Early Mars hydrology: 2. Hydrological evolution in the Noachian and Hesperian epochs

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[1] Mars was warmer and wetter during the early to middle Noachian, before a hydrologic and climatic transition in the late Noachian led to a decrease in erosion rates, a change in valley network morphology, and a geochemical shift from phyllosilicate to sulfate formation that culminated in the formation of widespread sulfate-rich sedimentary deposits in Meridiani Planum and the surrounding Arabia Terra region. This secular evolution was overprinted by episodic and periodic variability, as recorded in the fluvial record, sedimentary layering, and erosional discontinuities. We investigate the temporal evolution of Martian groundwater hydrology during the Noachian and early Hesperian epochs using global-scale hydrological models. The results suggest that the more active hydrological cycle in the Noachian was a result of a greater total water inventory, causing a saturated near-surface and high precipitation rates. The late Noachian hydrologic, climatic, and geochemical transition can be explained by a fundamental shift in the hydrological regime driven by a net loss of water due to impact and solar wind erosion of the atmosphere. Following this transition, the water table retreated deep beneath the surface, except in isolated regions of focused groundwater upwelling and evaporation, producing the playa evaporites in Meridiani Planum and Arabia Terra. This long-term evolution was modulated by shorter-term climate forcing in the form of periodic and chaotic variations in the orbital parameters of Mars, resulting in changes in the volume of water sequestered in the polar caps and cryosphere. This shorter-term forcing can explain the observed periodic and bundled sedimentary layering, erosional unconformities, and evidence for a fluctuating water table at Meridiani Planum.


1. Introduction

[2] The ancient surfaces of Mars preserve a record of warmer and wetter conditions in which liquid water played an important role in shaping the surface. Multiple lines of evidence are converging toward a consensus picture of the phenomenological history of water on early Mars. In the early Noachian, conditions were generally warmer and wetter than today, though likely arid by terrestrial standards [Howard et al., 2005; Stepinski and Stepinski, 2005; Barnhart et al., 2009]. These conditions led to the formation of dendritic valley networks [Carr and Malin, 2000; Craddock and Howard, 2002; Hynek and Phillips, 2003] and resulted in the alteration of some of the near-surface materials to phyllosilicates [Poulet et al., 2005; Bibring et al., 2006]. A significant shift in the ambient environment in the late Noachian

led to drier conditions, as recorded in a transition from dense runoff valleys to more sparsely dissected networks [Baker and Partridge, 1986; Harrison and Grimm, 2005], the cessation of valley network formation [Fassett and Head, 2008], a decrease in erosion rates [Golombek et al., 2006], and a change from widespread phyllosilicate alteration [Poulet et al., 2005] to the formation of localized evaporitic sulfate deposits [Bibring et al., 2006; Squyres et al., 2006]. The late Noachian to early Hesperian epochs were characterized by the formation of widespread playa evaporites in Meridiani Planum and related sedimentary deposits throughout the surrounding Arabia Terra region [Andrews-Hanna et al., 2010]. This secular evolution was overprinted by temporal variability on shorter time scales, expressed in the geologic record in evidence for a pulse of enhanced valley network formation in the Late Noachian [Irwin et al., 2005], periodic layering and bundling of layers within sedimentary deposits [Lewis et al., 2008], and erosional unconformities within the Meridiani sulfate deposits [Wiseman et al., 2010].

[3] This evidence for hydrologic and climatic variability over multiple time scales motivates a more detailed treatment of the time evolution of the hydrology of early Mars. We here
Evidence for the global hydrological evolution of early Mars history, a large total water inventory fueled high precipitation rates and a saturated near-surface zone, consistent with the widespread formation of phyllosilicates and valley networks in the early to middle Noachian. A net loss of water then drove a hydrologic and climatic transition in the late Noachian from wet conditions with a high level of surface and near-surface hydrologic activity, to arid conditions with a more sluggish hydrologic cycle and a surface that is desiccated across much of the planet. Following this transition, predicted regions of groundwater upwelling and evaporation match the observed distribution of sulfate-rich sedimentary deposits. Overprinting this long-term evolution, short-term changes in the available water inventory in response to periodic and chaotic changes in obliquity resulted in significant short-term variations in the precipitation and groundwater upwelling rates and the depth to the water table. These variations are shown to be consistent with the evidence for layer periodicity and bundling, and erosional discontinuities in the sedimentary record.

2. Observational Constraints on the Temporal Evolution of Martian Hydrology

2.1. Secular Evolution and the Late Noachian Transition

The widespread dendritic valley networks found throughout the low-latitude Noachian-aged terrains provide compelling evidence for more Earth-like conditions on early Mars [Carr and Clow, 1981; Baker, 1982; Carr and Chuang, 1997]. On the basis of the low drainage densities [Carr and Chuang, 1997] and morphologies similar to terrestrial groundwater sapping valleys on the Earth, it has been suggested that liquid precipitation and surface runoff may not have been required [Goldspiel and Squyres, 2000]. However, groundwater sapping mechanisms still require aquifer recharge, which must be brought about through either liquid precipitation or the accumulation and melt of snow, both of which would require warmer and wetter conditions than the current hyperarid cold desert. More recent high-resolution imaging and topographic data (Figure 1a) revealed that the drainage densities across much of Mars were significantly higher than previously thought [Irwin and Howard, 2002; Hynek and Phillips, 2003; Hynek et al., 2010], strengthening the argument for liquid precipitation.

Quantitative geomorphic analyses of the valley networks and comparisons to terrestrial fluvial systems suggest that conditions on early Mars were comparable to those on the Earth in arid environments today [Stepinski and Stepinski, 2005; Barnhart et al., 2009], consistent with the low erosion rates calculated for early Mars [Golombek et al., 2006]. A progression of valley network morphology is generally observed, from early formation of densely dissected, V-shaped, degraded valley networks suggestive of precipitation-induced runoff, to later formation of more sparsely dissected, U-shaped, pristine valley networks [Baker and Partridge, 1986; Williams and Phillips, 2001; Harrison and Grimm, 2005]. This transition has been interpreted as a result of either an increased contribution from groundwater sapping [Baker and Partridge, 1986; Williams and Phillips, 2001; Harrison and Grimm, 2005] or occasional flash flooding under arid conditions [Lamb et al., 2008]. Either interpretation of the transition in valley network morphologies suggests a drying of the climate...
with time, with a decrease in the precipitation and erosion rates and an increase in the depth to the water table below the surface [Harrison and Grimm, 2005]. This transition in the fluvial geomorphology was approximately contemporaneous with a decrease in the average surface erosion rates by several orders of magnitude in the late Noachian to early Hesperian [Golombek et al., 2006]. Similarly, landscape evolution models argue for a transition from both diffusive and advective erosion by rain splash and runoff, to primarily diffusive erosion by rain splash and mass wasting, arguing for increased infiltration and decreased runoff on an increasingly arid Mars [Craddock and Howard, 2002]. The record of both fluvial and nonfluvial erosion thus suggests that conditions in the Early Noachian were at least transiently similar to arid or semiarid environments on the Earth, but the surface became increasingly desiccated with time.

[7] These geomorphic interpretations of a climatic and hydrologic transition are corroborated by spectral observations of the Martian surface indicating a concomitant mineralogical transition. Spectral signatures indicative of the presence of phyllosilicates, including smectite, montmorillonite, and kaolinite, have been detected within ancient Noachian terrains across much of Mars (Figure 1b) [Poulet et al., 2005; Bibring et al., 2006; Mustard et al., 2008b]. Stratigraphic relationships suggest that phyllosilicate alteration predated the formation of the fluvial channels in at least some portions of the planet [Mustard et al., 2008a]. This is supported by improved estimates of valley network ages that place the termination of valley network formation at the Noachian–Hesperian boundary [Fassett and Head, 2008], after the termination of phyllosilicate formation prior to the end of the late Noachian [Bibring et al., 2006]. The early era of phyllosilicate formation was followed by an era of sulfate deposition in the late Noachian to early Hesperian [Bibring et al., 2006]. Unlike the widespread phyllosilicate deposits interspersed within the crust, the sulfates are generally stratigraphically above the ancient Noachian surfaces [e.g., Wiseman et al., 2008], and are localized primarily within the Meridiani Planum region in western Arabia Terra, as well as within the Valles Marineris canyons and chaos regions at the heads of the outflow channels [Gendrin et al., 2005; Murchie et al., 2009; Roach et al., 2010b]. The hydrated sulfate deposits are commonly associated with layered outcrops interpreted as sedimentary rocks (Figure 1c) [Malin and Edgett, 2000].

[8] In situ observations by the Mars Exploration Rover Opportunity at Meridiani Planum led to the interpretation of these deposits as evaporitic sulfate salts that have been extensively reworked by subaerial and fluvial processes in a playa-like environment, followed by multiple episodes of groundwater-mediated diagenesis [Grotzinger et al., 2005; McLennan et al., 2005; Squyres and Knoll, 2005; Arvidson et al., 2006; Squyres et al., 2006]. A similar origin has been suggested for the deposits in the canyons and chaos regions to the west, based on the stratigraphic similarities and the co-occurrence of sulfates and hematite observed in both locales [Glotch and Rogers, 2007; Murchie et al., 2009; Roach et al., 2010a], as well as similarities in the hydrological environment [Murchie et al., 2009]. Sulfate deposits outside of Arabia Terra, Valles Marineris, and the chaos regions appear to be restricted to isolated crater lakes such as Columbus crater to the west of Tharsis [Wray et al., 2011].

The transition from global phyllosilicate alteration to local and regional sulfate deposition has been suggested to signal a distinct change in the surface geochemical environment to more acidic and sulfate-rich conditions [Bibring et al., 2006], the cause of which is investigated in this work.

[9] The phyllosilicate–sulfate mineralogical and geochemical transition approximately coincides with the transitions in erosion rates and valley network morphology, suggesting a significant global hydrological, geochemical, and climatic change in the Late Noachian. This transition resulted in an increasingly arid surface, an increase in the depth to the water table, a decrease in the precipitation rates, and a transition from phyllosilicate to sulfate deposition. Arid, yet not fully desiccated, conditions then persisted in the Late Noachian and Early Hesperian, allowing the growth of local evaporite deposits while other evidence for water on the surface waned. Eventually, Mars transitioned into a colder climate, and further hydrological activity was limited to occasional outburst floods escaping from pressurized aquifers beneath a thick cryosphere to carve the outflow channels [Hanna and Phillips, 2006; Andrews-Hanna and Phillips, 2007].

2.2. Short-Term Periodic and Episodic Evolution

[10] The long-term secular drying of the surface and near-surface environment during the Noachian and Early Hesperian was overprinted by shorter-term temporal variability. Layering at the millimeter to centimeter scale observed by the Mars Exploration Rover Opportunity [Grotzinger et al., 2005] records the shortest time scale of variability. This finest-scale layering may correspond to annual cycles, individual sand avalanches down the slip faces of dunes, or other short time scale phenomena, but likely tells us little about the long-term climate evolution. A regular periodicity in the thickness of meter-scale layers deduced from HiRISE images and stereotopography for deposits across much of Mars argues for a periodic forcing mechanism (Figure 2a), likely supplied by orbital-driven periodicity in the climate evolution [Lewis et al., 2010] (also K. W. Lewis, Geologic setting of rhythmic sedimentary rocks on Mars, manuscript in preparation, 2011). Orbital control of the sedimentation is most clearly manifest in the cyclical bundling of layers into packets of 10 at Bucquerel crater (Figure 2b), which correlates with the 1.2 Myr cycle that modulates the maximum obliquity achieved during the shorter 120 kyr obliquity cycles [Laskar et al., 2004; Lewis et al., 2008].

[11] Variability of a more episodic, rather than periodic, nature is also observed in the geomorphic and sedimentary record. Erosional unconformities are observed in outcrops observed by Opportunity (such as the Welllington contact; Figure 2c) [Grotzinger et al., 2005] as well as in sedimentary layering in HiRISE images (Figures 2d–2e), suggesting temporary hiatuses in deposition accompanied by erosion of the deposits that could result from a change in the hydrologic or climatic environment. While angular unconformities such as these are observed relatively rarely from remotely sensed data, other depositional hiatuses may not have led to actual erosion of underlying strata before deposition resumed. The resulting parallel stratification would make detection of such an unconformity nearly impossible from orbit. Smaller-scale truncation surfaces in homogeneous lithologies such as the
example from Meridiani Planum may be common, but would be indiscernible to orbital instruments. On a larger scale, geomorphic and mineralogical mapping of the Meridiani deposits revealed a lateral facies change caused by erosion into preexisting layered deposits followed by deposition of relatively late stage sulfates, also suggestive of a hiatus in deposition leading to net erosion of the deposits, followed by continued sulfate deposition [Wiseman et al., 2010]. A similar erosional unconformity has been documented within the interior layered deposits in western Candor Chasma [Fueten et al., 2008].

Evidence also suggests temporal variability in the rate of valley network formation. Globally, valley network formation appears to have peaked toward the end of the Noachian [Howard et al., 2005; Irwin et al., 2005; Fassett and Head, 2008], reflecting a late increase in fluvial activity. Smaller-scale spatiotemporal variability in valley network activity is observed on the scale of individual drainage basins [Hoke and Hynek, 2009]. Combined with the evidence for a drying of the climate and a mineralogical transition in the late Noachian to early Hesperian, this late stage pulse of fluvial activity suggests that the transition from wet to dry conditions may have been both rapid and complex, possibly involving some overlap or interfingering of the periods of fluvial erosion and sulfate deposition.

Taken together, these various lines of evidence point toward short- and long-term variability in the hydrologic and climatic cycle of early Mars. This variability includes both periodic variations on time scales of 120 kyr to 1.2 Myr expressed in sedimentary layering, as well as episodic shifts in the hydrologic-climatic conditions expressed in erosional unconformities and changes in the rate and style of fluvial modification of the surface. While the concept of a transition from warm and wet to cold and dry conditions still holds to first order, this secular evolution was overprinted by the more complex behavior expected of a real climate system. While previous models of the hydrologic evolution of Mars have been successful in reproducing the observed equatorial sulfate deposits in Meridiani Planum and Arabia Terra [Andrews-Hanna et al., 2007, 2010], it is necessary to consider a more realistic representation of the temporal evolution of the hydrologic-climatic system. In the following sections, we investigate the temporal evolution of the hydrological cycle on early Mars from a groundwater perspective, focusing on the distributions of valley networks and sedimentary deposits, the underlying mechanisms controlling the Late
3. Groundwater Model Description

[14] We model the groundwater hydrology of early Mars using a fully explicit finite difference code representing unconfined groundwater flow in a spherical shell grid [Andrews-Hanna et al., 2007, 2010]. The models were run at a spatial resolution of 2.5 degrees per pixel. The aquifer properties are taken from the megaregolith model of Hanna and Phillips [2005]. Groundwater flow is driven by gradients in the hydraulic head, which are established as a result of precipitation-induced recharge in the low latitudes and evaporative loss of groundwater in regions where the water table reaches the surface. Full details and benchmarking of the hydrological model can be found in the companion paper [Andrews-Hanna et al., 2010].

[15] Conditions on early Mars are assumed to be arid by terrestrial standards, even during the period of valley network formation, as suggested by the low drainage densities and immature state of the fluvial landscape [Howard et al., 2005; Steinskin and Steinskin, 2005; Barnhart et al., 2009]. Groundwater is assumed to evaporate upon reaching the surface, thereby limiting the water table to remain at or beneath the surface. The presence of small-scale lakes and seas would not greatly affect the large-scale patterns of groundwater flow, since they would exist below the model resolution and would only change the local hydraulic head by a small amount. Large oceans in the northern lowlands [e.g., Di Achille and Hynek, 2010] or the Hellas and Argyre impact basins [Moore and Wilhelms, 2001] would have a more significant effect on the patterns of groundwater flow, though the existence of such water bodies is controversial. The model does not include such possible ancient oceans or seas, though their possible effect is discussed in section 4.

[16] The globally integrated evaporative loss of water in each time step is redistributed over the surface in a low-latitude precipitation belt, following a half-cosine distribution between ±45° latitude to match the first-order distribution of valley networks. This implicitly assumes that the conditions that prevented high-latitude valley network formation would have inhibited aquifer recharge as well. The lack of high-latitude valley networks may be a result of either a lack of precipitation, or persistently cold temperatures that would have prevented both runoff and infiltration of precipitation.

[17] The companion paper [Andrews-Hanna et al., 2010] demonstrated the importance of the dynamic interaction between the hydrology and the surface topography. Groundwater-mediated sedimentation alters the surface topography, which in turn alters the distribution and flow paths of groundwater. The formation of evaporites and evaporite cemented sedimentary deposits is represented in the models by assuming a groundwater salinity upon reaching the surface equal to 80% that of seawater [e.g., Handford, 1991], and that the deposits incorporate 50% by volume of clastic sediments based on Mini-TES observations at Meridiani [Glootch et al., 2006] and similar to other dirty evaporites in playas settings, such that evaporation of 100 m of groundwater produces 2 m of sediments. Assuming either different fluid salinities or different aquifer permeabilities results in a simple scaling of the rate of fluid flow and deposition. While there are great uncertainties in both of these parameters, the previous study found that the predicted rates of sedimentary deposition in Becquerel crater closely match the rates inferred from a correlation of the layer periodicity with the time scale of obliquity variations [Lewis et al., 2008; Andrews-Hanna et al., 2010].

4. Long-Term Hydrological Evolution During the Noachian and Hesperian

4.1. Hydrological Controls on Sulfate Deposition

[18] We first briefly review the results of the earlier work on the groundwater-mediated formation of evaporitic sulfates in the Late Noachian to Early Hesperian [Andrews-Hanna et al., 2007, 2010]. Previous groundwater hydrology models found that Meridiani Planum and the surrounding Arabia Terra region were areas of focused groundwater upwelling to the surface, driven by the regional topography of Arabia Terra [Andrews-Hanna et al., 2007]. In short, the breaks in slope on the northern and southern edges of Arabia Terra separating it from the lowlands and highlands, together with its location in the low latitudes where precipitation-induced recharge of aquifers was likely, led to a net flux of groundwater to the surface resulting in the formation of evaporites and evaporite cemented sediments.

[19] Subsequent high-resolution global and regional groundwater models that explicitly included the growth of sedimentary deposits through evaporite deposition and cementation of aeolian debris strengthened this prediction [Andrews-Hanna et al., 2010]. These models successfully predicted the approximate thickness and spatial extent of the Meridiani deposits, but also predicted that they should be part of a more extensive set of deposits covering much of the Arabia Terra region. Those predictions were borne out by observations of layered deposits, large intracrater deposits, and pedestal craters that preserve the remnant of this once more extensive set of deposits [Fassett and Head, 2007; Fergason and Christensen, 2008; Andrews-Hanna et al., 2010; Zabrisky and Andrews-Hanna, 2010]. The model results were found to successfully explain the measured dip [Hynek and Phillips, 2008] and inferred deposition rate [Lewis et al., 2008] of the deposits. Deposits are also predicted within the Valles Marineris canyons, where large sulfate-rich interior layered deposits are observed [Murchie et al., 2009]. Predicted deposits in topographic lows in the northern lowlands and large impact basins may be obscured beneath younger volcanic, sedimentary, and aeolian cover. Some support for ancient hydrological activity in the lowlands comes from recent observations of hydrated phyllosilicate outcrops exposed by craters in the northern lowlands [Carter et al., 2010], and evidence for mud volcanism possibly arising from a buried volatile-rich layer in Acidalia Planitia [Oehler and Allen, 2010].

[20] While the previous groundwater models considered the time evolution of the hydrological cycle for a fixed set of environmental conditions, they did not address the hydrological evolution in the face of an evolving climate on early Mars. Building on the success of the earlier work in explaining the salient features of the late Noachian to early Hesperian sedimentary record, we now investigate the temporal evolution of the hydrological cycle throughout early Mars history.
4.2. Effect of the Total Water Inventory: Wet and Arid Hydrological Regimes

[21] From a groundwater hydrology perspective, the hydrological state of the planet is determined primarily by the total water inventory available to the hydrologic system relative to the storage capacity of the global aquifer system, which is established in the models by the assumed initial mean water table depth below the surface (initialized at a constant depth prior to hydrological equilibration). This hydrologically available water inventory represents only that portion of the total water inventory that directly takes part in the hydrological cycle at any one time. The previous study [Andrews-Hanna et al., 2010] assumed a single constant value for the water inventory, for which the model predictions were found to be in agreement with the observed distribution of sulfate deposits. However, the hydrologically available water inventory of Mars is poorly constrained, and likely experienced significant periodic and secular changes over Mars history. A suite of global hydrological models were run with different assumed initial mean water table depths, ranging from 200 m to 1000 m. The models were run for 100 Myr to achieve hydrological equilibrium without any sedimentary deposition, and then run for an additional 50 Myr while tracking the evolving groundwater flux to the surface and sedimentary deposit thickness (Figure 3). This set of models assumed arid conditions leading to evaporite formation over the full range of initial mean water table depths and precipitation rates, an assumption we will break with in section 5.

[22] Models initialized with different initial mean water table depths produce substantially different outcomes. The strongest constraint on the nature of the hydrological cycle comes from the observed distribution and thickness of sulfate deposits formed in the Late Noachian to Early Hesperian. These deposits are localized primarily within Meridiani Planum and the surrounding Arabia Terra region, the Valles Marineris canyons, and the chaos regions at the sources of the outflow channels. The predicted extent of the deposits agrees

Figure 3. Hydrological model outputs for different initial mean water table depths (wt), representing different values of the hydrologically available water inventory. (left) Depth to the water table, (middle) predicted sedimentary deposit thickness after 50 Myr, and (right) distribution and rate of groundwater upwelling and evaporation after 50 Myr, for initial mean water table depths ranging from (top to bottom) 200 m to 1000 m.
In the wet regime models, the equilibrium storage capacity of the low-latitude aquifers is exceeded, so that the precipitation falls primarily on a saturated surface and the excess water continues to circulate through the climate system. While there is a dramatic difference between the hydrological behavior of Mars under wet and arid conditions, the transition between the two regimes is gradational rather than discrete (Figure 4).

[25] The high precipitation rates and the saturation of the surface in the wet hydrological regime violate the arid assumption in the models, and the precipitation would lead to runoff and ponding. With abundant water available at the surface, the rates of evaporation and precipitation would be dictated by the climate system [e.g., Richardson et al., 2007; Soto et al., 2010] rather than the groundwater system. The water table would lie at or near the surface over most of the planet, causing the groundwater hydrology to be dominated by short wavelength flow in local topographic basins [Grimm and Harrison, 2003]. The widespread evaporites predicted by the models as a consequence of the arid assumption (Figure 3b) would be replaced by fluvial erosion and ponding, dictated by the combination of the climatically controlled distribution of precipitation and the groundwater flow patterns.

[26] As the total water inventory is increased further, the wet hydrological regime would approach the present-day terrestrial hydrological cycle. The total water inventory on the Earth greatly exceeds the storage capacity of the crustal aquifers. The largest reservoir of terrestrial water is in the oceans, with less than 1% contained within aquifers [Deming, 2002]. As a result, there is at all times a large supply of water in direct communication with the Earth’s atmosphere, and the rates of precipitation and evaporation are dictated by the climate system rather than being limited by the rate of groundwater flow. Whether early Mars ever possessed oceans or a truly Earth-like hydrological system remains an open question.

[27] The model-predicted precipitation rates are likely lower bounds. These models assume that all of the precipitation infiltrates the surface (where it is not saturated) and contributes to recharging the deep aquifers. Thus, the precipitation rate in the models reflects only that part of the hydrological cycle involving exchange with the deep subsurface, with no explicit representation of runoff and ponding followed by evaporation prior to infiltration. Inclusion of a surface hydrological cycle would increase the actual precipitation rates significantly. In particular, the high precipitation rates in the wet regime would lead to runoff and ponding of a significant fraction of the precipitation. This surface reservoir of water would drive higher rates of precipitation [Soto et al., 2010] and a more vigorous hydrological cycle than can be represented in these groundwater hydrology models without an explicit representation of the atmospheric component of the hydrological cycle. The actual precipitation rates in the wet regime would be determined by the climate system rather than the groundwater hydrology. Similarly, during the arid regime a significant fraction of the precipitation may evaporate prior to infiltration, increasing the actual precipitation rate relative to the model value. For example, if only 20% of the precipitation infiltrated the surface to reach the deep aquifers, the actual precipitation rates would be a factor of 5 higher than predicted by the models.
4.3. Hydrological Controls on the Distribution of Valley Networks

[28] Just as the predicted regions of groundwater upwelling in the arid regime match the observed distribution of sulfates, the predicted distribution of near-surface groundwater during the wet regime with a greater available water inventory shows some correlation with the observed distribution of valley networks. The models predict a shallow water table in the low-latitude precipitation belt, with a much deeper water table in high southern latitudes resulting from the lack of precipitation-induced recharge at high latitudes and the presence of the Hellas basin acting as a hydrological sink. While this contrast between low and high latitudes is imposed in the models by the assumed precipitation distribution, the models also predict significant longitudinal differences in the midlatitudes, breaking with the longitudinal symmetry of the imposed zonal precipitation belt.

[29] In the southern midlatitudes, the water table lies much deeper beneath the surface surrounding the Hellas impact basin, while lying closer to the surface in the vicinity of Tharsis (e.g., Figure 3d). As a result of its great depth, Hellas acts as a large hydrological sink, drawing down the water table in the surroundings. The imposed low-latitude recharge belt over the northern half of the basin results in an asymmetric drawdown cone toward the south. In contrast, the high topography of Tharsis drives groundwater flow southward into the surrounding highlands, pushing the water table closer to the surface south of Tharsis. This large-scale pattern in the distribution of shallow groundwater is in first-order agreement with the observed distribution of valley networks (Figure 1a) [Carr, 1995; Hynek and Phillips, 2003; Stepiński and Collier, 2004; Hynek et al., 2010]. While the northern edge of the valley network distribution is imposed by the dichotomy boundary and the resurfacing of the northern lowlands, the southern edge follows an approximate great circle path dipping southward near Tharsis and northward near Hellas [Mutch et al., 1976]. The southern edge of the valley network distribution approximately coincides with the transition from a shallow water table in the low latitudes to a deep water table in the middle to high latitudes.

[30] This similarity suggests that the distribution of groundwater may exert some control over the formation of the valley networks, as might be expected given the importance of base flow from groundwater to rivers and streams on the Earth [Deming, 2002]. However, the specific fit of the valley networks from recent high-resolution mapping [Hynek et al., 2010] to the predicted regions of shallow water table is only approximate, suggesting that other processes likely also exerted a significant control over valley network formation, including spatial variations in the rate of precipitation on the surface [Soto et al., 2010].

4.4. Implications for the Long-Term Hydrologic and Climatic Evolution of Mars

[31] We suggest that the wet and arid hydrological regimes map approximately onto the Noachian and late Noachian–early Hesperian periods, respectively. Throughout much of the Noachian, the widespread valley networks, high erosion rates, and evidence for phyllosilicate formation suggests abundant near-surface water and elevated precipitation rates throughout the low latitudes. The decrease in erosion rates [Golombek et al., 2006], transition in valley network morphology [Baker and Partridge, 1986; Harrison and Grimm, 2005], and ultimate cessation of widespread valley network formation [Pavlov and Head, 2008] in the Late Noachian is consistent with the dramatic decrease in precipitation rates and the drop in the water table predicted for a wet to arid hydrological transition (Figures 3 and 4).

[32] Similarly, the geochemical change from widespread phyllosilicate formation to localized sulfate deposition [Bibring et al., 2006] would have been a natural outcome of the wet to arid hydrological transition. During much of the Noachian, the abundance of low salinity, near-neutral pH, meteoric rainwater and shallow groundwater would encourage widespread alteration of the primary igneous mineralogy to phyllosilicates. After the hydrological transition, the precipitation would rapidly infiltrate the arid surface over most of the planet, recharging aquifers deep beneath the surface without prolonged interaction with the near-surface crust. However, in a few regions, that coincide with the locations of observed sulfate deposits, this deep groundwater would reach the surface after flowing long distances in the subsurface. This upwelling groundwater would have had ample time to equilibrate with the aquifer host rocks and acquire a high solute concentration. Upon reaching the photochemically oxidized shallow subsurface, the fluids would develop a low pH and high concentration of sulfates [Burns, 1993; Burns and Fisher, 1993; Hurowitz et al., 2010]. Oxidation of the near-surface materials and fluids would have been encouraged by physical mixing of the playa deposits within dunes which would have enabled atmospheric and photolytic oxidation to penetrate to greater depths, and fluctuations in the height of the water table which would have allowed alternating oxidation of the near-surface sediments and fluid-sediment interaction. Laboratory experiments and geochemical models in which basaltic weathering fluids are evaporated under oxidizing conditions successfully predict the observed mineralogy at Meridiani, and further show a decreasing pH with evaporitic concentration [Tosca et al., 2005]. The surface geochemistry in regions of groundwater upwelling would be dominated by the chemistry of the upwelling brines, with evaporation leading to localized precipitation of sulfate minerals, including jarosite [Burns, 1993].

[33] Previous studies suggested that the geochemical transition from phyllosilicate to sulfate deposition may have been triggered by an increase in Tharsis outgassing in the Late Noachian [Bibring et al., 2006]. However, Tharsis outgassing alone fails to explain the change from broadly distributed phyllosilicates to locally concentrated sulfates within a few isolated regions [Bibring et al., 2006; Mustard et al., 2008b]. Layered deposits that appear to be genetically related to the Meridiani sulfate deposits extend to the eastern edge of Arabia Terra [Andrews-Hanna et al., 2010; Zabrusky and Andrews-Hanna, 2010], a distance of more than 5000 km from the edge of Tharsis. More than half of the planet lies within this distance from Tharsis, and yet sulfate deposits outside of Tharsis are largely isolated to locations in Meridiani Planum and Arabia Terra.

[34] Tharsis outgassing also fails to explain the timing of the sulfate formation. Tharsis-induced tectonism peaked during the Noachian [Anderson et al., 2001]. Tharsis outgassing would thus have been active throughout the Noachian, much...
of which was dominated by phyllosilicate rather than sulfate formation. Volcanic outgassing would have also been a significant source of CO₂ and H₂O to the early Martian atmosphere [Phillips et al., 2001], and the release of sulfur and other greenhouse gases has been invoked to explain the warm and wet conditions on early Mars during the period of phyllosilicate formation [Halevy et al., 2007; Johnson et al., 2008]. Tharsis outgassing cannot simultaneously explain both the warm and wet conditions during the era of phyllosilicate alteration and valley network formation, and the later transition to arid conditions and sulfate deposition. While Tharsis outgassing was likely an important contributor of sulfur to the atmosphere and hydrosphere of early Mars, we suggest that the transition between phyllosilicate alteration and sulfate deposition in the Late Noachian and the specific distribution of sulfates are the results of a hydrologic and climatic transition driven by a decrease in the hydrologically available global water inventory relative to the storage capacity of the crustal aquifers.

4.5. Water Loss Mechanisms and the Hydrological Transition

[35] The wet to arid hydrological transition corresponds to a change in the initial mean water table depth from approximately 200 to 600 m, resulting in a transition from a saturated near-surface throughout the low latitudes to a focusing of hydrological activity at Meridians Planum and Arabia Terra. This corresponds to a net loss of a global equivalent layer (GEL) of ~60 m of water, assuming a mean near-surface porosity of 0.15 [Hanna and Phillips, 2005]. Such a change could be brought about by either decreasing the total water inventory, or by increasing the storage capacity of the crustal aquifers or other storage reservoirs.

[36] Evidence for a decrease in the total water inventory of Mars is found in the elevated D/H ratios in the Martian atmosphere, interpreted as resulting from the erosion of atmospheric water by solar wind sputtering [Yung et al., 1988; Donahue, 1995; Jakosky and Jones, 1997]. Impact erosion of the atmosphere would have also contributed significantly to the loss of water [Melosh and Vickery, 1989]. The combined effects of solar wind sputtering and impact erosion may have eroded 95-99% of the early Martian atmosphere since the onset of the geologic record, with the vast majority occurring during the early Noachian [Brain and Jakosky, 1998]. Lesser amounts of atmospheric water loss are possible if the elevated deuterium concentration in Martian water were due in part to a greater cometary contribution to the primordial water inventory of Mars relative to the Earth [Lunine et al., 2003]. In section 5.1, we show that the loss rates due to solar wind stripping and impact erosion combined with estimates of the present-day water inventory predict the loss of a GEL of ~80 m of water during the late Noachian and early Hesperian epochs, which is sufficient to trigger a wet to arid hydrological transition.

[37] Alternatively, a number of mechanisms exist for increasing the total storage capacity of Martian water reservoirs, which would be accompanied by a drop in the water table and could trigger a wet-arid hydrological transition. The storage capacity of the aquifers could be increased by an increase in porosity due to continued impact-induced brecciation of the surface. An increase in the porosity of the top 5 km by only 0.01 could trigger a wet to arid hydrological transition. Water can also be removed from the active hydrological system by sequestration within the polar caps and the high-latitude ground ice as the climate cooled. It is not known whether the polar caps on early Mars under different pressure, temperature, and humidity conditions would have been larger or smaller than their present size, but they nevertheless constitute a possible reservoir for increased storage of water as ice. The present-day south polar cap and layered deposits are volumetrically dominated by water ice [Zuber et al., 2007] and are estimated to contain a GEL of 11 m of water [Plaut et al., 2007]. Assuming flat basal topography beneath the north polar layered deposits [Phillips et al., 2008], this repository contains a GEL of ~5 m of water. The near-surface high-latitude regions today contain also a significant fraction of ground ice [Feldman et al., 2004]. The top 1 km of the crust poleward of 60°S latitude could contain a GEL of ~6.5 m of water, assuming a mean fractional ice content of 10%. Freezing or melting of north polar permafrost will not significantly change the total water storage, since its location at low elevation would result in this region being water saturated under warm conditions, and the replacement of water with ice does not significantly change the total storage. These cryosphere reservoirs add up to the potential to change the total storage of water as ice by a 22 m GEL of water, which falls short of the volume required to induce a wet to arid transition but may have played a prominent role in short-term forcing of the hydrological cycle as discussed in section 5.

[38] While it is difficult to place firm bounds on the loss of water or increase in storage capacity that can be attributed to any one mechanism, it is clear that the sum total of all mechanisms is more than sufficient to account for the 60 m GEL loss or storage of water necessary to induce the wet-arid hydrological transition in the late Noachian. The net loss of water from Mars over time is supported by both geomorphic evidence for a wetter surface on early Mars and isotopic evidence for water loss from the atmosphere. The model results and interpretations above suggest that the observed geomorphic and geochemical evidence for the hydrologic and climatic evolution of Mars can be understood in terms of a wet to arid hydrological transition in the late Noachian driven by this net loss of water. While the specific loss history is poorly constrained, one scenario for the evolving water inventory and its hydrological ramifications is explored in detail in section 5.

5. Secular, Episodic, and Periodic Variability of the Hydrologic Cycle

5.1. Short- and Long-Term Evolution of the Available Water Inventory

[39] Based on the evidence for both the secular evolution and shorter-term perturbations to the hydrologic and climatic cycle described in section 2, and the sensitivity of the hydrological cycle to variations in the available water inventory demonstrated in section 4, we now investigate in more detail a specific scenario for the temporal evolution of the hydrology of early Mars. We first generate a simplified scenario for the evolution of the hydrologically available water inventory that reproduces qualitatively and at least semiquantitatively the magnitudes and time scales of the key processes at work. At present, there are no firm quantitative
constraints on the temporal evolution of the Martian water inventory, though numerous studies have investigated the various processes thought to have played a role. We synthesize the results of these studies into a quantitative representation of the evolving water inventory, including secular loss to solar wind stripping and impact erosion, and the changing storage of water in the cryosphere in response to orbital forcing. This scenario is not meant to be a unique predictor of the changes in water inventory, but rather to serve as a physically plausible proxy in order to enable an investigation of the hydrological ramifications.

[40] We first consider the secular evolution of the total water inventory, driven by loss over time to solar wind stripping and impact erosion of the atmosphere. These processes both act in a fractional sense on the amount of water in direct contact with the atmosphere at any one time. In order to construct a time series of the change in water inventory, we take the present-day inventory of an estimated 29 m GEL of water within the polar caps and near-surface ground ice from the section 4 (including the ground ice in the northern high latitudes) as representative of the volume in contact with the atmosphere in the present epoch. The present-day deep water inventory is unknown, but may be small due to the gradual desiccation of the subsurface [Grimm and Painter, 2009] and is not currently in direct communication with the atmosphere. We then reverse the loss rate to calculate the change in water inventory with time in the past, assuming that any increase in the water inventory in the past relative to the present remained in direct communication with the atmosphere. While this approach is an oversimplification, it allows the generation of an evolutionary scenario for the total water inventory that is both quantitative and consistent with hypothesized loss mechanisms.

[41] Water is lost to solar wind stripping at a constant fractional rate of 90% [Brain and Jakosky, 1998]. This neglects the possible shielding effect of an early actively generated magnetic field. Demagnetization of the giant impact basins suggests that the dynamo ceased by the early to middle Noachian [Mohit and Arkani-Hamed, 2004; Lillis et al., 2008], prior to the formation of much of the observed population of valley networks. Water is also lost to impact erosion of the atmosphere at a rate that varies with time in proportion to the impact flux [Melosh and Vickery, 1989]. Combining the impact and solar wind erosion of the atmosphere, the resulting evolution in the total water inventory yields a loss of 109.1 m GEL between 4.0 and 3.0 Ga, representing the middle Noachian through late Hesperian (Figure 5). During this time, an 80.4 m GEL is lost between 4.0 and 3.7 Ga, representing the middle and late Noachian and bracketing the time of the hydrologic and climatic transition. This loss history is consistent with the loss of a ~60 m GEL required between the onset of the geologic record and the late Noachian in order to induce the hydrologic and climatic transition from wet to arid conditions.

[42] Over shorter time scales, the evolution of the hydrologically available water inventory was likely driven primarily by changes in the storage of water in the polar caps and high-latitude permafrost induced by the orbital evolution of Mars. Short-term climate change is driven primarily by the 120 kyr obliquity cycle, with the maximum obliquity within this cycle modulated on a longer 1.2 Myr time scale [Laskar et al., 2004]. This regular behavior is overprinted by significant shifts in mean obliquity, commonly reaching mean values as high as 50° or as low as 10°. The evolution of the orbital parameters of Mars are reasonably well constrained for the past ~20 Myr, but over longer time scales the behavior is chaotic and unpredictable [Laskar et al., 2004]. It is impossible to uniquely determine the evolution of Mars’ obliquity and other orbital parameters over the past 4.5 Ga. However, the fundamental nature of the periodic and chaotic variations in the orbital parameters is similar in multiple simulations of the past 250 Ma. The 120 kyr obliquity cycle and its 1.2 Myr modulation persist through all simulations, while chaotic shifts in mean obliquity lead to periods of sustained high and low obliquity of variable duration. There is no indication that this general behavior would have changed appreciably since the orbits of the giant planets were stabilized after the Late Heavy Bombardment at 3.9 Ga [Gomes et al., 2005]. We adopt a single 250 Myr orbital simulation from Laskar et al. [2004] (solution 301003BIN_A.P001, available on the Web at http://www.imece.fr/Equipes/ASD/insola/mars/mars.html), as representative of the periodic and chaotic changes in orbital parameters. This simulation includes long periods of stability at both high and low obliquity, as well significant shorter obliquity excursions.

[43] We next relate this orbital evolution to the changing storage of water as ice in the cryosphere. Conditions on early Mars may have been similar to those on the Earth today, in which the total volume of water stored as ice in the polar caps, glaciers, and permafrost of the Earth is highly sensitive to changes in climate driven by orbital Milankovitch cycles [Crowley and Kim, 1994; Huybers and Wunsch, 2005]. The specific climatic conditions that prevailed on Mars in the Noachian and Hesperian are unknown, as are the conditions that governed the stability of the polar caps and cryosphere at that time. Nevertheless, the stability of the present-day polar caps and cryosphere have been shown to be highly sensitive to changes in the latitudinal distribution of insolation driven by the orbital evolution [Mellon and Jakosky, 1995; Levrard et al., 2007]. The stability of the north polar layered deposits has been parameterized as a function of the orbital parameters
for present-day Mars [Levrard et al., 2007]. The polar ice loss is primarily a function of the insolation at the summer solstice, while the polar ice gain is primarily a function of obliquity [Levrard et al., 2007]. The south polar layered deposits appear to be more stable than the north, though the specific dependence of the cap stability on the orbital evolution has not been investigated. As a first-order approximation, we use the stability conditions for the present-day north polar layered deposits as a function of obliquity and summer solstice insolation as a proxy for the stability of both polar caps and the permafrost on early Mars. While this approach is not strictly valid for the higher atmospheric pressure, temperature, and humidity likely on early Mars, it provides us with a simple means of representing the sensitivity of the storage of ice within the cryosphere on the orbital evolution and must suffice until future climate models provide more firm constraints on the early cryosphere and hydrosphere evolution. 

This approach neglects the possibility of the redeposition of ice in the low latitudes. Under the present cold climatic conditions, ground ice becomes more stable in the low to middle latitudes during periods of high obliquity while liquid water is everywhere unstable, and obliquity cycles primarily redistribute ice between the polar caps and ground ice [Mellon and Jakosky, 1995]. Under warmer climate conditions, we expect a significant fraction of the ice released from the poles at high obliquity to enter into the hydrological cycle, as occurs on Earth. Periods of high obliquity decrease the temperature contrast between the equator and poles. If the global mean temperature was at or above the freezing point, then polar warming at high obliquity would likely lead to release of water to the hydrosphere rather than ice deposition in the low to middle latitudes, analogous to the sea level rise during interglacial periods triggered in part by high obliquity on the Earth [Crowley and Kim, 1994]. The polar cap stability models implemented here [Levrard et al., 2007] are specifically for the case of exchange with the atmosphere, and do not include the effects of polar basal melting [Clifford, 1993; Clifford and Parker, 2001]. Polar basal melting associated with changes in obliquity would lead to short-lived ground-water mounds beneath the polar caps following excursions to high obliquity and would diminish the hydrological response to short-term forcing, but would not alter the long-term behavior of the system.

The parameterization of polar cap stability from Levrard et al. [2007] is applied to the orbital evolution scenario from Laskar et al. [2004] to construct a representative 250 Myr time series of the obliquity, insolation at summer solstice, and the resulting change in water storage in the polar caps and cryosphere (Δw; Figure 6). The maximum polar cap volumes were set equal to those of the present-day caps, though larger polar caps may have been possible. The imposition of this upper bound is necessary to keep the polar caps from reaching arbitrarily large sizes at low obliquity, which would likely be unstable to outward viscous flow. This 250 Myr time series is then reflected and repeated to generate a 1 Gyr continuous time series. This short-term periodic and episodic forcing is superimposed over the secular loss of water due to solar wind stripping and impact erosion of the atmosphere for the period of interest between 4.0 and 3.0 Ga (model P001a; Figure 7a), spanning the middle Noachian through the late Hesperian epochs [Hartmann and Neukum, 2001]. A second representation of the variation in the available water inventory was generated by shifting the time series representing the orbital forcing of the cryosphere storage by 250 Myr relative to the secular loss time series (model P001b; Figure 8a), such that the shifts in mean obliquity and resulting changes in cryosphere storage occur at different times relative to the evolution of the total water inventory.

The resulting representations of the change in hydrologically available water in Figures 7a and 8a provide reasonable representations of the possible effects of atmospheric loss and orbital forcing on early Mars. We emphasize that these are not intended to be unique solutions of the evolution of the water inventory, as such is beyond the reach of our current understanding of early Mars. Rather, these are intended only to be plausible and self-consistent scenarios to enable a hydrological study of the implications of the time evolution of the water inventory.

5.2. Modeling the Noachian–Hesperian Hydrological Evolution

The secular evolution and short-term perturbations to the hydrologically available water inventory generated above were input into the hydrological model as forcing functions. As water is cycled between the subsurface and atmosphere in
the models through groundwater evaporation and precipitation, some fraction is added or removed in each time step to match the requirements of the applied changes in total water inventory due to the combined effects of atmospheric loss and either cold trapping of water in the cryosphere or release of water to the atmosphere and hydrosphere from melting or sublimation of the cryospheric ice.

In addition to the relative change in total water inventory, it is necessary to establish a reference point at which the total water inventory can be constrained. The initial mean water table depth at the beginning of the simulation (representing Mars at 4.0 Ga) is set such that Meridiani Planum and Arabia Terra are regions of localized groundwater upwelling at the Noachian–Hesperian boundary at ~3.7 Ga. This is achieved for an initial mean water table depth of approximately 200 m. Substantially greater or lesser values for the initial mean water table depth would result in models in which groundwater does not ever reach the surface in Meridiani, or the low-latitude surfaces are saturated throughout the simulation, respectively. The hydrological model is run for 100 Myr until equilibrium is achieved, and then the 1 Gyr time series representing the hydrological forcing function is applied to perturb the hydrologically available water inventory beginning at a model time of 0 Myr.

The models include a simple representation of the different behavior of the system in the wet and dry hydrological regimes. In the wet regime, runoff and ponding of water is likely, and substantial evaporite deposits are not expected to form in the comparatively wet climate. In the arid regime, low precipitation rates and groundwater fluxes are expected to lead to evaporation of the groundwater upon reaching the surface, leading to the formation of evaporites and evaporite-cemented sediments. While the results of section 4.2 reveal the transition between the wet and arid hydrological regimes to be gradational rather than discrete, in order to simply represent these two behaviors in this model we specify a threshold precipitation rate to define a discrete boundary between the two regimes. Based on the results of the equilibrium models (Figures 3 and 4), this threshold precipitation flux is set to $2 \times 10^{-4} \text{ m/year}$, which corresponds to a focusing of hydrological activity at locations of observed sulfate deposits. Higher precipitation rates are assumed to result in fluvial activity and alteration of the surface to phyllosilicates, and lower precipitation rates are assumed to result in arid conditions with evaporite formation at loci of groundwater upwelling. While this threshold precipitation rate is lower than would typically be expected to result in significant runoff and fluvial modification of the surface, the

![Figure 7. Results from a 1 Gyr simulation representing the effects of orbital forcing and secular loss of water between 4.0 and 3.0 Ga for model P001a. (a) Change in hydrologically available total water inventory ($\Delta w$), (b) the evolving precipitation flux in comparison with the mean groundwater upwelling rate within Meridiani Planum and all of Arabia Terra, and (c) the mean depth to the water table within Meridiani Planum and Arabia Terra.](image)
model precipitation rates are lower bounds and only reflect that portion of the precipitation that leads to direct infiltration, as discussed in section 4.2.

[50] The hydrological model was run for 1 Gyr using the two scenarios for the changing water inventory, representing the time period between 4.0 and 3.0 Ga (Figures 7a and 8a). Evaporite-mediated deposition was allowed only at precipitation rates below the specified threshold. The time evolution of the precipitation rate and growth of sedimentary deposits were tracked (Figures 7b and 8b). The mean rate of groundwater upwelling to the surface and the mean depth to the water table as a function of time were calculated both over Meridiani Planum and the associated etched terrain [Hynek, 2004], as well as over the entire Arabia Terra region, defined here as the region bounded by the 0 and −2500 m elevation contours centered on 0°N 0°E (Figures 7b, 7c, 8b, and 8c). Global maps of the depth to the water table, deposit thickness, and groundwater upwelling rate are presented at key times for model P001b (Figure 9).

5.3. Model Results: Long-Term Evolution

[51] Mars starts out in the wet hydrological regime in the beginning of the simulations, with a saturated near surface and maximum precipitation rates of 60 cm/year (model P001a; Figure 7b) and 1 cm/yr (model P001b; Figure 8b). The difference in early precipitation rates is due to the fact that model P001a transitions into a high obliquity phase with the resulting release of water from the cryosphere into the hydrosphere early in the simulation. The water table is close to the surface throughout the low to middle latitudes early in these simulations (e.g., model P001b at 50 Myr; Figure 9a), but evaporite formation and induration of sedimentary deposits is inhibited by the wet climate conditions. In both models, fluvial erosion and phyllosilicate formation would be expected to dominate throughout the first 100 to 200 Myr of model time. As water is lost due to solar wind stripping and impact erosion of the atmosphere, the water table drops deeper beneath the surface in many regions of the planet, and the precipitation rate drops (Figures 7b, 7c, 8b, and 8c). The secular loss of water alone would drive a permanent transition from wet to arid conditions. However, the superimposed effects of orbital forcing result in a more complicated transition.

[52] A shift from either wet to arid or arid to wet conditions can be brought about by a perturbation to the hydrologically available water inventory in response to a shift in mean
obliquity. Mars is most susceptible to these chaotic obliquity shifts when the total water inventory and precipitation rate are close to the threshold level. In model P001a (Figure 7), after ~110 Myr the total water inventory has dropped to the point at which changes in the mean obliquity can drive temporary shifts from the wet to arid hydrological regime. In this simulation, three short excursions from high to low obliquity result in wet-arid transitions, each lasting 2–4 Myr. These brief excursions in mean obliquity would have caused alternating periods of valley network erosion and sulfate deposition, possibly leading to fluvial erosion of the sulfate deposits. At 137 Myr elapsed model time, model P001a transitions into a state of low mean obliquity that persists for 226 Myr, forcing an abrupt and stable hydrological transition from wet to arid conditions. At this point the increased aridity would allow significant evaporite deposits to form in loci of groundwater upwelling. The subsequent transition to high obliquity at 363 Myr in this model is insufficient to cause a shift back to the wet regime as a result of the cumulative effect of the continued secular loss of water to impact and solar wind erosion of the atmosphere.

In model P001b (Figure 8) a shift from low to high obliquity at 113 Myr reinforces the prevailing wet hydrological regime, causing an increase in the precipitation rate and a rise of the water table. The hydrological response to this release of water into the hydrosphere in this scenario provides a possible explanation for the evidence that valley network formation may have peaked in the Late Noachian [Howard et al., 2005; Irwin et al., 2005; Fassett and Head, 2008]. Later in this simulation, short excursions to low obliquity are sufficient to drive brief episodes of arid conditions beginning at 140 Myr model time. These arid regime episodes become more frequent as the total water inventory declines, until the model transitions permanently to the arid regime at 212 Myr elapsed model time.

Sedimentary deposition commences when the models transition into the arid regime, leading to the growth of evaporite-cemented sedimentary deposits in Meridiani Planum and much of Arabia Terra (e.g., model P001b at 240 Myr; Figures 8d–8f). The mean groundwater upwelling rates in Meridiani Planum are higher than in the broader Arabia Terra region, since much of the surface of Arabia

Figure 9. (left) Predicted depth to the water table, (middle) deposit thickness, and (right) groundwater upwelling rate during simulation P001b at 50, 240, 350, 390, and 600 Myr (see Figure 8).
Terra is unsaturated. Similarly, the mean depth to the water table over Meridiani is less than that over all of Arabia Terra. Shortly after the transition to arid regime conditions, the water table gradually rises to shallower depths beneath the surface in Meridiani and Arabia Terra despite the continued secular loss of water. This is observed in model P001a at 137–175 Myr (Figure 7c), and in model P001b at 212–248 Myr (Figure 8c). This rise of the water table is a result of the gradual sedimentary infilling of the deepest craters and other depressions within Meridiani and Arabia Terra, which allows the rise of the water table throughout the region [Andrews-Hanna et al., 2010]. However, the water table later resumes its drop to deeper levels below the surface as a result of the declining total water inventory.

The sedimentary deposition and diagenetic alteration of the deposits in Meridiani Planum and Arabia Terra are related to the rate of groundwater upwelling and the depth to the water table. Active upwelling of deep fluids to the surface under arid regime conditions will result in the formation of evaporites and evaporite cemented sedimentary deposits. Fluctuations in the depth to the water table may result in the diagenesis of the deposits at depth, with periods of stability at a particular water table depth leading to formation of a discrete diagenetic front (e.g., the Whatanga contact observed by Opportunity [Grotzinger et al., 2005]). A significant drop of the water table would leave the deposits exposed to aeolian erosion and deflation, possibly explaining the observed unconformities in HiRISE images (Figure 2) as well as in the large valley within the Meridiani deposits [Wiseman et al., 2010]. Alternatively, a significant increase in the precipitation rate during the period of sulfate deposition may result in fluvial erosion of the deposits.

Transitions to high mean obliquity and the associated release of water from the cryosphere result in an abrupt shallowing of the water table and increase in the precipitation rate during arid regime conditions (e.g., at ~370 Myr in model P001a; Figure 7c). Similarly, transitions to low mean obliquity result in an abrupt deepening of the water table. Short excursions in mean obliquity drive oscillations in the water table height with amplitudes of 100–200 m. These chaotic changes in mean obliquity generate disequilibrium hydrologic responses that can be observed in the mean depth to the water table if the obliquity stabilizes at its new value after the transition. Each decrease in mean obliquity results in an abrupt increase in the depth to the water table as more water is placed into storage in the cryosphere. This is followed by a gradual shallowing of the water table to an intermediate depth over the next ~50 Myr (e.g., from 630 to 680 Myr in model P001a; Figure 7c) as the planet comes into hydrological equilibrium with the lower available water inventory. This provides a measure of the mean hydrological response time of the planet of ~50 Myr. While the hydrological cycle responds to forcing on much shorter time scales than this, as will be seen in section 5.4, it only comes into equilibrium with an applied forcing on this time scale.

The loss of water and gradual drop in the water table eventually brings to an end the groundwater upwelling and sedimentary deposition in Meridiani and Arabia Terra after 190 Myr and 200 Myr, respectively, in model P001a. In model P001b, hydrological activity in Meridiani and Arabia Terra ceases after 180 and 400 Myr, respectively, following a general pattern of a northward shift in the loci of hydrological activity in this region (Figures 9d–9f and 9g–9i). In both models, Arabia Terra experiences renewed activity during periods of high obliquity, as deposition in the bordering northern lowlands allows the water table to rise further toward the surface (e.g., after ~500 Myr in model P001a, and 750 Myr in model P001b). However, the water table remains below the surface throughout Meridiani Planum in the latter parts of both simulations.

Even during periods of low obliquity late in the simulation, hydrological activity in the Valles Marineris canyons persists, due to their great depth relative to the surroundings (e.g., model P001b at 600 Myr; Figures 9m–9o). This is consistent with the generally younger age of the interior layered deposits within the canyons and chaos regions [Glotch and Christensen, 2005; Flahaut et al., 2010] and their greater thickness in comparison with the Meridiani deposits. Sedimentary deposition in the models is allowed to continue throughout the simulations wherever there is a flux of groundwater to the surface. In actuality, a transition to cold climate conditions sometime during the Hesperian likely brought an end to both the precipitation-induced aquifer recharge and the groundwater upwelling to the surface, setting the stage for outflow channel formation during the Hesperian. However, the presence of sulfate deposits that lie stratigraphically above chaos regions at the sources of outflow channels [Glotch and Christensen, 2005] suggests that this transition to cold temperatures was not a simple abrupt and irreversible change.

5.4. Model Results: Short-Term Periodicity

In both simulations, the model behavior over 10–100 Myr time scales is characterized by abrupt changes in the depth to the water table and the rate of groundwater upwelling, driven by perturbations to the hydrologically available total water inventory in response to chaotic changes in the mean obliquity. Over shorter time scales, the hydrology is dominated by the effects of the 120 kyr obliquity cycle and the modulation of the maximum obliquity with a 1.2 Myr period. This short-term periodicity is observed in both the precipitation rate and the groundwater flux at Meridiani (Figure 10). This hydrological periodicity could be expressed in the sedimentary record through modulation of the layer thickness or strength due to either variations in the precipitation rate, which would affect the supply of clastic material incorporated into the deposits, or variations in the groundwater flux, which would affect the supply of solutes and the degree of induration of the deposits.

The response of the aquifers to this short-term periodicity is limited by the hydrologic diffusion time scale for subsurface flow. The time scale for regional hydrological equilibration observed in the response to changes in mean obliquity in section 5.3 was ~50 Myr. On a regional scale, much of the groundwater flows at depths of up to a km or more for distances of 100s to 1000s of km before reaching the surface in Meridiani Planum and Arabia Terra. For the aquifer model of Hanna and Phillips [2005], the hydraulic diffusion time scale for subsurface flow with a water table at 1 km depth over horizontal length scales of 100–1000 km is ~0.3–30 Myr. For a water table located 100 m below the surface over the same range of length scales, the hydraulic diffusion time scale ranges from 0.04 to 4 Myr. This simple scaling analysis would suggest that the large-scale hydrology
in regions with a particularly deep water table should be unperturbed by the 120 kyr obliquity cycle, while regions with a shallow water table will be more strongly influenced. However, while the water table remains at depth below the surface for great distances, the aquifers experience precipitation-induced recharge throughout the low latitudes, including Arabia Terra. As a result, the groundwater upwelling at Meridiani is sourced from precipitation-induced recharge from all points between Meridiani and the hydraulic divide between Arabia Terra and the Hellas impact basin. Due to the shallow aquifers in the vicinity of the deposits and the range of flow path lengths that contribute to the groundwater upwelling, even the short 120 kyr obliquity cycle is strongly expressed in the rate of groundwater upwelling.

During some portions of the orbitally driven hydrological evolution, a relatively constant 120 kyr periodicity is observed in both the precipitation and groundwater upwelling rates at Meridiani (Figure 10g). During other periods, the 1.2 Myr modulation of the obliquity cycle is strongly expressed in the hydrologic response (Figures 10h–10i). These two hydrological behaviors provide a possible explanation for the observation that some sedimentary deposits show a uniform layering periodicity at HiRISE scale while others show layers bundled into packets of 10 [Lewis et al., 2008, 2010]. The bundled layer packets have been correlated to the 120 kyr obliquity cycle and its 1.2 Myr modulation [Lewis et al., 2008], suggesting that the individual layers in similar deposits with uniform periodicity may reflect forcing by the 120 kyr obliquity cycle without substantial 1.2 Myr modulation.

Within the framework of this model, the pronounced 1.2 Myr modulation of the hydrologic response arises primarily during periods of stable low (Figure 10b) or high (Figure 10c) mean obliquity. This appears to be in part an effect of the imposition of a maximum polar cap size at low obliquity, and a minimum (zero) polar cap size at high obliquity. In times of sustained low mean obliquity at values of \( \sim 20^\circ \) (Figure 10b), the polar caps reach their maximum size, and only experience significant loss during the periods of highest obliquity over the 1.2 Myr modulation of the obliquity cycle. Similarly, in times of sustained high mean obliquity at values of \( \sim 35^\circ \) (Figure 10c), the polar caps disappear entirely and only experience regrowth at periods of lowest obliquity during the 1.2 Myr modulation of the obliquity cycle. The more pronounced 1.2 Myr modulation of the precipitation and evaporation rates in Figure 10i is also attributable to the more pronounced 1.2 Myr modulation of the obliquity cycle at this time (Figure 10c).

In actuality, the hydrologic and climatic cycle was likely much more complicated than the simplified represent-
6. Conclusions and Discussion

[64] There is abundant evidence for the presence of water on the surface of Mars early in the planet’s history, and for the importance of groundwater in the hydrological cycle. We have used groundwater hydrology models to provide a theoretical framework in which to understand and interpret the observed record of water-related activity throughout the Noachian and early Hesperian epochs, and to integrate the different lines of evidence into a coherent picture of the global hydrologic and climatic evolution. The model results provide a mechanism for causing the inferred geomorphic and geochemical transition in the late Noachian to early Hesperian, and shed light on the factors controlling the distribution and timing of the formation of sulfates, phyllosilicates, and valley networks. While there is significant uncertainty in many of the model inputs, the resulting hydrological behavior is driven primarily by the large-scale topography of Mars and the effects of short- and long-term changes in the hydrologically available water inventory. The model results are not intended to provide a specific prediction of the actual time evolution of the hydrologic cycle, but rather to provide a qualitative and semiquantitative representation of a possible hydrologic and climatic history that is built on our current understanding of the key processes involved. In the context of this work, we suggest the following scenario for the hydrologic and climatic evolution of Mars during the Noachian and early Hesperian.

[65] Early Mars possessed an active hydrological cycle, with deep groundwater flow driven by a combination of low-latitude precipitation, groundwater evaporation, and the long wavelength topography. The nature of the hydrological cycle at any given time was determined primarily by the hydrologically available total water inventory, which underwent long- and short-term variations driven by the secular loss of water to impact and solar wind stripping, and periodic and episodic changes in the volume of water stored as ice in the polar caps and subsurface cryosphere induced by orbital forcing.

[66] During the Noachian, a greater total water inventory fueled a more vigorous hydrological cycle in what we term the wet hydrological regime. Mean precipitation rates were controlled by the climatic redistribution of water, with significant surface and shallow subsurface reservoirs of water in direct communication with the atmosphere. The high precipitation rates and shallow water table throughout the low latitudes resulted in phyllosilicate weathering reactions in the near surface and erosion rates comparable to those in arid and semiarid regions of the Earth today. Wet conditions favored surface runoff and ponding over evaporite deposition, though these were not explicitly included in the models. The first-order correlation of the distribution of valley networks with regions predicted to be underlain by a shallow water table suggests that groundwater may have played a role in controlling valley network formation.

[67] The steady loss of water to impact and solar wind erosion triggered a shift in the hydrological regime to arid conditions in the late Noachian. This transition required a loss of a GEL of only ~60 m of water, which can be easily accounted for by estimated atmospheric loss rates on early Mars. In the arid hydrological regime, the water table remained deep beneath the surface throughout much of the low latitudes, with groundwater only intersecting the surface in a few isolated locations, including the large impact basins and the northern lowlands. In this arid hydrological regime, the precipitation rate was dictated by the rate of deep groundwater flow, leading to a dramatic drop in precipitation and erosion rates.

[68] At some point intermediate between the extreme wet and arid hydrological regimes, Meridiani Planum and the surrounding Arabia Terra region emerged as one of the few regions of presently exposed Noachian-aged crust in which the water table reached the surface. The long path lengths of groundwater flow allowed ample time for equilibration of the fluids with the basaltic aquifers, resulting in high salinity, sulfate-rich fluids that became acidic upon interacting with the oxidized surface environment [Hurowitz et al., 2010]. The high ratio of deeply sourced groundwater to meteoric water in regions of groundwater upwelling within a few key regions resulted in evaporite deposition and cementation of aeolian sediments. A steady flux of groundwater to the surface in Arabia Terra sustained regional playa development in the absence of a topographic basin, driven by the combination of the general low topography of Arabia Terra relative to the highlands and the distinct breaks in slope separating Arabia Terra from the southern highlands and northern lowlands [Andrews-Hanna et al., 2007]. As Mars transitioned into this arid hydrological regime in the Late Noachian, higher-resolution hydrological models predict a sequence in which large craters within Arabia Terra first filled with evaporites and evaporite-cemented sediments, which allowed the regional water table to rise toward the surface resulting in broad regions of groundwater upwelling to fuel the playa formation at Meridiani [Andrews-Hanna et al., 2010]. Continued loss of water eventually terminated hydrological activity within Arabia Terra. Hydrological activity and groundwater-mediated cementation of sedimentary deposits would have continued in Valles Marineris long after the water table had dropped below the surface in Arabia Terra.

[69] Superimposed over this secular evolution, episodic perturbations to the hydrologically available total water inventory would have resulted from the change in storage of water as ice in the polar caps and high-latitude ground ice in response to chaotic changes in mean obliquity [Laskar et al., 2004; Levrard et al., 2007]. This change in available water volume would have resulted in episodic changes in the precipitation rates, water table depths, and flux of groundwater to the surface. These episodic changes may explain the terminal
epoch of enhanced fluvial activity in the Late Noachian [Irwin et al., 2005] and the rapid cessation of valley network activity at the end of the Noachian [Fassett and Head, 2008]. In this scenario, valley network activity in the Middle Noachian was waning due to the secular loss of water with time, under low obliquity conditions with increased storage of water as ice in the cryosphere. A shift to high obliquity in the Late Noachian then triggered melting and sublimation of the high-latitude ice deposits, driving a sudden increase in the hydrologically available water inventory and a shift to renewed wet conditions. A shift back to low obliquity could then have driven an equally abrupt shift to arid conditions and sulfate formation.

[70] Similar changes in mean obliquity in the Late Noachian to Early Hesperian would have caused abrupt changes in the rate of groundwater upwelling and the depth to the water table in Meridiani Planum and Arabia Terra, leading to sequences of groundwater upwelling and sedimentation, water table retreat and erosion, and water table rise causing diageneric modification and renewed deposition. Alternately, an increase in precipitation during the period of sulfate deposition may have led to fluvial erosion of the forming sedimentary deposits. Such episodic changes may explain erosional unconformities expressed in HiRISE images of layered sedimentary deposits, a large-scale erosional unconformity in northern Sinus Meridiani [Wiseman et al., 2010], and evidence for a fluctuating water table and diagenetic episodes expressed in the Meridiani deposits [Grotzinger et al., 2005; McLennan et al., 2005].

[71] On shorter time scales, perturbations to the hydrological cycle driven by the 120 kyr obliquity cycle and the 1.2 Myr modulation of that cycle resulted in similar periodicities in the precipitation and groundwater upwelling rates in Meridiani and Arabia Terra, equivalent to Milankovitch forcing of the Earth’s climate. Model results at different times show both a regular 120 kyr periodicity, as well as a 120 kyr periodicity that is modulated strongly by the 1.2 Myr cycle. These model behaviors correlate with the observation of both sedimentary deposits with a uniform periodicity at HiRISE scale [Lewis et al., 2010], as well as deposits in which the layer periodicity is bundled into packets of 10 [Lewis et al., 2008].

[72] Previous work has focused largely on the role of temperature changes in the climate evolution of Mars. The scenario developed here highlights instead the importance of the changing availability of water in both the hydrological and climatic evolution. The decline in valley network formation, the decrease in erosion rates, and the shift from phyllosilicate to sulfate deposition can all be explained by a change in the available water inventory under warm climate conditions. Changes in the mean surface temperature would have also exerted a significant control on the rate of water cycling and the nature of hydrological activity on the surface. Ultimately, the onset of cold climate conditions in the Late Hesperian trapped the aquifers beneath a thick cryosphere, essentially halting the hydrologic cycle. Rather than a simple transition from warm and wet to cold and dry conditions, we suggest that Mars underwent a transition from warm and arid, to warm and hyperarid conditions in the Late Noachian, followed by a transition to cold and hyperarid conditions in the Hesperian. Both the geologic record and these model results show that these transitions would have been gradual and complex rather than discrete and simple, but the decoupling of the temperature and moisture conditions is an essential aspect of the hydrologic and climatic history of Mars.

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