HYDROLOGIC EVOLUTION OF EARLY MARS: SECULAR AND PERIODIC CLIMATE FORCING AND IMPLICATIONS FOR THE SEDIMENTARY RECORD. J. C. Andrews-Hanna[1], [1]Department of Geophysics and Center for Space Resources, Colorado School of Mines, Golden, CO, e-mail: jcahanna@mines.edu.

Introduction: Early Mars records a hydrological cycle in transition. Warmer and wetter conditions during the Noachian resulted in high erosion rates, the formation of dendritic valley networks and the widespread alteration of the ancient crust to phyllosilicates [1]. During the Late Noachian and Early Hesperian, conditions became increasingly arid, leading to a change in the style of surface erosion, a decrease in the erosion rate [2], and the formation of groundwater-derived evaporitic sulfate deposits in select regions of the planet, including Meridiani Planum [3]. The sedimentary deposits hosting the sulfate minerals display fine scale layering. Periodic bundling of sedimentary layers in Becquerel crater (Figure 1a) match the predicted periodicity of climatic forcing from the obliquity and orbital evolution of Mars [4]. Thus, the early martian hydrological cycle experienced temporal variability over both the long timescale of the Noachian-Hesperian transition and the short timescale of the layering periodicity.

In previous work, groundwater models representing a global precipitation-evaporation driven hydrologic cycle resulted in the emergence of Meridiani Planum and Arabia Terra as sites of sustained groundwater upwelling and evaporation [5]. The predicted distribution of deposits, layer dips, and deposition rates match the observed values [6]. This study now investigates the short and long term hydrologic-climatic evolution of Mars during the Noachian and Early Hesperian.

Time evolution of the hydrologic system: The primary sensitivity of the model behavior is to the total water inventory of the planet. Earlier work [7] found that models with a greater total water inventory resulted in a saturated near surface throughout the low to mid-latitudes and high precipitation rates (the "wet" hydrologic regime). These models predict hydrological activity to be widespread across the surface. The high precipitation rates and shallow water table are consistent with conditions during the Early to Middle Noachian, leading to valley network formation, phyllosilicate alteration, and high erosion rates.

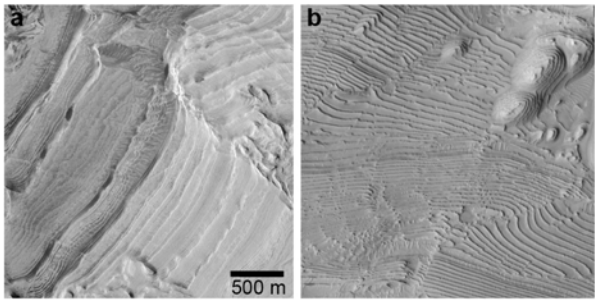

Figure 1. Periodic layering in Becquerel crater (a; HiRISE image PSP_007440_1845) and more uniform layer spacing in an outlyer of the Meridiani deposits (b; image PSP_002878_1880; NASA/JPL/University of Arizona).

Models with a lower total water inventory (the "arid" hydrologic regime) predict the water table to be deeper beneath the surface, only intersecting the surface in a few regions, including Meridiani Planum. The greater pathlengths for groundwater flow lead to a slower cycling of water between the aquifers and atmosphere and lower precipitation rates. These models successfully predict the observed distribution of evaporites [6], and are consistent with the arid climate in the Late Noachian. As the water inventory is decreased further, Mars becomes increasingly desiccated, with exceedingly low precipitation rates and a water table deep beneath the surface throughout the southern highlands. This progression suggests that the hydrological and climatic transition in the Late Noachian may have been driven by a shift in the hydrologic regime due to the declining total water inventory [7].

Model: The temporal evolution of the hydrological cycle was affected by both long term secular changes and short term periodic changes in the total hydrologically-available water inventory. Secular changes in the water inventory were driven by impact erosion and solar wind stripping of the atmosphere. We assume a present-day water inventory in communication with the atmosphere of a global equivalent layer (GEL) of 29 m, assuming 11 m GEL in the present-day SPLD [8], 5 m in the NPLD, and 6.5 m as high latitude ground ice around each pole. This value is extrapolated back in time, assuming 90% loss by solar wind stripping over the past 4.5 Ga and a time-variable rate of impact erosion [9, 10]. This scenario results in a total loss of a GEL of 168 m since 4.0 Ga, or loss of a GEL of 109 m in the Middle Noachian through Late Hesperian between 4.0 and 3.0 Ga (Figure 2a).

This long-term loss is modulated by short term changes in the storage of water as ice in the polar caps and cryosphere. The behavior of the cryospheric ice reservoirs in the present epoch can be parameterized in terms of the orbital parameters [11, 12]. While this parameterization is not strictly valid at other epochs, a qualitatively similar dependence of cryosphere ice volume on oribital parameters is likely. To construct a time series of the evolution of the storage of ice within the cryosphere, a representative 250 Myr orbital evolu-

tion model including both short-term periodicity and chaotic shifts in mean obliquity [11] was repeated and reversed to make a 1 Gyr continuous series, and this was used to calculate the changing cryosphere ice volume [12]. While the specific orbital evolution between 4.0 and 3.0 Ga is unconstrained due to the chaotic nature of the system, this time series is qualitatively representative of both the short and long term evolution.

The orbitally-driven changes in water storage in the cryosphere were superimposed on the long term trend due to secular water loss. The resulting evolution of the total available water inventory was input into a global hydrological model [5, 6] by adding or removing water from the precipitation flux as needed. As the total water inventory is modulated, the depth to the water table and precipitation rate varies accordingly. A threshold precipitation rate was chosen to divide the "wet" and "arid" hydrological regimes, with evaporite deposits only forming in the arid regime.

High precipitation rates in the first ~100 Myr indicate a wet climate conducive to phyllosilicate alteration and valley network formation (Figure 2b). Declining precipitation rates indicate a transition to a more arid climate, allowing evaporite formation at loci of groundwater upwelling and evaporation. Groundwater upwelling at Meridiani ceases after ~200 Myr as a result of the growth of the deposits and increase in the surface elevation relative to the regional water table. However, groundwater evaporation in the surrounding Arabia Terra region persists for ~500 Myr.

As the total water inventory continues to decline, the planet becomes increasingly hyper-arid, punctuated by occasional short episodes of increased precipitation rates fueled by the release of water from the cryosphere into the hydrologic system during periods of high obliquity. At some times, a relatively uniform short term periodicity is observed (Figure 2c), consistent with sedimentary outcrops exhibiting sequences of layers with nearly uniform thickness (Figure 1b). At other times, a bundling of the periodicity in the precipitation and groundwater fluxes is more pronounced (Figure 2d), similar to the layer bundling in the sedimentary outcrops in Becquerel crater (Figure 1a) [4]. The predicted distribution of evaporites is similar to that predicted previously by models with a constant total water inventory [6], with Meridiani and the surrounding Arabia Terra region among the few regions of exposed Noachian crust for which evaporite deposits are predicted. Predicted deposits within the giant impact basins and northern lowlands would have been obscured by subsequent volcanic and sedimentary resurfacing. The widespread deposits predicted throughout Arabia Terra are consistent with evidence for erosional remnants of a once larger deposit [13].

Conclusions: The evolution of the early martian environment, as expressed in the sedimentary and geomorphic record, can be understood in terms of the influence of the evolving global water inventory on the hydrologic cycle. The combined effect of the declining total water inventory and periodic perturbations due to orbital oscillations provide explanations for both the long term phyllosilicate-sulfate transition and the short term sedimentary layering periodicity.

References: [1] F. Poulet, et al. (2005) *Nature 438*, 623-627. [2] M. P. Golombek, et al. (2006) *JGR 111*, E12S10, doi:10.1029/ 2006JE002754. [3] S. W. Squyres and A. H. Knoll (2005) *EPSL 240*, 1-10. [4] K. W. Lewis, et al. (2008) *Science 322*, 1532-1535. [5] J. C. Andrews-Hanna, et al. (2007) *Nature 446*, 163-166. [6] J. C. Andrews-Hanna, et al. (2009) *JGR*, doi:10.1029/2009JE003485, in press. [7] J. C. Andrews-Hanna, et al. (2008) *LPS 39*, Abstract 1993. [8] J. J. Plaut, et al. (2007) *Science 316*, 92-95. [9] D. A. Brain and B. M. Jakosky (1998) *JGR 103*, 22689-22694. [10] H. J. Melosh and A. M. Vickery (1989) *Nature 338*, 487-489. [11] J. Laskar, et al. (2004) Icarus 170 343-364. [12] B. Levrard, et al. (2007) *JGR 112*, E06012, doi:10.1029/2006JE002772. [13] K. Zabrusky and J. C. Andrews-Hanna, (2010) *LPS, this volume*.

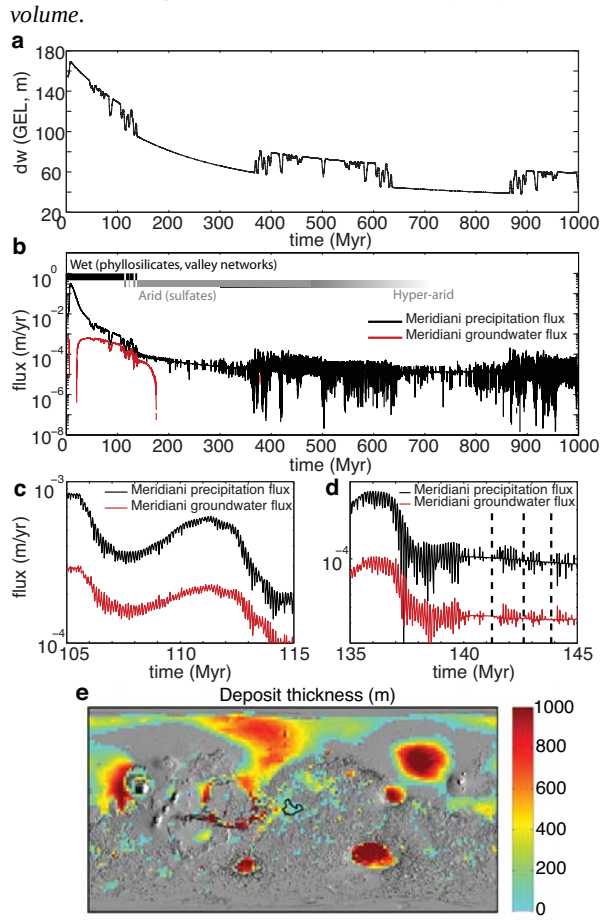

Figure 2. a Secular and periodic changes to the global water inventory over time input into the model. **b-d** Predicted precipitation and groundwater upwelling rates at Meridiani. **e** Predicted thickness of evaporites after 500 Myr.