THE ROLE OF THERMAL VAPOR DIFFUSION IN THE SUBSURFACE HYDROLOGIC AND MINERALOGIC EVOLUTION OF THE MARTIAN CRUST. S. M. Clifford and J. Lasue, Lunar and Planetary Institute, 3600 Bay Area Blvd, Houston, TX 77058, clifford@lpi.usra.edu.

Introduction: Based on a conservative estimate of the volume of water required to erode the outflow channels, and the likely extent of their subsurface source regions, Carr [1] has estimated that Mars may possess a planetary inventory of water equivalent to a global ocean 0.5–1 km deep, the vast bulk of which is believe to be stored as ground ice and, possibly, as groundwater, in the subsurface [1, 2].

The distribution of ground ice on Mars is determined by the thermal structure of the crust, which mirrors the first-order variation in topography, but will extend down to a depth of from several to many km beneath the surface [2, 3]. In contrast, in the absence of atmospheric replenishment, groundwater will saturate the lowermost porous regions of the crust, having a water table (where unconfined by the cryosphere) that will conform to a surface of constant geopotential. As shown in Figure 1, the vertical distance separating any groundwater from the base of the cryosphere may, in some regions, be many kilometers while, in others, these two reservoirs of subsurface H_2O may be in direct contatct.

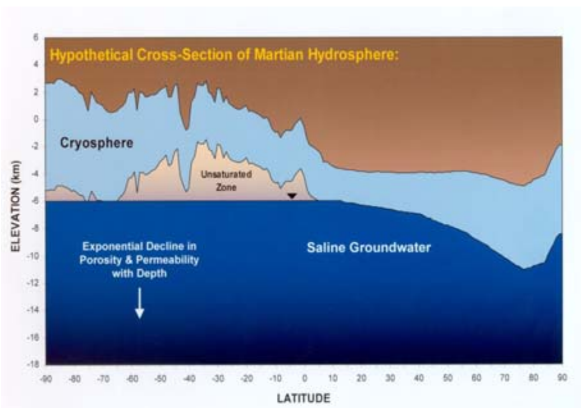


Figure 1. A hypothetical pole-to-pole cross-section of the Martian hydrosphere, illustrating the potential relationship of the cryosphere and groundwater.

Thermal vapor diffusion. Where there exists an unsaturated zone, between the base of cryosphere and groundwater table, the presence of a geothermal temperature gradient will give rise to a corresponding vapor pressure gradient, such that vapor will diffuse from the the higher temperature (higher vapor pressure) depths to the colder (lower vapor pressure) region at the base of the cryosphere by a process known as thermal vapor diffusion [2, 4].

The physical basis for this thermally-driven flux of vapor can be understood by considering first the equilibrium distribution of vapor in an isothermal crust. For this condition, the distribution of H_2O above the water table is given by the standard barometric relationship, where the scale-height of water vapor, above the water table, depends on the groundwater temperature.. For example, if the temperature at the grounwater table is 290 K, the water vapor scale-height will be ~36 km. Therefor, at a height of 1 km above the water table, the resulting baramotric reduction in vapor pressure is ~3% (Figure 2).

Now consider the effect of a geothermal gradient. Assuming a temperature gradient of 15 K km^{-1}, the crustal temperature at a height of 1 km above the water table is 275 K, which reduces the saturated vapor pressure at this height by 68%. Thus, the thermally induced gradient in saturated vapor pressure greatly exceeds the barometric gradient – causing vapor to diffuse upward in an effort to achieve an equilibrium barometric profile. However, as this vapor encounters the shallower and colder regions of the crust, the associated reduction in saturated vapor pressure causes some of the ascending vapor to condense, ultimately draining back to the water table as a liquid. As a result, the flux of vapor that leaves the groundwater table greatly exceeds that which finally reaches the freezing front at the base of the cryosphere. As shown by *Jackson et al.* [5], once a closed system has been established (i.e., the pore volume of the cryosphere has been saturated with ice), a dynamic balance of opposing fluxes is achieved, creating a circulation system of rising vapor and descending liquid condensate (Figure 3).

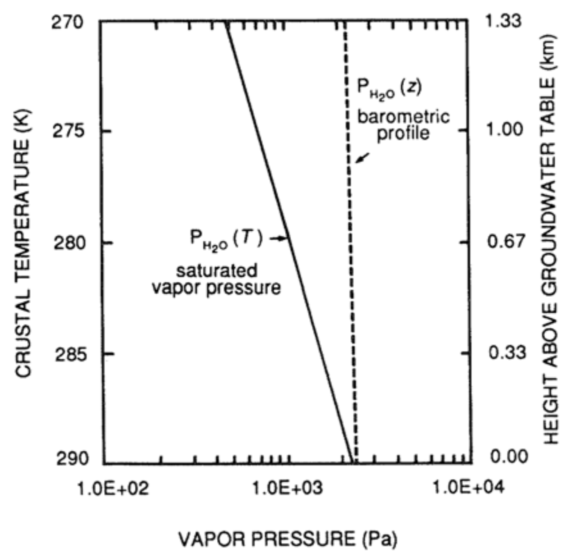


Figure 2. Comparison of the vapor pressure of H2O above a Martian groundwater table given by the barometric relationship (dashed line) and resulting from a geothermal gradient of 15 K km^{-1}.

For a geothermal gradient of 15 K km^{-1}, a groundwater temperature of 290 K, and effective crustal pore sizes of 1 and 10 μm, the flux of water vapor (per unit area) reaching the freezing front at the base of the cryosphere is ~8.3×10^{-3} – 2.8×10^{-4} m H_2O yr^{-1}. This flux is equivalent to the vertical transport of ~1 km of water every 10^6–10^7 years, or roughly 10^2–10^3 km of water over the course of Martian geologic history.

The magnitude of this thermally induced vapor flux was almost certainly greater in the past. Models of the thermal history of Mars suggest that 4 billion years ago the planet's internal heat flow was ~3–5 times larger than it is today [6, 7]. Since the flux rate is directly proportional to the temperature gradient, this implies a similar increase in the volume of water cycled through the early crust.

Consequences for the hydrologic and mineralogic evolution of the Martian crust. If the Martian valley networks were carved by atmospheric precipitation during a warmer, wetter Noachian climate, it suggests that Mars must have once possessed groundwater flow systems similar to those now found on Earth, where, as a consequence of atmospheric recharge, the water table conformed to the shape of the local terrain (Figure 4, T0). However, with the transition to a colder climate -- and the progressive decline in Mars' internal heat flow -- a freezing front eventually developed in the regolith that propagated downward with time, creating a thermodynamic sink for any H_2O within the crust. Initially, water may have been cold-trapped within this developing region of frozen ground from both the atmosphere and underlying groundwater. However, as the pores of the near-surface regolith becames saturated ice, the deeper crust was ultimately sealed off from any further communication with the atmosphere. From that point on, the only source of water for the thickening cryosphere would have been the thermally driven upward flux of vapor from the underlying groundwater (Figure 4, T1)

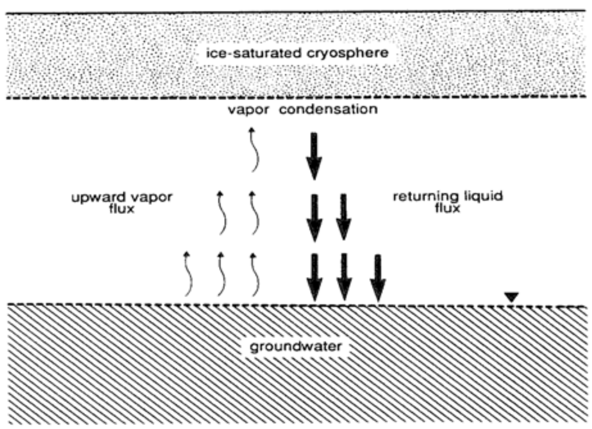


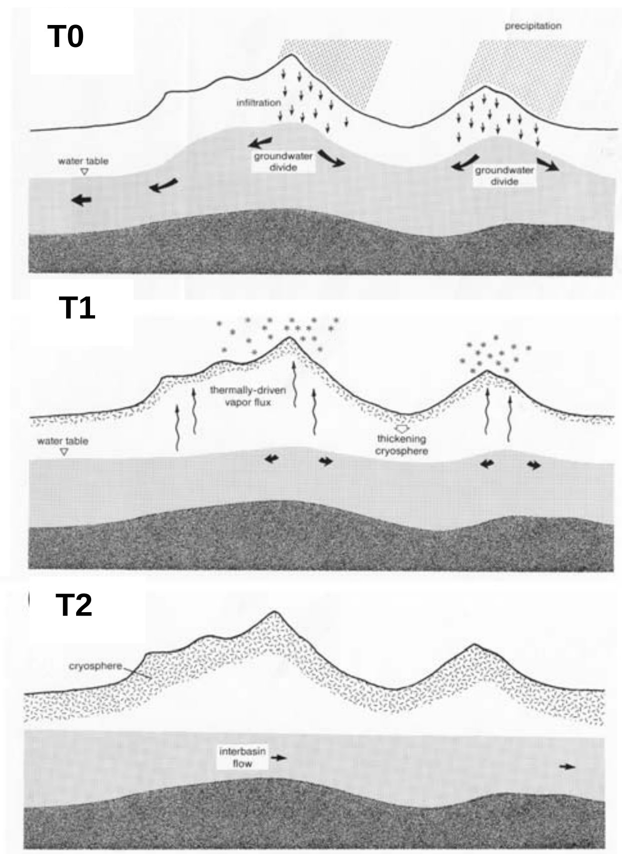
Figure 3. Low temperature hydrothermal cuirculation between the groundwater table and base of the cryosphere in response to the presence of a geothermal gradient.

With the elimination of atmospheric recharge, the elevated water tables that once followed the local topography eventually decayed. The continuity of pore space provided by the large-scale permeability of the crust would have then allowed the water table to hydrostatically readjust until it ultimately conformed to a surface of constant geopotential (Figure 4, T2) – a conclusion is supported by studies of areally extensive groundwater systems on Earth that experience little or no precipitation [2].

The time scale for any reasonable scenario of the transition from an early warm and wet Martian climate, to a sub-freezing one, is sufficiently great (i.e., $>10^6$ yrs) that the base of the cryosphere can be considered to have been in effective thermal equilibrium with the mean temperature environment at the surface. For transition times this long, the downward propagation of the freezing front at the base of the cryosphere would have proceeded at a rate that is suffi ciently slow (compared to the geothermally-induced vapor flux arising from the groundwater table) that the geothermal gradient would have had little trouble in supplying enough vapor to keep the cryosphere saturated with ice throughout its development.

From a mass balance perspective, the thermal evolution of the early crust effectively divided the subsurface inventory of water into two reservoirs: (1) a slowly thickening ice-rich region of frozen ground and (2) a deeper region of subpermafrost groundwater [2, 3]. Regardless of how rapid the transition to a colder climate actually was, the cryosphere has continued to thicken as the geothermal output from the planet's interior has gradually declined. One possible consequence of this evolution is that, if the planet's initial inventory of outgassed water was small, the cryosphere may have eventually grown to the point where all of the available H_2O was taken up as ground ice. Alternatively, if the inventory of H_2O exceeds the current pore volume of the cryosphere, then Mars has always had extensive bodies of subpermafrost groundwater.

Figure 4. The impact of the transition from a warm to cold early Mars on the evolution of the hydrosphere.



Ths geochemical evolution of the Martian crust was likely strongly affected by the convective cycling of 10^2–10^3 km of water (per unit area) between the water table and the base of the cryosphere (Figure 3) – which would have deplete the intervening crust of any easily dissolved substances, concentrating them in the underlying groundwater to levels far in excess of saturation. The resulting precipitation of these minerals beneath the water table is expected to have lead to widespread diagenesis and to the development of distinct geochemical horizon within the crust [*Soderblom and Wenner*, 1978].

References: [1] Carr, M. H. (1986) Icarus 68, 187-216. [2] Clifford, S. M. (1993) JGR 98, 10973-11016. [3] Clifford, S. M. and T. J. Parker (2001) Icarus 154, 40-79. [4] Clifford, S. M. (1991) Geophys. Res. Lett. 18, 2055–2058. [5] Jackson, R. D. et al. (1965) Nature 205, 314-316. .Fanale, F. P. (1976) Icarus 28, 170-202. [6] Solomon, S. C. and J. W. Head (1990) JGR 95, 11073-11083. [7] McGovern P. J. et al. (2004) JGR 109, E07007.