill core retrieved anywhere on Earth, the structure and thermophysical properties of a planetary crust vary dramatically on size scales that range from ~10^{-3} - 10^{3} m. Given the shear number of physical properties that may vary, the potential amplitude of these variations, and the random spatial frequency and thickness of the resulting strata, the diffusive properties of rock and soil can easily change by orders of magnitude over a depth interval of just a few meters. Past studies of the stability, evolution, and ultimate distribution of ground ice on Mars [1,2,3,4], have demonstrated the enormous sensitivity of ground ice to the assumed column-averaged thermal and diffusive properties of the crust. This abstract addresses how stratigraphic variations in these same properties will affect the sublimation and ultimate vertical distribution of equatorial ground ice. I find that variations in local regolith stratigraphy and heat flow can result in crustal desiccation down to depths that range from ~1-10^{3} m, with the potential for complex variations in crustal ice content extending hundreds meters beneath the local sublimation front. I conclude that the natural range and statistical variability of regolith physical properties will have a dominant, and inherently unpredictable, influence on the subsurface distribution of ground ice – effectively precluding reliable geographic predictions of its volatile state based on the thermal and radiative properties of the surface alone.

Given the current range of mean annual temperatures and H_2O partial pressures at the Martian surface, ground ice is unstable within the latitude band of ±40° [1]. Early theoretical studies [2,3] suggested that, for reasonable 'globally-averaged' values of regolith diffusive properties, the near-equatorial crust has probably been desiccated to depths of 300 - 500 m over the past 3.5 billion years. However, in a subsequent analysis [5], it was noted that, as the sublimation front propagates into the crust, it might ultimately reach a depth where the diffusive loss of ground ice is exactly balanced by the upward thermal migration of H_2O (arising from the geothermally-induced increase in temperature and vapor pressure at depth). Although such replenishment has the ability to significantly limit the depth of equatorial desiccation, I argued that the processes and conditions governing the occurrence of equilibrium are sufficiently complex that calculating a specific depth at which it is reached is virtually impossible without a detailed knowledge of the local thermal and diffusive structure of the crust.

In a recent study, *Mellon et al.* [6] have attempted to take the concept of an equilibrium depth a step further by calculating a specific range of depths over which it might occur. This analysis has led the authors to some fundamentally different conclusions about how well this range of depths is constrained, the factors that influence it, and the subsequent consequences for the volatile evolution of the crust. These differences originate from their assumption of a homogenous crust. As demonstrated here, stratigraphic variations in regolith diffusive properties can result in equilibrium conditions at both significantly greater and shallower depths.

The effect of a stratigraphic inhomogeniety on the equilibrium depth of ground ice can be seen in Figure 1a & 1b. In these highly-idealized cross-sections, the crust is depicted as an initially ice-saturated homogenous medium that is divided by a stratigraphic layer of lower gaseous permeability. Reductions in diffusive transport across such a layer might arise from a number of factors, including: a lower porosity, smaller effective pore size, greater tortuosity, lower thermal conductivity (which reduces the local thermal gradient and associated vapor pressure gradient), or any combination of the above. The impact of these factors is further modulated by the thickness, depth, and relative position of an individual strata with respect to the others that are present in the crust.

When the less-permeable layer is located between the surface and the equilibrium depth predicted on the basis of a homogenous crust (*i.e.,* equation (4a) of [6]), the sublimation front will propagate through the upper layer, slow as it penetrates the less-permeable layer, and then stagnate at the top of the lower layer – where it may remain indefinitely, or until all of the underlying ice is thermally redistributed and sublimed away (Figure 1a). The reason for this behavior is that, as the sublimation front attempts to propagate beneath the less-permeable layer, it opens up pore space in a region where the effective diffusion coefficient is higher than it is within the layer above, causing the pore space to resaturate faster than it can be depleted. The location of the boundary between the low permeability layer and deeper crust thus defines an equilibrium depth for the long-term survival of ground ice that is independent of regolith temperature and determined solely by the relative diffusive properties of the crust.

While stratigraphic variations in regolith diffusive properties can result in equilibrium depths that are shallower than those predicted on the basis of a homogeneous crust, they can also result in equilibrium depths that are substantially greater (*e.g.,* Figure 1b). This is particularly likely in regions possessing large geothermal gradients – a condition that generally favors both shallow equilibrium depths and large sublimation rates. Under such conditions, the propagation of the sublimation front will proceed normally until it hits the depth of equilibrium predicted on the basis of a homogeneous crust (Figure 1b, T1). There, it will pause until the ice between this depth and the low-permeability layer lying beneath it, is sublimed away. At that point, the position of the low-permeability layer will define a new equilibrium depth, where the sublimation front may remain indefinitely. Alternatively, given the presence of a second (or multiple) low-permeability strata beneath the first, it is also possible that the sublimation front could advance to

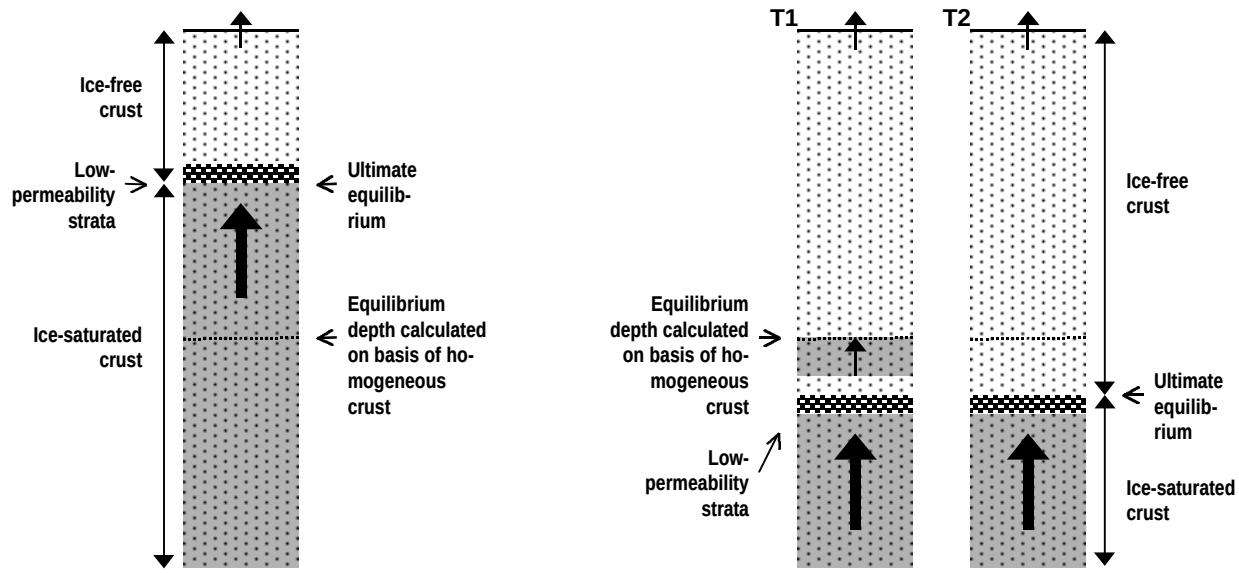

Figure 1a. Effect of a shallow low-permeability strata.

Figure 1b. Effect a low-permeability strata at depth.

also possible that the sublimation front could advance to even greater depths by passing from one 'quasi' equilibrium depth to another, stagnating at a particular level for perhaps millions (or even billions) of years – before exhausting the local supply of ice and rapidly advancing to the next deeper level. By this process, the regolith could be readily desiccated to depths far in excess of those predicted on the basis of a homogeneous crust.

As suggested by such scenarios, real world permutations of crustal diffusive and thermal properties will result in complex combinations of low- and high-permeability strata that are likely to yield equally complex distributions of ground ice within ~10^2 - 10^3 m of the surface. Examples of these are seen in Figure 2, where the presence of multiple strata, with differing properties, could readily result in steady-state ice contents similar to any one of the three columns. Alternatively, the columns could also represent three phases in the complex evolution of ground ice at a single location.

The principal conclusion to be drawn from this study is that, given any geologically reasonable description of the Martian crust, local stratigraphic variations in regolith thermal and diffusive properties will play a determining, and inherently unpredictable, role in the evolution and vertical distribution of equatorial ground ice. This is especially true of any attempt to calculate the depth of equilibrium, where the uncertainty associated with the potential range and statistical variability of regolith thermal and diffusive properties effectively prevents a reliable geographic prediction of this depth (or any other volatile-related aspect of the crust), short of obtaining a local measurement of crustal heat flow and the recovery, and detailed laboratory analysis, of a km-length drill core.

References: [1] Farmer, C. B. and P. E. Doms, JGR 84, 2881-288, 1979; [2] Clifford, S.M. and D. Hillel, JGR 88, 2456-2474, 1983; [3] Fanale, F.P. et al., Icarus 67, 1-18, 1986 [4] Mellon, M. and B. Jakosky, JGR 100, 11781, 1993; [5] Clifford, S.M., JGR 98, 10973-11016, 1993; [6] Mellon et al.., JGR 102, 19537, 1997.

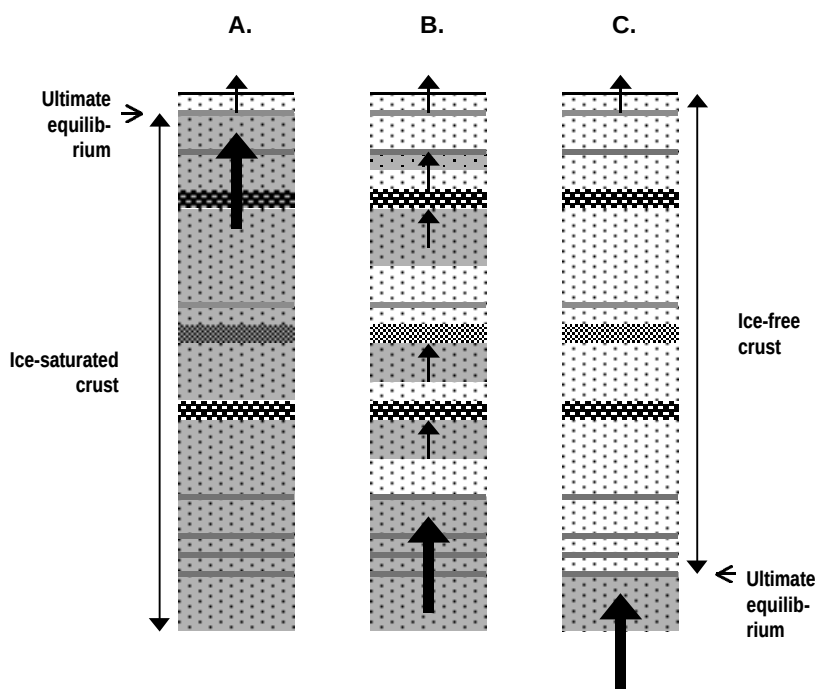

Figure 2. Potential effect of multiple low-permeability strata.