MARTIAN HYDROLOGY: THE LATE NOACHIAN HYDROLOGIC CYCLE. James W. Head[1] , Michael H. Carr[2], Patrick S. Russell[1], and Caleb I. Fassett[1] [1]Department of Geological Sciences, Brown University, Providence, RI 02912, [2]U. S. Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025 (james_head@brown.edu)

Summary: The global climate of Mars is thought by many to have changed to its present cold and dry state from warmer and wetter conditions earlier in its history during the Noachian. Here we summarize evidence for a major transition in near-surface hydrogeologic conditions in the Late Noachian, and a fundamental change in the martian hydrological cycle. Hydrogeologic conditions then were characterized by five main domains: 1) an accumulation zone at higher altitudes, where atmospheric water entered the system through pluvial/nivial activity and was transported laterally by valley networks for tens to hundreds of kilometers before evaporating, sublimating, or completely reentering the vadose zone, 2) an upper mid-altitude region dominated by the vadose zone where pluvial/nivial activity was less important, and valley networks were much less common, 3) a lower mid-altitude region where the groundwater table occasionally reached the surface and theater-headed valleys and large fretted channels formed by groundwater sapping and headward retreat, 4) a lower altitude region, where the groundwater table normally resided and intersected the surface, and where fretted and knobby terrain formed by large-scale groundwater sapping, and 5) a very low altitude region (the northern lowlands), largely below the groundwater table, where groundwater discharge accumulated. Variations in the exact altitude distribution of these zones and the often transitional boundaries between them, strongly suggest that the groundwater system was irregularly recharged during this period and that the groundwater table oscillated vertically with time. Changing atmospheric and near-surface conditions at the end of this period resulted in the freezing of the outer layers of the crust to form a global cryosphere. At the end of this period, the hydrological cycle changed from one which was vertically interconnected from the atmosphere through the surface and subsurface to the groundwater system, to a horizontally layered one in which the groundwater reservoir is separated from the surface reservoir by a global cryosphere, a condition that that still characterizes Mars today, ~3.5 billion years later.

Introduction and Background: Controversy surrounds that nature of early climatic conditions on Mars [1, 2]. In our approach, rather than trying to uniquely determine the nature of the Noachian climate from the geological record (e.g., valley networks [3]) or from global climate models [4], we have adopted the strategy of using the present environmental conditions (cold dry polar desert [5]) as a baseline, and working back in geological time until the geological evidence forces us to the conclusion that the climate must have been different. When and if such evidence emerged, this information might provide insight into the manner in which the environment changed and thus provide independent insight into Noachian climatic conditions. We outline elsewhere [6] the detailed evidence that leads us to the conclusion that cold, dry polar desert conditions and a globally continuous cryosphere [7] characterized the martian climate and near-surface conditions as far back as into the Early Hesperian. Local breaching of the cryosphere and outflow of sequestered groundwater characterized major hydrogeological activity during this 3+ billion year period, and although short-term climate variations may have occurred at these times [8], any changes appear to have been insufficient to alter the globally continuous cryosphere. Three major types of features common in the Late Noachian signal a fundamental change in these conditions: 1) **Fretted and knobby terrain**, which we interpret to represent the presence of a groundwater table intersecting the surface, and the consequent sapping and erosion of the globe-encircling highland-northern lowland boundary [9]. **2) Theater-headed valleys/Fretted channels/Large valley networks**, which we interpret to represent groundwater sapping occurring commonly near the dichotomy boundary, and focused sufficiently to cause significant erosion and headward retreat to form large sapping valleys [10]. 3) **Valley networks**, [e.g., 3, 11] which occur primarily at higher elevations [1] are interpreted to represent overland flow and seepage of water and channelization; we interpret these to represent the result of pluvial/nivial activity and to produce recharge through the vadose zone into the groundwater system [12]. Previously, we have outlined the basic hydrologic principles that govern the hydrological cycle and related processes in environments like those on Mars [13,14]. Here we outline a synthesis of these findings that describe our model of Late Noachian hydrogeology and the transition to a radically different hydrologic cycle than that in existence today [e.g., 7, 15].

The Late Noachian Hydrologic System: We believe that the Late Noachian hydrologic system shares many of the basic characteristics of the present terrestrial hydrologic cycle [13,14], modulated by some of the conditions described above. On the basis of our interpretation of the major terrain types listed above, we envision the hydrogeologic elements and hydrologic cycle at this time as follows.

The most critical element for recognizing the nature of the hydrological cycle is the location of the top of the groundwater system, the water table. This most commonly occurs in the subsurface in land areas on Earth, or at the edge of large standing bodies of water, such as lakes, seas and oceans, where the margins of the water body and the water body equipotential surface itself delineate the water table. On Mars, any Late Noachian standing body of water [e.g., 15] is no longer present, and thus indirect evidence must be sought as to its location.

We interpret the fretted and knobby terrain occurring at the dichotomy boundary and encircling the majority of the boundary between the northern lowlands and the southern uplands at elevations between -1 and -4 km to represent the approximate location of the water table during the Late Noachian [9]. The fretted and knobby terrain is clearly derived from the collapse and degradation into knobs and mesas of adjacent upland cratered terrain. On the basis of 1) its very widespread distribution around almost the entire edge of the exposed upland terrain at the northern lowland boundary, 2) its apparent Late Noachian age (although degradation processes continued to modify it), and 3) its consistent distribution in terms of altitude range [9], we interpret this unit as marking the location of the water table and having originated in the following manner. Above this general level, the surface of Mars was a zone of infiltration, where water falling on the surface ultimately percolated vertically through the vadose zone into the saturated zone and then flowed laterally. In the vicinity of the north-south dichotomy boundary scarp, the water table intersected the surface [7]. In this region, groundwater flows through the porous rock and soil layers discharged to the surface by seepage, and by localized flow as springs.

This eroded and undercut the surface topography causing channelization and backwasting of the scarp and upland cratered terrain. Discharged water and sediment flowed downslope into the northern lowlands. If this fretted and knobby zone is correctly interpreted as the location of the water table, then its presence means that groundwater readily exchanged with the surface on a global scale and that the global cryosphere had not yet developed. Furthermore, the fact that this terrain is not seen in any abundance in younger terrain elsewhere on Mars suggests that this extensive distribution is revealing geological processes that are not common later in Mars' history.

What were the processes responsible for charging and recharging the global aquifer under these conditions? The valley networks provide evidence for the presence of liquid water, surface runoff, and stream activity at higher elevations in the southern uplands. Their presence strongly suggests that water was falling onto the surface due to pluvial or nivial activity, leading to subsequent overland flow and stream channel formation. Valley networks are more common at higher elevations [16,17] in the southern uplands and occur on the flanks of craters at the highest elevations there. If the valley networks were to represent *effluent streams* drawing groundwater from the surrounding regions and were also undergoing significant related groundwater sapping, as envisioned by some [e.g., 16], then the implication is that the water table is just below the surface at elevations of ~3 km, for example in the circum-Hellas highlands. This implies that the global water inventory involves virtually all crustal pore space and thus provides a global water volume well in excess of 1 km global equivalent layer [1,7]. Instead, we believe that the upper part of the regolith in the highlands represents the vadose zone and that the water table occurs at a much deeper level below the surface. We interpret valley networks to be *influent streams*, not *effluent streams*. As *influent streams*, valley network channels form from collection of overland flow from pluvial or nivial water deposition on the surface, lateral transport in the channels, and ultimate drainage down into the vadose zone over the course of their flow. In this manner, they feed the groundwater system largely from above and maintain the level of the water table, which varies depending on the amount of water entering the groundwater system by precipitation and infiltration and the amount leaving the system, for example by evaporation or sublimation back into the atmosphere. Although the depth to the water table is not necessarily constant across the surface, the location of the intersection of the water table and the surface in the fretted and knobby terrain suggests that there may be as much as 3-4 km between the highest surface in the southern uplands and the water table there. This strongly suggests that there is a vadose zone in the southern uplands that may be up to several kilometers thick, depending on rates of infiltration and recharge.

Evidence supporting the presence of a vadose zone comes from the mid-altitude region of the southern uplands where valley networks are much less common. We interpret these to represent areas where pluvial/nivial activity was much less important than in the highlands, and where valley networks had largely lost their transported water by influent processes and seepage and infiltration into the vadose zone. In this model, the lower abundance of valley networks at lower elevations are a natural consequence of their formation in the vadose zone and their influent behavior. Indeed, the unusual nature of many aspects of valley networks [17] can be readily explained by influent streams. If this interpretation is correct, convolved in their characteristics is important information about soil porosity and permeability, and water flux [12].

Located in a zone between the fretted/knobby terrain and the valley networks is a series of very large valley network-like features known as fretted channels and theater-headed valleys [17]. These are broad, flat-floored, steep-walled valleys up to 20 km wide that extend from the margins of the northern lowlands deep into the uplands. The presence of headward linear closed depressions and collapsed margins strongly suggest that the channels and valleys formed by subsurface groundwater movement and sapping [17]. They are primarily located between elevations of -3 km and +1 km, overlapping with the elevation range and area in which there are fewer valley networks. The range in the elevation distribution of the sapping channels may be due to their headward erosion, or could signal differences in the level of the water table. More discharge into the regolith would raise the water table and enhance sapping at higher levels. Alternatively, as the northern lowlands freeze and the cryosphere migrates southward, perhaps the water table rises and the groundwater builds up hydrostatic head [10].

Summary: These data and correlations, and the similarities to terrestrial hydrogeologic features and the hydrologic cycle, suggests that this model (Fig. 1) may reasonably approximate the nature of the Late Noachian hydrologic cycle. This scenario predicts that the northern lowlands were largely below the level of the water table and thus may have been flooded, although the high latitudes indicate that much of the region might have been frozen. In related contributions, we analyze each of the major geological features and assess their nature and formation mechanisms in the context of this model [6,9,10,12].

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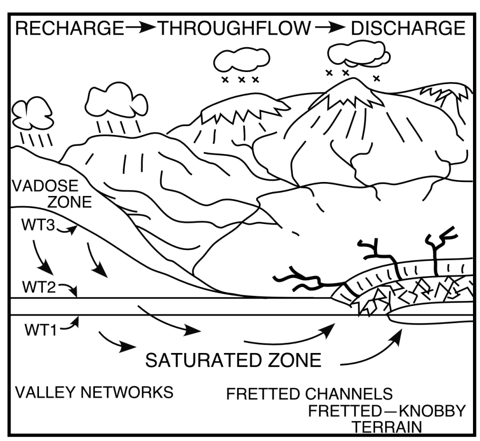

Figure 1. The Late Noachian hydrological cycle.