THE STABILITY OF GROUND ICE IN THE EQUATORIAL REGION OF MARS. S.M. Clifford* and D. Hillel**, *Dept. of Physics and Astronomy, **Dept. of Plant and Soil Science, University of Massachusetts, Amherst, MA 01003.

Consideration of the partial pressure of H_2O in the Martian atmosphere and the range of mean annual temperatures at the Martian surface, suggests that the occurrence of ground ice in equilibrium with the atmosphere is restricted to latitudes poleward of $\pm 40^\circ$ (1). However, there is a growing body of morphologic evidence which indicates that substantial quantities of ground ice may have been present in the equatorial regolith throughout Martian geologic time (2,3,4). The accepted explanation for this apparent contradiction has been that the H_2O found near the equator is a relic, emplaced very early in Martian geologic history (>3.5 billion years ago) and under substantially different climatic conditions. It is generally believed that this fossil ground ice layer has been preserved to the present day by the diffusion limiting properties of a relatively shallow layer (10 meters) of fine-grained regolith. This explanation is based on an extrapolation of the work of Smoluchowski (5), who showed that under certain limited conditions of porosity, particle size, temperature, and depth of burial, a 10 meter thick layer of ground ice in disequilibrium with the atmosphere might survive for as long as a billion years. In light of our present understanding of the physical and chemical properties of the Martian regolith and of the magnitude of climatic change on Mars, the lifetime of an unreplenished layer of ground ice, lying in the equatorial band of $\pm 30^\circ$, has been reconsidered (6).

To investigate the stability of ground ice in the equatorial region of Mars it was necessary to make certain assumptions regarding the physical properties of the regolith as well as the quantity and vertical distribution of ice within it. After Toon et al. (7), and in accord with the porosity determinations made of the Martian reoglith by the Viking Landers (8), we assumed that the regolith had a mean column porosity of 50%. The amount of ice contained in a vertical column of the regolith was taken to be 10^4 grams/cm^2 - based on the estimate of Pollack and Black (9) that the global inventory of H_2O on Mars is equivalent to a 100 meter layer of ice averaged over the surface of the planet. We assumed that this ice occupied the available pore space in a single massive layer which initially extended from 100 to 300 meters in depth. To maximize the lifetime of this buried ice layer we considered the top 300 meters of the Martian regolith to be isothermal. Finally, the temperature range which was considered in this analysis (215-220 K) corresponds to the range of mean annual temperatures for the latitudes lying between $\pm 30^\circ$.

The evaporative loss of ground ice was calculated by means of the parallel-pore model of gaseous diffusion (10,11). This model was chosen primarily for its well documented ability to predict diffusion and flow through porous solids with broad pore size distributions (12,13) - an important asset when considering mass transport through a layer of soil. With this model, the flux of H_2O molecules from the buried ground ice layer was calculated by:

$$N_A = \frac{D_{AB}\, P}{\tau k T z \alpha} \sum_{r\,min}^{r\,max} \ln \left(\frac{1 - \alpha y_{AL} + D_{AB}/D_{KA}}{1 - \alpha y_{A0} + D_{AB}/D_{KA}} \right) \Delta\varepsilon(r) \qquad (1)$$

where $\Delta\varepsilon(r)$ is the void fraction for pores with a mean size r in the interval Δr, and where the remaining constants and variables have their usual meanings (summarized in Table 1). Fine-grained soils typically exhibit broad pore size distributions (14); for such soils the void fraction is frequently found to follow a lognormal distribution. Therefore, in equation 1, $\Delta\varepsilon(r)$ was given by:

$$\Delta\varepsilon(r) = \frac{E}{r\sigma\sqrt{2\pi}} \exp\left\{ -\frac{1}{2}(\ln r - \ln r_m)^2/\sigma^2 \right\} \Delta r \qquad (2)$$

The recession of the evaporating upper surface of the ground ice from an initial depth of 100 meter to a final depth of 300 meters was taken into account by increasing the depth 'z' in equation 1 by one meter for every 50 gm H_2O lost by evaporation. Calculated total lifetimes for the ground ice layer, for three different pore size distributions, are summarized in Table 2. It is important to note that for the given regolith properties these figures represent maximum lifetimes, for they neglect at least three potentially important effects: the contribution to the total flux made by surface diffusion, the effect of the geothermal gradient, and the possibility that climatic variations on Mars will effectively "flush" the regolith pores of diffusing H_2O molecules as the result of the continuous cycling of CO_2 between the regolith and polar caps (15). (A more extensive discussion of these factors and their relative importance is presented in (6)). As can be seen from Table 2, even when conditions for the long term survival of ground ice are optimized, the lifetime of a 200 meter thick layer of ground ice buried beneath a 100 meter layer of ice-free regolith falls well short of the 3.5 billion year lifetime required to explain the observations of Johansen (2,3) and Allen (4).

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TABLE 1. VARIABLES AND CONSTANTS

N_A	= flux of H_2O (mol/cm^2 sec)	y_{AL}	= mole fraction at z=0
D_{AB}	= mol. diff. coef. CO_2-H_2O (cm^2/sec)	y_{AO}	= mole fraction at ice surface
D_{KA}	= Knudsen diffusion coef. H_2O (cm^2/sec)	$\Delta\varepsilon(r)$	= void fraction
τ	= tortuosity factor (=5)	E	= overall porosity
k	= Boltzmann's const. 1.38×10^{-16} (erg/K)	r	= pore size (cm)
T	= temperature (K)	r_m	= median pore size (cm)
z	= depth (cm)	r max	= max. pore size (cm)
α	= $[1-(M_A/M_B)^2]$	r min	= min. pore size (cm)
M_A	= molecular wt. H_2O (gm/mole)	Δr	= pore size interval (cm)
M_B	= molecular wt. CO_2 (gm/mole)	σ	= standard deviation
P	= total pressure (dynes/cm^2)		

TABLE 2. LIFETIME OF A BURIED GROUND ICE LAYER*

PORE SIZE (Meters)				LIFETIME (10^9 YEARS)	
median	mode	r min	r max	T = 215 K	T = 220 K
1×10^{-6}	1.8×10^{-8}	1.4×10^{-9}	7.2×10^{-4}	.49	.26
1×10^{-7}	" $\times 10^{-9}$	" $\times 10^{-10}$	" $\times 10^{-5}$	.90	.48
1×10^{-8}	" $\times 10^{-10}$	" $\times 10^{-11}$	" $\times 10^{-6}$	2.8	1.5

*Adopted values: initial depth to top of ice layer = 100 m, depth to bottom of ice layer = 300 m; E =.5 y_{AL}=0, τ=5, and σ=2.

In conclusion, the stability of ground ice in the equatorial region of Mars has been reconsidered (6). The results of the study suggest that in this region it is by no means clear that the diffusion inhibiting effects of a thick and fine-grained regolith are sufficient to preserve ground ice over much of Martian geologic time. The fact that there appears to be a growing body of morphologic evidence which suggests ground ice has existed in this region for such a time span would seem to imply that there must exist some efficient mechanism for its continuous or periodic replenishment.

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