from the groundwater table) that the cryosphere should have remained 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 evolving reservoirs: (1) a slowly thickening zone of near-surface ground ice and (2) a deeper region of subpermafrost groundwater. 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 the available H_2O was taken up as ground ice [7]. 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. As argued by Clifford [8], this latter possibility is strongly supported by the apparent occurrence of outflow channels as recently as the Mid to Late Amazonian [e.g., 9,10].

Early Climate: Like the Present: Of course, if early Mars was cold from the start, the initial emplacement of ground ice would have differed significantly from that described by the warm scenario. This possibility was first considered by Soderblom and Wenner [7], who suggest that the initial emplacement of crustal H_2O was the result of the direct injection and migration of juvenile water derived from the planet's interior. There are at least two ways in which this emplacement may have occurred. First, by the process of thermal vapor diffusion [6], water exsolved from cooling magmas will migrate from the warmer to colder regions of the crust. Upon reaching the cryosphere, this H_2O will then be distributed throughout the frozen crust by a variety of thermal processes [11]. As a result, any part of the cryosphere that overlies or surrounds an area of magmatic activity will quickly become saturated with ice. The introduction of any additional water will then result in its accumulation as a liquid beneath the frozen crust, where, under the influence of the growing local hydraulic head, it will spread laterally in an effort to reach hydrostatic equilibrium. As this flow expands beneath areas where the cryosphere is not yet fully charged with ice, thermal vapor diffusion [6] and the other thermal processes discussed by Clifford [11] will redistribute H_2O into the frozen crust until its pore volume is either saturated or the local source of groundwater is finally depleted.

However, the fate of water released to the cold martian atmosphere is significantly different. The direct injection of a large quantity of vapor into the atmosphere (e.g., by volcanism) will lead to its condensation as ice on, or within, the surrounding near-surface regolith. As the available pore space in the upper few meters of the regolith is saturated with ice, it will effectively seal off any deeper region of the crust as an area of potential storage. From that point on, any excess vapor that is introduced into the atmosphere will be restricted to condensation and insolation-driven redistribution on the surface until it is eventually cold-trapped at the poles. Should such polar deposition continue, it will ultimately lead to basal melting [12], recycling water back into the crust beneath the caps. As the meltwater accumulates beneath the polar cryosphere, it will create a gradient in hydraulic head that will drive the flow of groundwater away from the poles. As the flow expands radially outward, it will pass beneath regions where, as a result of vapor condensation from the atmosphere, only the top few meters of the cryosphere have been saturated with ice. As before, the presence of a geothermal gradient will then lead to the vertical redistribution of H_2O from the underlying groundwater until the pore volume of the cryosphere is saturated throughout. In this way, the early martian

crust may have been globally charged with water and ice without the need to invoke an early period of atmospheric precipitation.

This analysis suggests that, whether the early martian climate started warm or cold, thermal processes within the crust played a critical role in the initial emplacement of ground ice. An important consequence of this fact is that, below the depths of equatorial desiccation predicted by Clifford and Hillel [13] and Fanale et al. [14], the cryosphere has probably been at or near saturation throughout its development, or at least until such time as the total pore volume of the cryosphere grew to exceed the total volume of the planet's outgassed inventory of water. The existence of outflow channels with apparent ages of less than 1 b.y. [9,10] raises considerable doubt as to whether this last stage in the evolution of the martian cryosphere has yet been reached.

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THE HYDROLOGIC RESPONSE OF MARS TO THE ONSET OF A COLDER CLIMATE AND TO THE THERMAL EVOLUTION OF ITS EARLY CRUST.   S. M. Clifford, Lunar and Planetary Institute, Houston TX 77058, USA.

Morphologic similarities between the martian valley networks and terrestrial runoff channels have been cited as evidence that the early martian climate was originally more Earth-like, with temperatures and pressures high enough to permit the precipitation of H_2O as snow or rain [1,2]. Although unambiguous evidence that Mars once possessed a warmer, wetter climate is lacking, a study of the transition from such conditions to the present climate can benefit our understanding of both the early development of the cryosphere and the various ways in which the current subsurface hydrology of Mars is likely to differ from that of the Earth. Viewed from this perspective, the early hydrologic evolution of Mars is essentially identical to considering the hydrologic response of the Earth to the onset of a global subfreezing climate.

If the valley networks did result from an early period of atmospheric precipitation, then Mars must have once possessed near-surface groundwater flow systems similar to those currently found on Earth, where, as a consequence of atmospheric recharge, the water table conformed to the shape of the local terrain. However, with both the transition to a colder climate and the 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 entered this developing region of frozen ground from both the atmosphere and underlying groundwater. However, as ice condensed within the near-surface pores, the deeper regolith was ultimately sealed off from any further atmospheric supply. From that point on, the only source of water for the thickening cryosphere must

have been thermally driven upward flux of vapor from the underlying groundwater [3,4].

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 sediments, breccia, and interbasin faults and fractures should have then allowed the water table to hydrostatically readjust on a global scale until it ultimately conformed to a surface of constant geopotential. This conclusion is supported by investigations of areally extensive groundwater systems on Earth that experience little or no precipitation [e.g., 5,6].

The time required for the development of the cryosphere can be calculated by solving the transient one-dimensional heat conduction equation for the case of a semi-infinite half-space with internal heat generation, where

$$\frac{\partial^2 T}{\partial z^2} + \frac{S}{k} + = \frac{1}{a}\frac{\partial T}{\partial t} \tag{1}$$

and where T is the crustal temperature, z is the depth, t is time, k is the crustal thermal conductivity, a is the thermal diffusivity ($= k/\rho c$), and S is the heat generation rate per unit volume ($= 3Q_g/R$, where Q_g is the geothermal heat flux and R is the radius of Mars) [7]. An upper limit can be placed on how rapidly the cryosphere evolved if we assume that the surface temperature of Mars underwent an instantaneous transition from a mean global value of 273 K to its current latitudinal range of 154–218 K. For these conditions, equation (1) was solved numerically using the method of finite differences. The results indicate that, given a present-day geothermal heat flux of 30 mW m^{-2}, the freezing front at the base of the cryosphere will reach its equilibrium depth (~3700 m) at the equator in ~4.6 × 10^5 yr, while at the poles it will take roughly 1.5 × 10^6 yr (z = 7900 m). Given the elevated geothermal conditions that probably characterized the planet 4 b.y. ago (i.e., Q_g ~ 150 mW m^{-2}), the corresponding development times are 2 × 10^4 yr (z = 700 m) and 1.3 × 10^5 yr (z = 1600 m) respectively. These calculations are based on a thermal conductivity of 2.0 W m^{-1} K^{-1}, a freezing temperature of 273 K, and a maximum latent heat release (due to the condensation of H$_2$O vapor as ice in the pores) that does not exceed Q_g, a limit imposed by the geothermal origin of the vapor flux reaching the base of the cryosphere [e.g., 3,4]. Note that although these development times assume an initially dry crust, they would not be significantly different even if the crust were initially saturated throughout. Although the early growth of the cryosphere would be slowed by the ready supply of latent heat, this period represents only a small fraction of the total time required for the cryosphere to reach equilibrium. In the later stages of growth, which are controlled almost exclusively by conduction through the frozen crust, the rate of heat loss is sufficiently small that the effect of latent heat release can be virtually ignored.

Although the assumption that Mars underwent an instantaneous transition from a warm to cold early climate is clearly incorrect, this extreme example serves to illustrate an important point, i.e., on a timescale greater than ~10^6 yr, the base of the cryosphere is essentially in thermal equilibrium with mean temperature environment at the surface. As a result, for any reasonable model of climate evolution, the growth of the cryosphere is not controlled by the rate

of conduction through the crust, but by how rapidly the mean surface temperature environment changes with time. Pollack et al. [2] estimate that if the primary mechanism driving climate change was the removal of a massive (1–5-bar) CO$_2$ atmosphere by carbonate formation, then the transition from a warm to cold early climate must have taken between 1.5 × 10^7 and 6 × 10^7 yr. For transition times this slow, the downward propagation of the freezing front at the base of the cryosphere proceeds at a rate that is sufficiently small (when compared with the geothermally induced vapor flux arising from the groundwater table) that the geothermal gradient should have no trouble 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 zone of near-surface ground ice and (2) a deeper region of subpermafrost groundwater [8]. 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 the available H$_2$O was taken up as ground ice [9]. Alternatively, if the inventory of H$_2$O exceeds the current pore volume of the cryosphere, then Mars has always had extensive bodies of subpermafrost groundwater.

Because the pore volume of the cryosphere was probably saturated with ice throughout its early development, the thermally driven vapor flux arising from the reservoir of underlying groundwater could have led to the formation and maintenance of near-surface perched aquifers, fed by the downward percolation of condensed vapor from the higher and cooler regions of the crust. Eventually the hydrostatic pressure exerted by the accumulated water may have been sufficient to disrupt the overlying ground ice, allowing the stored volume to discharge onto the surface. Such a scenario may have been repeated hundreds of times during the planet's first 500 m.y. of geologic history, possibly explaining (in combination with local hydrothermal systems driven by impact melt [10,11] and volcanism [12]) how some valley networks may have evolved in the absence of atmospheric precipitation [13,14]. However, as the internal heat flow of the planet continued to decline, the thickness of the cryosphere may have grown to the point where it could no longer be disrupted by the limited hydrostatic pressure that could develop in a perched aquifer, thus terminating the potential contribution of low-temperature hydrothermal convection to valley network formation.

Finally, the postcryosphere groundwater hydrology of Mars will differ from its possible precryosphere predecessor (and therefore from present-day terrestrial groundwater systems) in at least one other important way. In contrast to the local dynamic cycling of near-surface groundwater that may have characterized the first 500 m.y. of martian climate history, the postcryosphere period will necessarily be dominated by deeper, slower interbasin flow. Aside from polar basal melting, there are at least three other processes that are likely to drive flow under these conditions: (1) tectonic uplift (essentially the same mechanism proposed by Carr [8] to explain the origin of the outflow channels east of Tharsis), (2) gravitational compaction of aquifer pore space (perhaps aided by the accumulation of thick layers of sediment and basalt on the surface), and (3) regional-scale hydrothermal convection (e.g., associated with

major volcanic centers such as Tharsis and Elysium). Note that, with the exception of active geothermal areas, the flow velocities associated with these processes are likely to be orders of magnitude smaller than those that characterize precipitation-driven systems on Earth.

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THE EARLY MARTIAN ENVIRONMENT: CLUES FROM THE CRATERED HIGHLANDS AND THE PRECAMBRIAN EARTH.

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There is abundant geomorphic evidence to suggest that Mars once had a much denser and warmer atmosphere than present today. Outflow channels [1], ancient valley networks [2], and degraded impact craters in the highlands [3] all suggest that ancient martian atmospheric conditions supported liquid water on the surface. The pressure, composition, and duration of this atmosphere is largely unknown. However, we have attempted to place some constraints on the nature of the early martian atmosphere by analyzing morphologic variations of highland impact crater populations, synthesizing results of other investigators, and incorporating what is known about the geologic history of the early Earth. This is important for understanding the climatic evolution of Mars, the relative abundance of martian volatiles, and the nature of highland surface materials.

The duration of the martian primordial atmosphere and the interval of time water existed as a liquid on the surface can be estimated from the ages of features thought to have formed by fluvial processes. Formation of the large outflow channels occurred from the late Noachian (e.g., Ma'adim Vallis [4]) until the early Amazonian (e.g., Mangala Valles [5]). Formation of the ancient valley networks [6] and degradation of the cratered highlands [3] also occurred during this period, and the timing of both these processes appears to be dependent upon elevation. Formation of valley networks and degradation of highland impact craters ceased at higher elevations before they shut off at lower elevations. This implies that the highland volatile reservoir became depleted with time or, alternatively, the density of the martian atmosphere decreased with time. In the latter scenario, precipitation would occur throughout the highlands initially fairly independent of elevation. With time and loss of atmosphere, cloud condensation (and thus precipitation) could occur only at progressively lower altitudes. Condensation of the Earth's primordial steam atmosphere occurred ~4.0 b.y. ago [7]. Assuming that the martian primordial atmosphere

also condensed at approximately the same time (perhaps sooner given Mars' distance from the Sun), the maximum interval of time liquid water existed on the surface is either ~1.2 b.y. or ~450 m.y. The differences in these estimates are due to the uncertainties in the absolute ages of the martian periods and are based on two different models of the cratering flux at Mars [8,9 respectively].

Because the early Sun is thought to have had a lower luminosity than today [10], ~5 bar of CO_2 may have been needed to maintain the ancient martian surface temperature above freezing [11]. On the other hand, models incorporating early solar mass loss [12] suggest that early solar luminosities were actually much higher than today. This would allow the early martian atmosphere to be much thinner (~1 bar) and yet warm enough for liquid water. Regardless, the age and elevation relationship of features contained in the cratered highlands suggest that the pressure of the martian primordial atmosphere was never fixed at a high level but steadily decreased to <1 bar at about the beginning of the Amazonian. If sapping and seepage of groundwater were the mechanisms for ancient valley network formation [2] and highland degradation [3], a recharge mechanism is still needed for the aquifer in order to maintain these processes over the interval of time they were operating (tens to hundreds of millions of years at any given elevation). Again, martian atmospheric pressures must have been maintained >1 bar for a long time in order to produce the weather patterns necessary to efficiently recharge the highland aquifer at higher elevations. Based on the amount of time fluvial processes occurred on Mars, a rough estimate of the primordial atmospheric pressure is ~5–10 bar. Possible recharge of the atmosphere through impact-induced CO_2 [13] suggests that highland degradation may have also been periodic, but such a mechanism would have become less efficient with time to correlate with the age/elevation relations of highland features. If the weak Sun paradox is wrong [11], the primordial atmosphere would still need to be between ~5 and 10 bar initially to allow ancient valley network formation and highland degradation to occur over the interval of time observed.

The primordial terrestrial atmosphere and oceans were highly reducing [14]. Similarly, it is probable that Mars also had a primordial, highly reducing atmosphere and surface waters. Possible release of martian water in a CO_2-rich atmosphere by precipitation and channel-forming processes has led numerous investigators to speculate on the creation of massive martian carbonate deposits [e.g., 11]. The formation of such deposits would tend to remove CO_2 from the martian atmosphere and would require a substantially thick primordial atmosphere (~20 bar [11]) for ancient valley network and highland degradation processes to operate for ~450 m.y. or ~1.2 b.y. However, these hypotheses have been based on the assumption that an acidic primordial atmosphere (pH <1–3 [15]) was buffered by cations released through the weathering of rock. Precipitation of calcium carbonate occurs only in water with a high pH (>7.8 [16]). On Earth, precipitation of calcium carbonate did not become a common phenomenon until the Proterozoic (2.5 b.y.) when stable, shallow marine cratons developed, thus allowing weathered cations to concentrate [17]. Simply, terrestrial oceans were in existence ~1.5 b.y. before precipitation of calcium carbonate started to occur, and even then it was in unique circumstances!

On Mars two scenarios exist for standing bodies of water, the extreme being Oceanus Borealis [18]. This large ocean, thought to occupy much of the northern plains, postdates most of the fluvial features on Mars (up to the middle Amazonian), is needed to explain