MARS CLIMATE HISTORY: A GEOLOGICAL PERSPECTIVE

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Introduction and Approach: Deciphering climate history has been one of the major goals of the scientific exploration of Mars because of the significance of climate as a proxy for understanding: 1) planetary volatile accretion, 2) outgassing history, 3) the distribution and stability of water and the nature and evolution of the water cycle, 4) the surface weathering environment, 5) the presence, stability, and abundance of liquid water, 6) the implications for environments conducive to the origin and evolution of life [1], and 7) the influence of climate on the cratering process. Recent intensive exploration has contributed significantly to the understanding of current Mars weather, and lengthening observational baselines are beginning to reveal the basic elements of climate. This baseline knowledge is essential to the proper understanding of the longer-term history of climate. Assessing longer-term climate change and its history can be approached from a process-response standpoint through the identification of cause and effect [2] (Fig. 1). Among the most important causes of climate change (input parameters) are external forcing functions linked to spin-axis and orbital variations, elements whose nature and history have recently become much more well-understood in both the time and frequency domain [3]. The influence of these external forcing functions on the climate system (the internal response mechanism) are becoming more well-known through increasingly more sophisticated atmospheric general circulation models [4-7], including the behavior of water. Finally, the consequences of the causes (the external forcing functions, spin-axis/orbital parameters, operating on the internal response mechanism, the climate system) produces an effect in the time and frequency domain (the geological record); increasing availability of global data is providing a more comprehensive view of over four billion years of geological history [8]. Specifically, increased knowledge of the structure of current polar deposits [9], the location of geological deposits that chronicle the distribution and history of non-polar ice [10], and the context in which to interpret ice deposits in extremely cold hyper-arid Mars-like conditions [11], have all contributed to an increased understanding of the climate history of Mars. We synthesize this here.

Amazonian: (present to ~3 Ga; [20-22]) A robust prediction of the spin-axis/orbital parameter-based insolation input to the climate system has been developed for the last 20 Ma [3] and these predictions have been used to begin to decipher the history of the polar cap [12-14], the nature of recent ice ages [15], the timing of active layers at high latitudes [16], and the conditions under which liquid water might form gullies during this time [17]. Prior to the last 20 Ma, deterministic predictions are not currently possible because solutions based on the input parameters become chaotic; nevertheless exploring this parameter space, Laskar et al. produced 15 scenarios showing candidate obliquity histories over the last 250 Ma (Fig. 2), and predicted that mean obliquity would be ~38° [3]. Analysis of these 15 examples shows the huge range of options for Late Amazonian climate history. In contrast to the last 20 Ma, where input parameters to the climate system are well-known, there is no robust prediction for a specific input parameter history to use as a test in interpreting the geological record. Therefore, we have adopted a different approach and use the geological record of non-polar ice deposits [10] (the output of the external forcing function and climate system) and a general knowledge of the behavior of the GCM and climate system under different obliquity baselines, to evaluate the 15 candidate scenarios of the obliquity component of the external forcing function.

Earlier Amazonian: Using a general knowledge of the behavior of the GCM under different obliquity conditions, we chose four mean baselines to form a framework for evaluating the 15 candidate obliquity scenarios for the last 250 Ma (Fig. 2) [18]. We applied the geological observations, in terms of interpreted latitude and time [10], to assess the candidate obliquity scenarios and found that the obliquity scenario that was most consistent with age and obliquity constraints (Fig. 2-8) is characterized by 45° obliquity at the times of both the early and late TMGs, and obliquity at or close to 35° during mid-latitude glaciations. Examination of the geological record of non-polar ice deposits, together with related information strongly suggests that the climate of Mars throughout the Amazonian was much like at is today, but with migration of surface ice in response to variations in spin-axis/orbital parameters, primarily obliquity. A corollary is that the hydrological cycle was horizontally stratified during the Amazonian [19].

The Hesperian Period: (~3-3.6 Ga; [20-22]): The martian outflow channels debouched into the northern lowlands primarily in the Late Hesperian Period [1] and their characteristics suggest to many workers that a large standing body of water, or ocean, was produced as a result. Characteristics of northern lowland deposits in the Early Amazonian Period suggest that by this time that if such an ocean existed it was gone. The evolution of water loaded with sediments emplaced by outflow channel formation has been modeled [23]; results suggest that it would freeze and sublime on very short time scales. The Late Hesperian Vastitas Borealis Formation may be the sublimation residue of the individual outflow channels [23]. In the Early Hesperian Period, a significant flux of volcanism occurred in the form of the Hesperian ridged plains, and this may well have represented a major pulse of volatiles into the atmosphere [24-25]. In addition, there is clear evidence of interaction of these volcanic deposits and large volatile-rich deposits in the south polar region [26], causing melting and drainage of liquid water.

Over the last 80% of the history of Mars, permafrost and the cryosphere dominate the surface. Although there is compelling evidence that liquid water formed occasionally on the surface and moved locally, there is no compelling evidence that indicates that the global cryosphere was absent at any time throughout the most recent 80% of the history of Mars. Mars surface conditions appear to have been cold and dry throughout most of its history, very similar to the way they are now. Further evidence of this is the limited amount of aqueous chemical alteration detected from orbit [27] and in martian meteorites [28]. Obliquity extremes, and intrusive volcanic activity related to the two major rises, Tharsis and Elysium, appear to have redistributed some water but liquid water was transient on the surface for the vast majority of Mars' history.

The Noachian Period: (>3.6 Ga; [20-22]): Geological evidence has been cited to support a 'warm, wet' era [29] in the late Noachian Period (e.g., valley networks, degradation rates, etc.). Critical assessment of this evidence and new data lead to several scenarios for the emplacement style, location and fate of water on early Mars during the first 20% of its history, and the important transition to conditions similar to those of today. This traditional view has recently been challenged by several developments [19]: 1) The growing evidence that mineralogic indicators for early phyllosilicates (interpreted to support warm and wet surface conditions [30]) could also be explained by subsurface hydrothermal effects in an early period of high thermal flux [31]; 2) The difficulty of producing and maintaining an atmosphere that could lead to a warm and wet early Mars with pluvial activity [32]; 3) Evidence that south circumpolar ice deposits are consistent with cold lower latitude surface temperatures [33]; 4) The poor integration of the surface hydrologic system (valley networks, open-basin lakes [34-35], suggesting short term activity, rather than long term integrated pluvial systems; 5) Emerging evidence in the Antarctic Dry Valleys that Mars-like fluvial and lacustrine activity can occur under surafce climate conditions with mean annual temperatures (MAT) well below 0°C [11]; 6) The possibility that surface drainage features could be explained by top-down transient atmospheric effects caused by punctuated volcanism during the late Noachian-early Hesperian (LN-EH) [36]. Three alternate scenarios for a "non-warm and wet" early Mars appear to be consistent with the six new developments outlined above [19]. Could Mars have been cold and dry or cold and wet, instead of the pluvial warm and wet early Mars envisioned by many [e.g., 29]? Our current data and analyses suggest that Mars was more likely to have been characterized by a "cold and icy" early history and a horizontally stratified hydrologic system throughout most of its history. In this scenario, the Hesperian represents a *perturbation* on the historically horizontally integrated hydrological system, rather than a *transition* from vertical integration to horizontal stratification. We continue to test these scenarios.

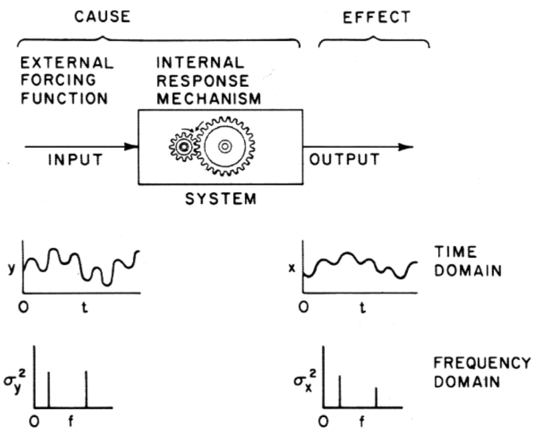

Fig. 1. Process-response framework for analysis of the climate system on Mars [2].

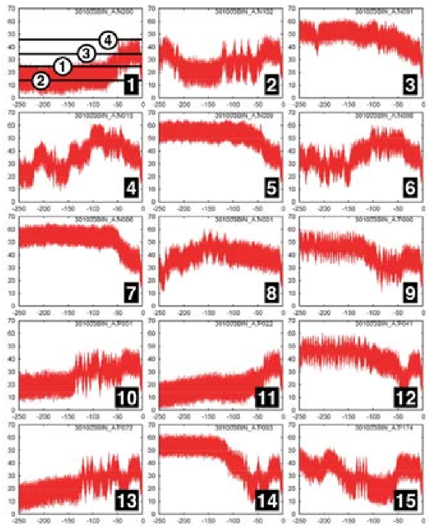

Fig. 2. Examples of possible evolution of Mars' obliquity over the past 250 Myr [3]. Numbered lines in 1 indicate four obliquity scenarios.

In contrast to a "warm and wet" early Mars climate scenario, recent Late Noachian GCMs [32,37] produce mean annual temperatures (MAT) well below 0°C. Above a few tens of millibars, atmospheric-surface coupling yields adiabatic cooling [3] and creates a highlands cold trap leading to a Late Noachian Icy Highlands (LNIH) climate model [32,37]. Melting to account for the abundant LN fluvial/lacustrine features comes from extreme variations in spin-axis/orbital paramenters and/or punctuated heating melting events such as impact or volcanism. The McMurdo Dry Valleys (MDV) provide a similar hyperarid, hypothermal environment, a -20°C mean annual temperature, adiabatic effects, and very limited melting. We examine the MDV hydrological system and cycle to gain insight into the possible configuration of the LNIH, and develop a conceptual model for Late Noachian Mars under MDV-like conditions [38].

MDV Conditions and Application to the LNIH: In the MDV, MAT are well below 0°C producing a regional permafrost layer and a horizontally stratified hydrologic system (Fig. 3). Snow and glacial ice provide the meltwater source. Top-down heating and melting of these ice deposits takes place when peak seasonal (PST) and peak daytime (PDT) temperatures are >0°C. Here we assume that the peak seasonal/daytime temperatures in the Late Noachian icy highlands model can rise above 0°C for limited periods and we explore the consequences of this scenario. The extended summer season on Mars approximately doubles the time when melting could take place. This meltwater forms a perched aquifer above the ice table aquilude. The resulting fluvial activity is ephemeral, but repeated yearly events can carve valleys and form lakes. Lakes are semi-permanent due to ice cover, and thus meltwater is stored there during periods when temperatures fall below 0°C. Variations in the hydrologic system are introduced by landscape-induced snow and ice dynamics (e.g., volume, altitude, and insolation geometry of flowing ice) and by small fluctuations in input parameters to solar insolation (e.g., spin axis/orbital parameters).

In the LNIH scenario, the southern hemisphere uplands would be blanketed by a layer of ice and snow tens to hundreds of meters thick [39] and snow would concentrate at high altitudes above the +1.0 km surface ice stability line (Figs. 4-5) [32]. Below this altitude, snow and ice could also accumulate on local highs depending on local and regional topography and atmospheric circulation patterns [40]. In a steady-state situation, any surface liquid water at low-altitudes (equatorial and northern lowlands) would rapidly freeze, sublimate, and be transported back to the southern high altitudes, replenishing the snow and ice cover. The upper part of the regolith below the surface ice stability line would be dry above the top of the ice table to a depth determined by diffusive equilibrium with the atmosphere. The Noachian hydrologic system would be horizontally stratified due to the global permafrost aquiclude (Fig. 2). Repeated seasonal melting would cause warming of the cryosphere but the melting isotherm would be unlikely to penetrate deep into/through the km-thick cryosphere.

Derivation of Meltwater: 1) Regional snow and ice deposits above the surface ice stability line (Fig. 4) would undergo altitude/latitude dependent warming during each Mars summer (about 6 Earth months); 2) meltwater runoff from the ice sheet would drain and flow downslope to the edge of the ice sheet, where meltwater channels would encounter Noachian cratered terrain topography and flow across the surface forming valley networks, and around and into craters, forming closed-basin and open-basin lakes; fluvial drainage systems on top of aquicludes would be extensive, but might be poorly integrated; 3) snow and ice accumulations below the snowline would also undergo melting, producing a more integrated drainage system controlled by the presence of snow; 4) seasonal top-down heating and melting of the top tens of meters of continuous ice would produce a volume of water, based on inferred ice sheet size [39], well in excess of the total volume interpreted to have occupied open-basin/closed basin lakes [41].

Hydrological System and Cycle: 1) Meltwater would initially infiltrate into and erode the dry regolith to the top of the ice table, producing a perched aquifer and more efficient lateral erosion than deeper infiltration [42]; 2) time periods above 0°C would be long enough to cause extensive melting and runoff; 3) this Noachian icy highlands, atmospheric-surface coupling induced, adiabatic cooling effect-dominated water cycle would persist until MAT dropped to below 0°C; 4) once MAT returned to values well below 0°C at the end of warming, lower altitude/latitude snow and ice would sublimate and return to high altitudes as snow to re-establish the nominal Noachian icy highlands climate regional snow and ice deposits.

Noachian Ice Sheet Melting: Fluvial Processes: Surface melting of a Noachian ice sheet has the following consequences (Fig. 4): 1) meltwater is focused in streams near the edge of the ice sources and overland flow is thus limited to the location of the channels at the edge of the ice sheet; 2) streams therefore may be of low order (due to being linked to individual ice sheet drainage channels, not integrated overland flow) and poorly integrated with widths and depths significantly influenced by the shallow ice table [42]; 3) sediments are pre-processed by impact cratering, volcanic, and eolian processes; the source rocks are already highly modified; 4) stream activity acts to further physically alter the sediments, producing sorting and rounding; 5) in streams, the hyporheic zone (Fig. 3) defines the focus for chemical and isotopic exchange, and chemical weathering; 6) if simple life existed on Mars at this time, ecosystem development might be focused in streams during wet periods; on longer time scales these deposits might become ecological legacies for the sustenance and reactivation of ecosystems; 7) inter-stream areas are not significantly influenced by the fluvial phase and thus net erosion rates are minimal there and for the terrain in general.

Noachian Ice Sheet melting: Lacustrine processes: Transported meltwater collects and resides in lacustrine environments: 1) Streams drain into local lows to form ponds and lakes, predominantly in intercrater and intracrater regions; 2) local ponds form in irregular lows from peak discharge drainage; these could contain significant amounts of solutes from erosion of surface salts and from water flushed from the hyporheic zone; 3) some depressions (typically impact craters) fill with water, breach the rim crest and drain, creating open-basin lakes; 4) closed-basin lakes (also often in craters) are formed when water flux is insufficient to fill the depression; 5) lakes are likely to be ice covered, losing ice by sublimation but adding ice by freezing of inflowing meltwater to the base or on top of the ice cover; 6) lakes can persist between periods of melting due to their ice cover; smaller ponds and lakes may disappear at these times due to sublimation; 7) the dominance of sublimation over evaporation in these lakes disfavors, but does not preclude, the formation of evaporates on the lake floors following transition to another climate regime.

Summary: Additional sources of punctuated top-down warming, the environmental effects of impact cratering events and massive volcanic eruptions, could potentially produce a short-lived warmer climate and surface hydrological activity on the multi-decadal-centennial time scale. Regardless of the melting mechanism or its duration, the icy highlands model provides a robust mechanism for recharging highland water sources through water migration from lowland streams and lakes, back to higher altitudes to be redeposited as snow. Thus, the MDV hydrological system and cycle guidelines provide insight into a conceptual model for Late Noachian Mars under MDV-like conditions [38] and permit further testing of the LNIH [29,32,37] model.

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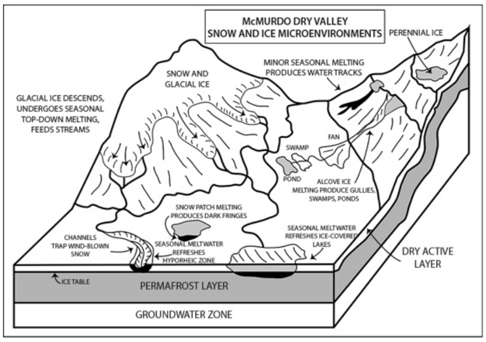

Fig. 3. McMurdo Dry Valley snow and ice microenvironments illustrating the altitude dependence of meltwater sources and the horizontally stratified hydrologic system.

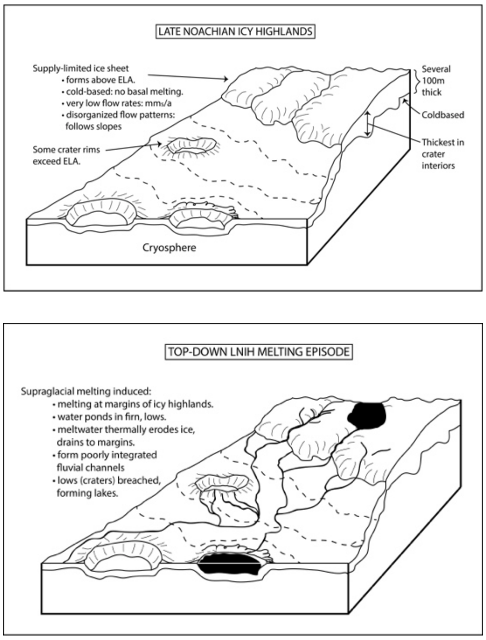

Fig. 4. Late Noachian Icy Highlands configuration (top) and the results of a top-down melting episode (bottom).

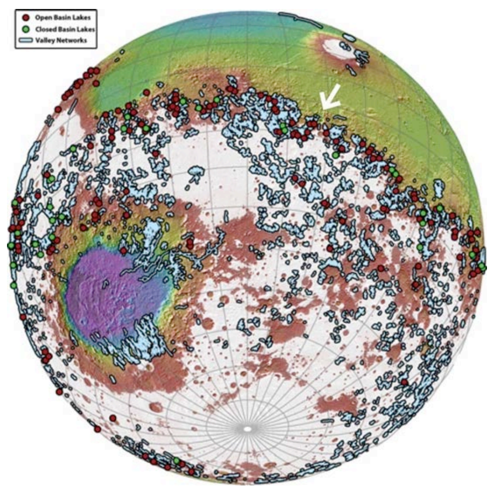

Fig. 5. LNIH snow and ice configuration (above ELA of +1 km) and observed meltwater features [4,43].