MERIDIANI PLANUM: IMPLICATIONS FOR THE HYDROLOGIC AND CLIMATIC EVOLUTION OF MARS.
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Introduction: The MER Opportunity rover found compelling evidence for a water-rich environment at Meridiani Planum, including extensive sulfate deposits, postulated to have formed as evaporites, with later reworking by fluvial and aeolian processes [1]. Recent work has shown Meridiani to be a region in which sustained groundwater upwelling would be predicted to result from the global-scale patterns of deep groundwater flow [2]. By placing Meridiani within a global hydrological context, we now consider the implications of this unique environment for the global hydrologic and climatic evolution of Mars. We find that the formation of the Meridiani deposits, together with geomorphic and geochemical evidence for a changing global surface environment, are consistent with a shift from a wet to arid hydrologic regime in response to either a decrease in the global water inventory or an increase in the storage capacity of the crustal aquifers in the Late Noachian, that preceded the change to cold-climate conditions.

Hydrological modeling: Global-scale flow of groundwater may have played a key role in the hydrology of Mars [3]. We investigated the hydrological evolution of early Mars, with the global-scale patterns of groundwater flow driven by a combination of the surface topography, precipitation-induced recharge, and evaporative loss upon reaching the surface [2]. The resulting patterns of flow predicted groundwater upwelling and evaporation along the dichotomy boundary, in the northern lowlands and large impact basins, and in the Meridiani Planum region. Meridiani was one of the few regions of exposed Noachian-aged crust predicted to have experienced significant groundwater upwelling, with the flow driven primarily by the regional slopes in the surrounding Arabia Terra region (Figure 1a, 'AT'). We here ignore the effects of Tharsis formation, which had only a minor effect on the hydrology at Meridiani.

The nature of the global hydrology of early Mars in this work is most sensitive to the total inventory of water in the system. The models assume arid conditions, in which groundwater evaporates upon reaching the surface, and is then distributed as precipitation throughout the tropics and mid-latitudes. This "arid-regime" hydrology does not permit significant storage of water above the surface in the form of lakes or seas. The precipitation rate is dictated by the globally-integrated evaporation rate, which in turn is limited by the rate of groundwater flow. However, when the initial global water inventory is

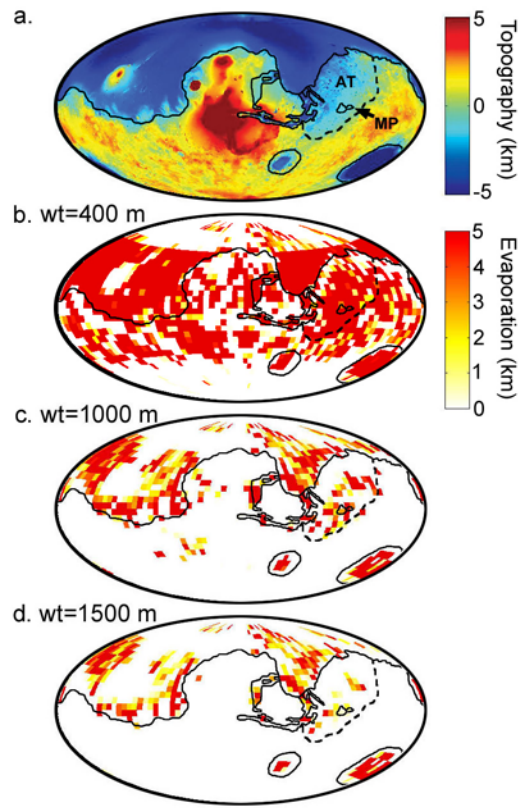

Figure 1. Global topography (a) and evaporative loss of water after 500 Myr for models with initial water table depths (wt) of 400 m (b), 1000 m (c), and 1500 m (d). Meridiani Planum (MP) denoted by arrow.

increased, the arid-climate assumption becomes untenable. Once the equilibrium storage capacity of the crustal aquifers in the mid-latitudes is exceeded, the precipitation falls everywhere on a saturated surface, and runoff and ponding would be expected. With a substantial inventory of water at the surface, the hydrology will be in the "wet-regime". The amount of water available for evaporation and precipitation is no longer limited by the flux of deep groundwater to the surface, and a more Earth-like hydrology will dominate. *Grimm and Harrison* [4] found that flow patterns with the water table at or near the surface will be dictated by local drainage divides, with the average flow path-lengths on the order of 10's to 100's of km.

In our nominal model, we initialize Mars with a globally-uniform water table depth of 1000 m, and the resulting patterns of groundwater flow predict Meridiani Planum to be one of the few regions of the highlands for which substantial groundwater upwelling

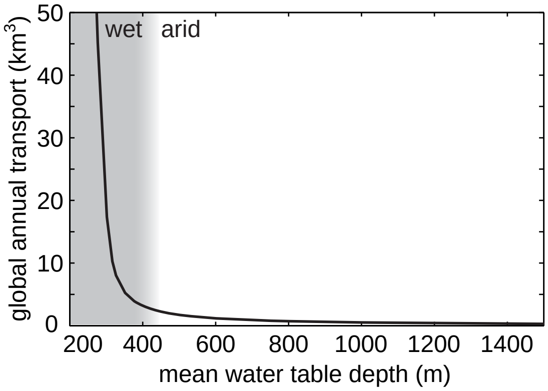

Figure 2. Globally integrated annual cycling of water between the aquifers and the atmosphere as a function of the initial mean water table depth in the models. The transition from the wet- to arid-regime hydrology is shown.

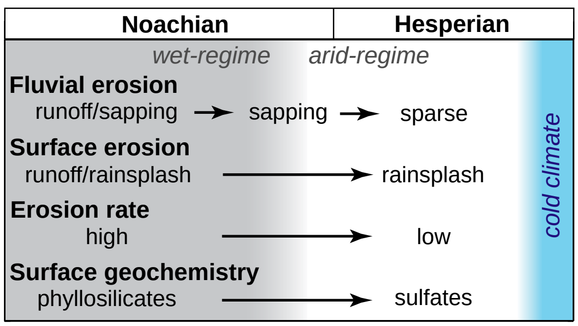

Figure 3. Schematic diagram outlining evidence for a wet to arid hydrological transition in the Late Noachian [6-11], before the onset of cold-climate conditions (for conceptual purposes only; timing and nature of transitions is uncertain).

and evaporation is predicted (Figure 1c). For initial water table depths less than ~400 m, the water table at equilibrium reaches the surface throughout the mid-latitudes (Figure 1b). This breakdown of the arid-climate assumption results in an asymptotic increase in the rates of precipitation and evaporation (Figure 2), with the total volume of water in excess of the aquifer storage capacity evaporating and precipitating in each timestep of the model. In the wet-regime, Mars could have possessed substantial surface reservoirs of water, allowing total water inventories well in excess of this threshold. For an initial water table depth of ~1500 m, there is minimal groundwater evaporation at Meridiani (Figure 1d). Changing the aquifer permeability was found to scale the evaporation rates proportionately without affecting the flow patterns appreciably.

Geomorphic and geochemical observations: While there is much contention regarding the early environmental history of Mars, there is strong evidence to suggest that early Mars was more Earth-like than at present, with surface temperatures above freezing and liquid precipitation likely required to carve the dense networks of fluvial valleys in the mid-latitudes [5,6]. A number of workers have proposed refinements to the first-order paradigm of a warm-wet to cold-dry transition on early Mars [7,8].

Valley network formation came to an end gradually, with valleys continuing to form into the Hesperian with a lower drainage density [6]. Similarly, there is a transition in morphology from V-shaped valleys typical of surface runoff, to U-shaped valleys more suggestive of groundwater sapping [7,9], as well as a transition from dense to sparse drainage networks [7,8]. While precipitation is likely required to recharge the aquifers at the heads of the sapping valleys [6], the transition in morphology suggests that it rapidly infiltrated the surface. Patterns of crater modification in the Noachian indicate both diffusive and advective processes, signifying the importance of both rain-splash and surface runoff [10]. Diffusive erosion appears to have persisted longer than advective, suggesting that precipitation was later outpaced by infiltration. Rates of erosion also declined by several orders of magnitude near the end of the Noachian, coinciding roughly with the formation of the Meridiani deposits [11]. Taken together, this evidence suggests a transition in the Late Noachian from wet to arid conditions, while temperatures remained above or near freezing to allow liquid water at the surface [8].

Recent data suggests that these changes in erosion styles on early Mars were accompanied by a transition in the surface geochemisty [12]. Spectral evidence for phyllosilicates interbedded within ancient Early Noachian surfaces [12-14] are suggestive of low-temperature weathering reactions between near-neutral pH water and rock at or near the surface of Mars. In contrast, during the Late Noachian and into the Hesperian, deposits of hydrated minerals at the surface are dominated by sulfate salts, likely formed from evaporation of high-solute low-pH waters [12].

Synthesis: We suggest that both the geomorphic and geochemical evolution of Mars can be understood in terms of the global hydrological evolution in response to a change in the "active water volume", defined as the difference between the global water inventory and the storage capacity of the crustal aquifers. As the active water volume decreased, the global hydrology would have transitioned from the wet to the arid regime (Figure 3). Precipitation and erosion rates would have decreased dramatically as the flux of water into the atmosphere became limited by the timescales of long-wavelength groundwater flow, providing a mechanism for the decreasing precipitation rates inferred by others [7,8]. The water table would have dropped below the surface, leading to an increase in infiltration relative to runoff, and a transition from runoff to sapping-dominated valley networks [8]. As the water table dropped further, hydrological activity would have been limited to regions of groundwater upwelling, such as Meridiani Planum [2].

This transition would have also been marked by a distinct change in the nature of the fluids at the surface. In the wet-regime hydrology, surface fluids would have derived directly from local precipitation, with residence times at or near the surface on the order of days to years. The resulting fluids would have had low salinity and mildly acidic pH as a result of dissolved atmospheric CO_2 and SO_2 [15]. The flux of water from deep groundwater flow would have been dramatically lower than the precipitation and runoff rates, and the deep fluids would have had little influence on the surface environment. Weathering of the basalt at the surface would have produced the observed Early Noachian phyllosilicates [12-15].

Under the arid-regime hydrology, precipitation would have rapidly infiltrated the surface to contribute to the deep groundwater aquifers. Hydraulic gradients in the models suggest residence times on the order of 10’s of Myr for typical flow path-lengths, allowing for chemical equilibration between the fluids and the aquifer rocks. Following the model of *Burns* [16-17], the mildly oxidizing fluids would have reacted with pyrrhotite in the basaltic aquifers, producing substantial acidity and liberating dissolved ferrous sulfate. Consumption of the oxygen would have led to reducing conditions. This acidic, reducing groundwater would have leached Fe^{2+}, Mg^{2+}, and Ca^{2+} from the aquifer rocks, which could have been transported over long distances in the subsurface. Upon reaching the surface, these fluids would have interacted with the photochemically oxidized surface environment, leading to precipitation of oxidized Fe minerals such as jarosite and generating further acidity. The addition of the dissolved Fe, Mg, Ca, and SO_4 to the weathered basaltic materials at the surface can explain the observed surface mineralogy [18]. Alternately, if volcanic outgassing resulted in a reducing environment at the time the Meridiani deposits formed [15], cations would have been derived solely from acid-mediated leaching of the aquifer rocks. Evaporation of the fluids at the surface would have produced deposits of sulfite minerals, which would have been later oxidized to sulfates by photochemically produced O_2.

The proposed decrease in the active water volume could have resulted from either a decrease in the global water inventory, or from an increase in the storage capacity of the crustal aquifers. The models suggest that a decrease in the initial water table depth by 600 m could trigger a transition from the wet to the arid hydrological regime such that Meridiani was one of the few regions of predicted groundwater evaporation in the highlands. This equates to loss of a global equivalent depth (GED) of 90 m of water, or a total volume of 1.3×10^7 km^3. D/H ratios in the martian atmosphere suggest loss of at least 90% of the water interacting with the atmosphere over time due to solar wind sputtering [19], with estimates of the total loss ranging from a GED of 3 to 100 m [19-20]. Impact erosion would have removed a similar amount [21]. These processes remove a fraction of the water in direct communication with the atmosphere, and so a sharp decrease in the surface and atmospheric reservoir of water after the transition to the arid regime would have caused a similar decrease in the absolute water loss rates. As a result, the total inventory of water on Mars might be expected to stabilize upon transitioning to the arid-regime hydrology, allowing for long-lived groundwater upwelling at Meridiani.

An increase in the total storage capacity of the crustal aquifers would have had a similar effect, causing the water table to drop deeper beneath the surface. An upper limit on the maximum depth of aquifer stability is dictated by the depth of the brittle-plastic transition in the crust [22], which would have increased with time as the surface temperature and internal heat flux decreased. Continued tectonism and meteoritic bombardment would have generated porosity within the newly-brittle crust at depth. Estimated maximum aquifer thicknesses of 10-20 km [22] for a heat flux of 65 mW/m^2 in the Early Noachian [23] would be increased to ~12-24 km for a heat flux of 55 mW/m^2 in the Hesperian, sufficient to cause the wet to arid hydrologic transition. Continued impact bombardment of the surface could also increase the mean porosity of existing aquifers. An increase in the mean porosity of a 20 km thick aquifer by only 0.0045, roughly 5% of the mean porosity, would be required.

An increase in the storage of water could also be affected through hydration reactions in the crust or storage as ice. Recent observations show that a GED of 11 m of water is currently stored in the south polar layered deposits [24]. Additional storage of ice in the north polar deposits and as high latitude ground ice would add to this amount. While this volume is not sufficient to induce the wet to arid hydrological transition, fluctuations in the amount of ice storage in response to climate oscillations may have played a role in driving short-term hydrological perturbations.

While we have explicitly considered the effects of changes in the active water volume, the surface temperatures were included in only a first-order sense. Temperatures above freezing appear to be required to explain the formation of the Meridiani deposits and the existence of a precipitation-evaporation driven hydrological system. While changes in temperature and water inventory were likely contemporaneous, the formation of the Meridiani deposits suggests that the transition to arid conditions preceded the onset of cold-climate conditions and growth of a thick cryosphere, in agreement with the geomorphic evidence [8].

Summary: The evaporitic sulfate minerals at Meridiani Planum can be explained by a global-scale hydrology driven by low levels of precipitation and evaporation operating under arid conditions. This arid environment stands in contrast to the inferred wetter conditions during the Early Noachian. This environmental change could have been the result of a hydrological transition in response to either a net loss of a minimum GED of ~90 m of water through solar wind sputtering and impact erosion, or an equivalent increase in the storage capacity of the crustal aquifers. Such a hydrological transition is also consistent with observed changes in the erosion style and surface geochemistry of early Mars.

The presence of evaporite deposits at Meridiani Planum contributes to the growing evidence [*e.g.* 7-10] for an intervening warm-arid period between the warm-wet early history and the cold-dry Mars of today. While much attention has been paid to CO_2 and the temperature evolution of early Mars, we suggest that changes in the total inventory and distribution of water also played a key role in the evolving surface environment.

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