THE EVOLUTION OF THE MARTIAN HYDROSPHERE AND ITS IMPLICATIONS FOR THE FATE OF A PRIMORDIAL OCEAN. S. M. Clifford[1] and T. J. Parker[2]. [1]Lunar and Planetary Institute, 3600 Bay Area Blvd, Houston, TX 77058; clifford@lpi.jsc.nasa.gov., [2]Jet Propulsion Laboratory, MS 183-501, 4800 Oak Grove Dr., Pasadena, CA 91109; tparker@mail1.jpl.nasa.gov.

The existence of a primordial ocean in the northern plains of Mars appears to have been an inevitable consequence of the hydraulic and thermal conditions that existed during the Early Noachian. In this abstract we demonstrate that the progressive crustal assimilation of this early surface reservoir of H_2O (punctuated by possible episodes of less extensive flooding) was a natural consequence of the planet's subsequent climatic and geothermal evolution.

Background. – The possibility that a large ocean once occupied the northern plains of Mars was first raised by Parker et al. [1,2], who identified evidence of potential shorelines in Viking Orbiter images. This interpretation has recently received additional support from elevation measurements made by the Mars Orbiter Laser Altimeter (MOLA). These measurements indicate that at least one of the putative shorelines lies along a boundary of near constant elevation – a result that is most easily explained by erosion associated with a fluid in hydrostatic equilibrium [3]. While the geologic evidence for a former ocean appears increasingly persuasive, the existence of a primordial ocean on Mars can be deduced independently by considering the hydraulic conditions required to explain the origin of the circum-Chryse outflow channels, and extrapolating them backwards in time.

The origin of the outflow channels during the Late Hesperian is generally attributed to the catastrophic release of groundwater from a sub-permafrost aquifer, whose discharge flowed from the equatorial highlands and into the northern plains. An essential requirement of this model is the need to maintain an elevated water table in hydrostatic disequilibrium with the planet's surface topography. This condition is made possible during the Late Hesperian by the confinement of groundwater beneath a thick layer of frozen ground, a hydraulic barrier whose existence is consistent with the climatic and geothermal conditions that are thought to have characterized the planet at this time.

Barring a mechanical or thermal disruption of the crust, the cryosphere is capable of confining groundwater under a significant hydraulic head as long as the hydrostatic pressure does not exceed the lithostatic pressure exerted by the local thickness of frozen ground, *i.e.*,

$$\rho_b g \Delta z \geq \rho_w g(\Delta h + \Delta z) \qquad (1)$$

where ρ_b ($\sim 2.5\times10^3$ kg m^{-3}) is the bulk density of frozen ground, Δz is its thickness, ρ_w ($\sim 10^3$ kg m^{-3}) is the density of liquid water, g (3.71 m s^{-2}) is the acceleration of gravity, and Δh is the height of the global water table above the local terrain.

Clearly, the hydrostatic pressure on the cryosphere will be greatest where the surface elevation is lowest. In the northern plains, this minimum lies near the pole [4]. The difference between the mean elevation of the outflow channel source regions and the north polar plains is ~4-5 km. Substituting this figure for Δh in (1), and solving for Δz, indicates that, at the time the channels were formed, 2.7-3.3 km of frozen ground would have been necessary to insure confinement. This value falls well within the 2.1-3.7 km-thickness of the polar cryosphere estimated from theoretical models of the thermal evolution of the crust. These calculations assume a geothermal heat flux of 65-95 mW m^{-2}, groundwater freezing temperature of 252-273 K, crustal thermal conductivity of 2.0 W m^{-1} K^{-1}, and a mean polar surface temperature of 154 K.

Implications for the Noachian. – While the thickness of the polar cryosphere was sufficient to support the elevated water table of the Late Hesperian, various lines of evidence suggest that substantially different conditions existed during the Noachian. In particular, the presence of the valley networks has been interpreted as evidence of an early greenhouse climate where rainfall and surface runoff occurred over much of the planet. If this interpretation is correct, then the distribution of the valley networks at latitudes as high as 65°S [5] indicates that the early climate was too warm, and the cryosphere too thin, to support a global water table equivalent to that which existed during the Late Hesperian.

Note that this conclusion is still valid, even if the early climate was cold. Given a cryosphere in equilibrium with the present range of mean annual surface temperatures, the resulting thickness of frozen ground would still have been too thin to support a Late Hesperian water table – a consequence of the 2-5x greater heat flux of the Early Noachian over the Late Hesperian [6]. Another consequence of this high early heat flow was that, during the Noachian, a substantially larger fraction of the planet's total inventory of H_2O must have existed as a liquid – effectively eliminating any remaining potential for widespread confinement.

In the absence of a sufficient confining layer, the distribution of water on Mars would have been dominated by its effort to reach hydrostatic equilibrium – responding to local perturbations caused by evaporation and precipitation (as well as seismic and thermal disturbances), by flowing to saturate the regions of lowest geopotential. Given the height of the global water table inferred from the later development of the outflow channels, an inevitable consequence of this behavior was the formation of a primordial ocean in the northern plains. The former existence of such a body is consistent with the tentative identification of ancient shorelines [1,2] and of features that resemble Icelandic table mountains throughout the northern plains [7].

Of course, the inability of the Noachian cryosphere to support a Late Hesperian water table raises the question of how such a relationship later evolved. The current absence of a large visible body of frozen water in the northern plains poses a similar question about the fate of the primordial ocean. The answers to both questions appear related, in that the assimilation of a primordial ocean may have charged the crust with the water required for the later development of the outflow channels. The process by which this occurred appears to be a natural consequence of the evolution of the post-Noachian climate and heat flow.

Early Thermal and Hydraulic Evolution. – While the Noachian may have started warm, theoretical models of atmospheric evolution suggest that, at its close, the transition to the current climate was probably rapid, taking $<10^7$ years [8]. With the onset of these colder conditions, and the exponential decline in the planet's internal heat flow, several things began to happen. In the northern plains, the primordial ocean began to freeze, developing an ice cover that thickened with both time and increasing latitude; similarly, in the south, a freezing front developed in the highland's crust that acted as a cold-trap for the condensation of H_2O.

The expanding thickness of frozen ground in the cratered highlands had three important effects:

First, as ice condensed within the near-surface pores, it sealed off the water in the deeper crust from any further contact with the atmosphere [9]. Given a reasonable estimate of the large-scale permeability of the crust (*i.e.*, ≥10 md), the elimination of atmospheric recharge would have led to the decay of any precipitation-induced influence on the shape of the highland water table in $\sim 10^7$ years. Following this adjustment, the highland groundwater and ice-covered ocean were effectively in hydrostatic equilibrium – a condition that necessarily persisted until the ocean was frozen to its base.

Second, as the cryosphere deepened with time, the condensation of ice behind the advancing freezing-front created a growing sink for the planet's inventory of groundwater. Where the cryosphere and water table were in direct contact, the transition from groundwater to ground ice was straightforward. However, in many locations throughout the highlands, the vertical distances separating the base of the cryosphere from the water table may have been measured in kilometers. Under such conditions, the depletion of groundwater occurred in response to the local geothermal gradient, which pumped water vapor from the higher temperature (higher vapor pressure) depths, to the colder (lower vapor pressure) pore space behind the advancing freezing-front [9]. As discussed later, the resulting decline in the planet's inventory of groundwater limited the potential for later episodes of flooding in the northern plains.

A final consequence of the thickening cryosphere was its increased ability to confine a groundwater system under significant hydraulic head. However, this potential alone does not explain the elevated water table of the Late Hesperian unless a corresponding mechanism can be identified for charging the subsurface with groundwater.

Crustal Assimilation by Polar Basal Melting. – The mechanism we propose for the crustal assimilation of a primordial ocean is similar to that originally advanced by Clifford [10] to explain the removal and subsurface storage of an ancient Martian ice sheet. The process is initiated when the instability of ice at low-latitudes leads to the redistribution and cold-trapping of H_2O at the poles. In response to this added layer of insulation, the melting isotherm at the base of the cryosphere will rise until thermal equilibrium is reestablished. As deposition at the surface continues, the melting isotherm eventually rises to initiate melting at the actual base of the deposits. By this process, the H_2O associated with a primordial ocean may have been introduced into the subsurface at both poles, ultimately raising the water table of the global aquifer, confined by the cryosphere, to the level required by the elevated source regions of the outflow channels in the Late Hesperian. While this scenario outlines the basic process of crustal assimilation, there are some important details that are unaddressed by this simple picture – the most notable being the effect of the differing polar environments in the north and south on the evolution of their respective caps.

At the south pole, the deposition of H_2O, derived from the sublimation of ice at lower latitudes, contributed to the development of the perennial ice cap and the recharge of the global water table by basal melting. However, in the north, the presence of an ice-covered ocean over the pole caused it to evolve in a much different manner. Because the mean polar surface temperature and local heat flow fixed the thickness of ocean ice, the deposition of H_2O over its surface necessarily resulted in the melting of an equivalent layer at its base. This fact, combined with the inability of the underlying water to support a topographically-induced basal shear stress, precluded the development of a north perennial cap until the primordial ocean was frozen throughout. Ultimately, the continued propagation of the freezing front into the underlying crust provided an anchor that allowed the processes of sublimation and deposition to reshape the topography of the northern plains through the redistribution of ice.

One of the earliest manifestations of this change was the formation of the north polar cap. But perhaps the most important consequence of the deepening cryosphere was its greater confinement potential – an attribute that enabled the hydrosphere to begin its slow evolution away from hydrostatic equilibrium. While the thermal conductivities of ice and rock are nearly the same, their bulk densities are not. Thus, as the cryosphere deepened and encompassed more rock beneath the frozen northern ocean, its ability to confine a groundwater system under significant hydraulic head also increased. It was this critical factor that allowed the global water table to rise in the highlands as the H_2O from the subliming primordial ocean was assimilated into the crust by basal melting.

Rise of the Global Water Table and the Potential for Episodic Reflooding. – The density difference between ice and rock also suggests that the potential for reflooding the northern plains was greatest during the early development of the north polar cap. This is because the stability of the cap, and the global aquifer confined beneath it, depended on maintaining a lithostatic pressure greater than the hydrostatic pressure exerted by the underlying groundwater. However, due to both the low density of the polar ice and the position of the cap at the lowest point of the northern plains, the north polar cap is the most susceptible location for hydraulic disruption. Thus, if global water table rose too quickly, the local increase in hydrostatic pressure at the pole may have destabilized the cap – permitting the underlying aquifer to discharge to the northern plains until the local hydraulic head had fallen sufficiently for the cryosphere to refreeze and reestablish its hydraulic seal. Note that, even with a catastrophic failure of the north polar seal, the maximum potential flood level would have declined with time, as a larger fraction of the planetary inventory of H_2O was cold-trapped into the thickening cryosphere. As before, the water associated with these outbreaks eventually froze and was reintroduced into the crust by basal melting. As the planet cooled, and the cryosphere thickened, such outbreaks became less frequent – allowing the global water table to rise, as the bulk of the primordial ocean was assimilated into the crust. In this way, the water table ultimately rose to the level required to explain the Late Hesperian outflow channels.

The Present Epoch. – Theoretical studies suggest that some relic of the floodwaters that inundated the northern plains my still persist beneath the mantle of dust and debris that has accumulated since the water froze [11]. Given the potential for significant reflooding (associated with the evolution of the polar cap, outflow channel activity, and local disruptions of the cryosphere by impacts, earthquakes, and volcanism), the resulting volatile stratigraphy of the northern plains is likely to be quite complex – consisting of multiple layers of massive ice (meters to hundreds of meters thick) interfinged by thin layers of eolian sediments and volcanics. This possibility is consistent with MOLA observations of the extraordinary flatness of the northern plains [12].

At the poles, the present thickness of the north and south polar caps appears too thin to support melting at the base of the deposits under current climatic and geothermal conditions. This suggests that the melting isotherm currently lies several kilometers beneath the local surface of the polar crust (*e.g.*, as in Figure 4b of [10]). Although a detailed reconstruction of the thermal and volatile history of the caps will require extensive *in situ* investigations, it is possible to identify several factors that may have influenced their recent basal evolution.

Clearly, as the geothermal heat flux has declined with time, the thickness of the polar deposits required for basal melting has increased. If this decline occurs faster than new material is being deposited at the poles, then the melting isotherm will retreat into the underlying crust. However, should a large impact, or renewed volcanic and outflow channel activity, suddenly introduce a large volume of water into the atmosphere and surface environment, then the resulting increase in polar deposition could easily reverse the deeper propagation of melting isotherm in response to the decline in planetary heat flow. Should the polar deposits then grow thick enough to undergo deformation at their base, a sliding velocity of as little as 10 m yr^{-1} under a basal shear stress of 100 kPa would be sufficient to cut the required thickness for basal melting by half [10]. Changes in polar insolation due to the chaotic evolution of the obliquity cycle may also enhance or further inhibit the conditions for basal melting over time. Depending on the magnitude of such events, the potential for basal melting can vary significantly over geologically short timescales, even during the present epoch.

Summary. – This analysis suggests that the existence of a primordial ocean on Mars was an inevitable consequence of the hydraulic and thermal conditions that existed during the Early Noachian. It further suggests that the assimilation of the resulting frozen ocean, and the episodic reflooding of the northern plains, was a natural result of the evolution of the post-Noachian climate and heat flow. Whether the early climate was warm or cold, the former presence of a standing ocean in the northern plains has profound implications for the potential development of life and subsequent hydrologic evolution of the planet [13].

References : [1] Parker et al., Icarus 82, 111, 1989; [2] Parker et al., JGR 98, 11061, 1993; [3] Head et al., GRL 25, 4401, 1998; [4] Zuber et al., Science 282, 2023, 1998; [5] Baker et al., in Mars, U. of Arizona Press, 493, 1992; [6] Schubert et al., in Mars, U. of Arizona Press, 147, 1992; [7] Allan, C. C., JGR 84, 8048, 1979; [8] Haberle et al., Icarus 109, 102, 1994; [9] Clifford, S.M., JGR 98, 10973, 1993; [10] Clifford, S.M., JGR 92, 9135, 1987; [11] Carr, M. H., Icarus 87, 210, 1990; [12] Zuber et al., GRL 25, 4393-4396, 1998; [13] Clifford, S. M. and T. J. Parker, submitted to *Icarus*, 1999.