Hydrologic System and Cycle Throughout Mars History: A Combined System Science Approach (Hydrosphere, Atmosphere, Cryosphere, Lithosphere, Geologic History).

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Introduction: We analyzed the hydrological system and cycle throughout Mars history in order to help constrain the implications for the ambient climate and its evolution (1). We adopted a Mars System Science approach, calling on information from the atmosphere, hydrosphere, cryosphere, lithosphere, and geologic history for an integrated organizational framework of inquiry. We 'followed the water', focusing on the characteristics of the hydrological system/cycle, their individual component water reservoirs, and their relationships and interconnectedness through time. We examined the ancillary hydrological cycle environments/processes (fluvial, lacustrine, glacial, cryospheric, groundwater) required for a robust, vertically integrated hydrological cycle to support long-duration Northern Lowland oceans, arguably the largest proposed water reservoirs in Mars history.

Four critical overarching themes and questions have emerged from multiple studies: 1) Did ocean-scale bodies of water and sustained *marine environments* exist on Mars in its past history, and if so, when and for how long? 2) All researchers agree that there is extensive evidence for the presence of surface liquid water forming valley network fluvial channels (2,3), lacustrine environments (open and closed-basin lakes) (4,5), delta-like features (6,7) and fluvial outflow channels (8). But what is the duration of these water-related environments, are they interconnected by a robust and sustained hydrological system and cycle, and are they together capable of feeding and sustaining northern lowland oceans? 3) How do other elements of the geologic record and history of Mars (e.g., presence and depth of groundwater, presence of phyllosilicates, weathering rates, landform degradation rates, the nature of the ambient climate) inform us about the presence and persistence of water and the robustness and interconnectedness of the hydrological system and cycle during Mars history? 4) What are the implications of these three themes and questions for the ambient climate and nature and locations of environments that might have favored the origin and evolution of life on Mars, and the most likely environments for the preservation of extant and extinct life and related biosignatures?

We first focused on exploring this largest potential water reservoir on Mars, and assessed the evidence for the presence of oceanic-scale water bodies, and interpreting the nature of their marine environments in the geologic history of Mars. We utilized the geologic history of Mars as our historical framework (9-13) **(Figure 1)**. Geological data have been cited to support the presence of two separate oceans (14-15) in the past history of Mars **(Figure 2)** (16,17), one during the Late Noachian and a later one during the Late Hesperian (9,18). Working backward in time, we briefly reviewed the history of these concepts and then used a series of questions to address the current state of understanding of the hypothesis of the two oceans, and the presence of a supporting robust and interconnected *vertically integrated hydrological system and cy*cle **(Figure 3a)**.

Synthesis of the Martian Hydrological System and Cycle.

1. Evidence for Oceans in the History of Mars. On the basis of our analyses, we found no compelling consistent positive evidence (shoreline locations, deltas, etc.) for the presence of a long-duration, ocean-scale standing body of water in the Northern Lowlands in either the Late Hesperian-Early Amazonian (Contact 2), or in the Late Noachian-Early Hesperian (Contact 1). The most compelling additional evidence against the volumes of water implied by Contacts 1 and 2 is the inability to account for: 1) a source of such huge volumes of surface water (Contact 2: ~110 m GEL; Contact 1: up to 5000 m GEL), and 2) the fate of these water volumes (Where is the water now?). Instead, the evidence suggests that any significant input of water into the northern lowlands would very rapidly freeze and sublimate, returning to surface cold traps.

2. Evidence for a Robust Vertically-Integrated Hydrological System and Cycle. Most workers agree that by the time of the hypothesized Late Hesperian-Early Amazonian ocean (Contact 2), the hydrological system of Mars was not vertically integrated, but *horizontally stratified* (**Figure 3b**), with a global cryosphere separating the surface from the groundwater system. Various cryospheric-breaching mechanisms are called on to enable groundwater to reach the surface, and debouch into the Northern Lowlands where it collected, likely froze rapidly and sublimated, returning water to surface cold traps (19-20). In contrast, the hypothesized presence in earlier Mars history of a Late Noachian-Early Hesperian ocean (Contact 1) implies a robust, *vertically integrated hydrological system and cycle* (**Figure 3a**), including oceanic/lacustrine water evaporation, elevated atmospheric water contents, precipitation as rainfall and snowfall, infiltration into the subsurface to reach the water table, surface runoff in fluvial channels where precipitation exceeds infiltration, local staging (collection in areas of low topography as open and closed-basin lakes), and finally, completing the cycle by resupplying the ocean through surface overland flow and subsurface groundwater flow. We analyzed the evidence for the nature of all elements of such a vertically-integrated hydrological system and cycle, and found little supporting evidence for the robustness or the interconnected nature of these individual elements. Rainfall precipitation rates as currently understood, are predicted to be very low (21-22). The fluvial systems are immature and often do not reach the Northern Lowlands. The characteristics of fluvial runoff events (derived from coupled OBL-CBL systems) appear to involve low water volumes, to be dominantly short-term and episodic in nature (lasting 10^2-10^5 years) (23), and thus likely to be caused by transient surface events and conditions, rather than a continuous robust source-to-sink fluvial-lacustrine system feeding an ocean (e.g., (24)).

3. Implications for the Nature of the Martian Hydrological System and Cycle. The apparent lack of a robust, vertically integrated hydrological system and cycle during the Late Noachian-Early Hesperian valley network period of Mars history suggests that, in a manner similar to that later in the Hesperian, the hydrological system and cycle were more likely to have been *horizontally stratified*, with the surface separated from the groundwater system by a global cryosphere (**Figure 3b**). On the basis of a globally temporally declining geothermal flux, the cryosphere in the Late Noachian-Early Hesperian is predicted to be thinner than in later times. Such a horizontally stratified systems during the Late Noachian means that water sequestered in the cryosphere/groundwater system is effectively not in touch with the atmosphere, and thus becomes a *non-exchangeable reservoir*, with important implications for the surface water budget and the evolution of the D/H ratio.

In addition, the observed Early and Middle Noachian very high erosion rates (25), and the phyllosilicate formation period (26), are both plausibly related to the transient effects of torrential hot rains associated with the three impact basins (Hellas, Isidis and Argyre) (27)) (**Figure 4**). In this interpretation, neither process requires a long-duration period of surface erosion and mineralogical alteration, nor, as often envisioned for the Late Noachian-Early Hesperian period, that it be characterized by an ambient climate of significantly elevated surface temperatures (>273 K MAT) and abundant water availability.

Finally, the high Late Noachian-Early Hesperian geothermal heat flux argues for a relatively thinner cryosphere than later in history, and the presence of geothermally warmed groundwater below the cryosphere that would favor further mineralogical alteration and nutrients to produce a potentially habitable subsurface environment.

4. Implications for the Nature and Evolution of the Martian Atmosphere. The likely presence of a horizontally stratified hydrological system and a global cryosphere since the Late Noachian implies that the ambient climate was characterized by a mean annual temperature well below 273 K (**Figure 5).** Such an ambient climate is likely to involve snowfall precipitation and accumulation, rather than an ambient 'warm and wet/arid' climate characterized by rainfall, infiltration and runoff. The lack of evidence for significant vertical water exchange through the cryosphere suggests that water on the surface was limited, the atmosphere was relatively dry, and surface water was primarily sequestered in cold traps, whose locations were dictated by altitude and latitude. Water lost to space since the Late Noachian would have largely come from surface/near-surface water ice reservoirs.

5. Synthesis of the Geological History of Mars. On the basis of this review and synthesis, our current understanding strongly suggests that Early and Middle Noachian large impact basin formation (Hellas, Isidis, Argyre) were accompanied by transient torrential hot rainfall events that were responsible for both the high erosion rates and phyllosilicate formation. As the climate returned to ambient conditions in the Late Noachian, it was likely to have been extremely cold (MAT<<273 K) **(Figure 5),** with the crust dominated by a global cryosphere **(Figure 3b),** and abundant warm groundwater in the subsurface below. Surface hydrology would have been characterized by short-duration transient periods of liquid water availability, and an immature, unintegrated, transient hydrologic system. Any sea/ocean-scale body of water in the Northern Lowlands would have been transient, freezing and disappearing rapidly to surface cold traps. The presence of Hesperian-aged, hydrated sulfates focused in the equatorial Valles Marineris region is attributed to the release of sub-cryospheric groundwater by the 8+ km of VM vertical offset, filling of the basin with sulfur-rich groundwater, forming the Interior Layered Deposits (ILD), and the occasional transient release into the Chryse basin and northern lowlands.

Observed Amazonian scattered and local valley networks are likely false-positives for ambient climate conditions with MAT >273 K, being due to local transient insolation melting, volcano-ice interactions (e.g., Ceraunius Tholis (28)) and hot impact ejecta interaction with surface snow and ice (e.g., Lyot Crater (29)). Over the course of the ~3 billion year Amazonian, the ambient surface climate would have been cold and relatively dry, with spin-axis orbital dynamics (e.g., Milankovich obliquity cycles) at higher obliquity sublimating and transporting water from polar reservoirs equatorward to form regional midlatitude ice sheets and tropical mountain glaciers (30-31)), and returning it back to the polar regions when obliquity decreased toward its current value. In summary, the fundamental structure of the *horizontally stratified hydrological cycle* is likely to have been established in the Late Noachian, and to have remained structurally unchanged for the remainder of Mars history, with trends in increasing cryospheric thickness and decreasing groundwater abundance attributed to global heat loss with time.

Outstanding Questions, Future Research and Exploration. Our synthesis of the geological, hydrological and climatological history of Mars highlights some critical questions and themes to pursue in order to provides tests, clarifications, refinements and/or rejection of its components. A critical element is a better understanding of the initial water budget of Mars, its partitioning and sequestration as a function of time, and its relationship to the ambient atmosphere with time (32-33). Tightly integrated with this is the need for an improved understanding of the fate of the *primary atmosphere* and the construction and timing of the *secondary atmosphere*. Improved understanding of the depth of the cryosphere and the current groundwater budget, obtained through global seismic networks, would significantly constraint this water/atmosphere history. Finally, further research is needed on short-term factors that could serve to elevate surface temperatures periodically (34-35)) or episodically (e.g., spin-axis/orbital perturbations (36)). Our synthesis emphasizes that Mars is likely to have been characterized by a horizontally stratified hydrological system, and a harsh hypothermal, hyperarid polar desert surface environment (**Figure 3**) for more than 3 billion years (**Figure 1**). Essential to the future quest for evidence for life on Mars is a deeper understanding of analogous polar desert environments on Earth, such as the ~2000 km^2 ice-free terrain in the Antarctic McMurdo Dry Valleys (MDV) (37). Here, a vibrant cold-desert ecosystem exists despite a horizontally stratified hydrologic system and cycle, and extremely harsh surface conditions. MDV hydrologic reservoirs include glaciers, soils, permafrost, water tracks, streams, hyporheic zones, lakes and the atmosphere (without rainfall). The interconnectivity of these reservoirs, and thus the highly abbreviated hydrological cycle, is governed by the daily, seasonal, and annual surface energy balance that is primarily regulated by climate dynamics (38)**.** A deeper understanding of the MDV abbreviated hydrological system and cycle, and the nature and response of the cold-desert ecosystem, will assist in future research and exploration strategies for the location and detection of biosignatures on Mars. Furthermore, we have identified the very high likelihood of a sub-cryospheric, geothermally warmed groundwater system, that could host a global trogdylitic biota and biosignatures that would be widely dispersed across Mars by periodic groundwater release and impact cratering.

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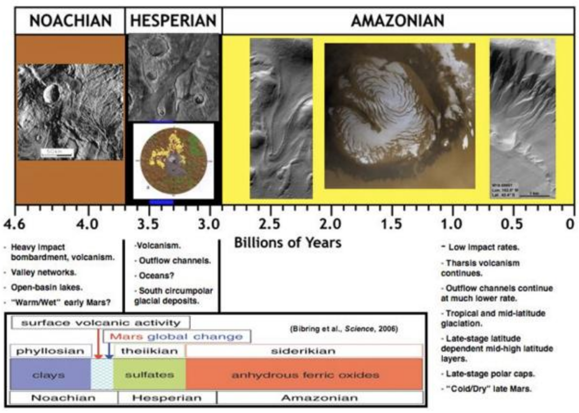

Figure 1. Generalized diagram of the geological history of Mars, noting major events and processes that occur in each major geologic era (after 9-11). Also shown are the mineralogic subdivisions of (13) and their climatic interpretations. Noachian: Valley networks and lakes suggest 'warm and wet/arid' conditions. Hesperian: Large South Polar cap (inset), extensive volcanism, followed by Late Hesperian outflow channels. Amazonian: The majority of Mars history is characterized by a 'cold and icy' hyperarid/hypothermal climate, anhydrous ferric oxide weathering, with surface po-

lar caps and lower latitude glaciers, and a horizontally stratified hydrological system with a thick cryosphere separating the surface from a deeper groundwater system.

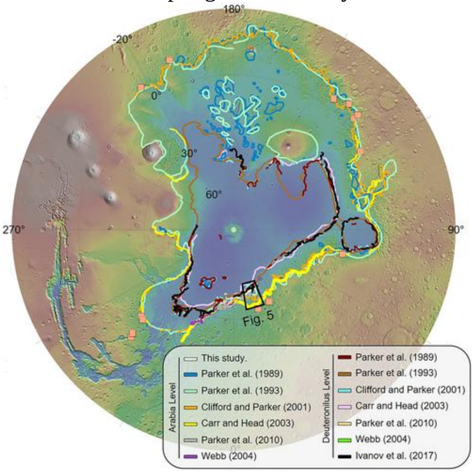

Figure 2. Locations of hypothesized oceanic shorelines in the Northern Lowlands (39). The composite locations of the Arabia (Late Noachian) and Deuteronilus (Late Hesperian) hypothesized shoreline levels synthesized from various published figures. Bold yellow line (the Arabia Level segment from (40)) that was used in subsequent deformation models. Open deltas (6-7) are indicated by orange squares.

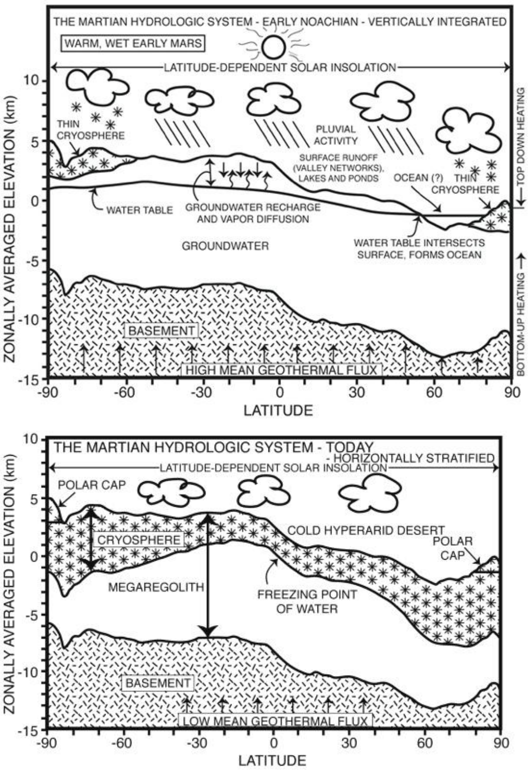

Figure 3. Hydrological systems and cycles (41).Top: Vertically integrated hydrological system: On Earth today, water evaporating from lakes and oceans forms clouds and precipitates out as rainfall or snowfall depending on latitude and altitude. Rainfall infiltrates into the subsurface to join the groundwater system, and runs off where infiltration limits are exceeded, forming fluvial channels and lakes. Both groundwater and overland fluvial flow serve to recharge oceans. Highest latitude polar regions ae characterized by a cryosphere. Noachian Mars is generally interpreted to have been characterized by a vertically integrated hydrological system and cycle. Bottom: Horizontally stratified hydrological system: On Mars today, the Mean Annual Temperature (MAT) is hypothermal (~213 K), the atmosphere is hyperarid (limiting weathering to anhydrous ferric oxides), and the surface is separated from a groundwater system by a kilometers-thick global cryosphere. The surface water cycle is highly abbreviated, with spin-axis/orbital cycles causing sublimation and redeposition of snow and ice from polar regions to lower latitudes and back. The current horizontally stratified hydrological cycle is generally thought to have been characteristic of at least the entire Amazonian, representing the vast majority of Mars history (Figure 1).

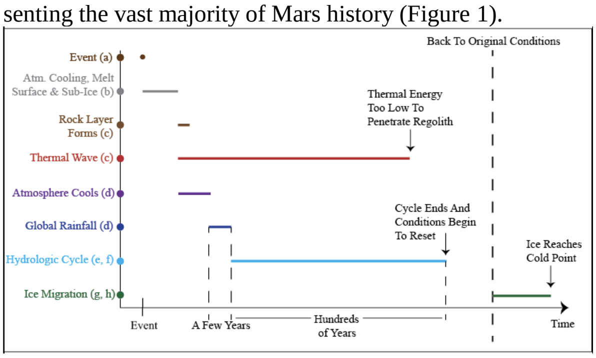

Figure 4. The global effects of basin-scale impact events (27), such as Hellas, Isidis and Argyre in the Early and Middle Noachian. Stages in the basin-scale impact event: Following target impact melting, vaporization and ejection (stages a-d) the atmosphere cools to the point that water vapor is globally catastrophically precipitated and a several year deluge of hot rains ensues, followed by an intense surface-near-surface water cycle (stages e-f) causing landform planation and rock and mineral alteration to clays. After several hundreds of years, the intense event ceases and conditions begin to return to ambient, pre-basin impact conditions. The anomalously high Early-Middle Noachian degradation rates (25), the distribution of phyllosilicates (26), and the distribution of Noachian-aged terrains are together plausibly attributed to the three Early-Middle Noachian Hellas, Isidis and Argyre impact basin events (1,27).

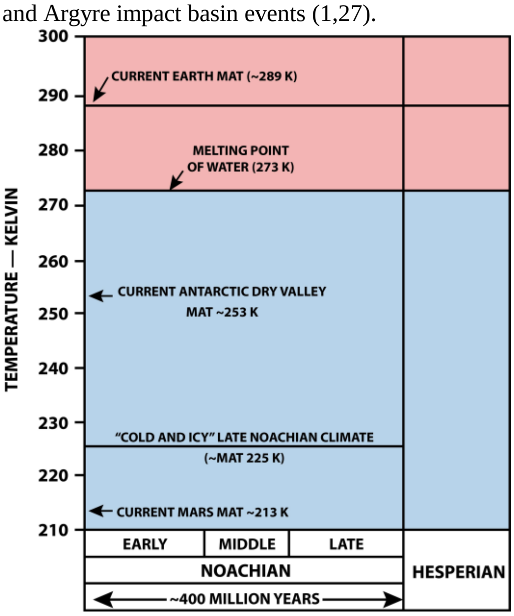

Figure 5. Plots of Mean Annual temperature (MAT) and time during the ~400 million year duration of the Noachian, and into the younger Hesperian. Temperatures in relation to the 273 K melting point of water ice (above, red shaded area,

the ‘Warm and Wet’ ambient climate (42); below, blue shaded area, contains the “Cold and Icy”) ambient climate (43-45). Shown are the current Earth MAT (~289 K), the current Antarctic McMurdo Dry Valley MAT (~253 K) (37-38), and the current Mars MAT (~213 K).