COLD AND ICY NOACHIAN MARS: INSIGHTS INTO THE HYDROLOGICAL SYSTEM AND CYCLE FROM THE ANTARCTIC McMURDO DRY VALLEYS.

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Late Noachian Mars Climate?: Examination of the geological record of non-polar ice deposits [1] strongly suggests that the climate of Mars throughout the Amazonian (the last ~66% of Mars history), was much like it is today, a cold and dry climate regime, characterized by the latitudinal migration of surface ice in response to variations in spin-axis/orbital parameters, primarily obliquity [2]. But what of the earlier history of Mars? What characterized the climate regime during the Noachian, the first ~20% of Mars history? Many lines of evidence and reasoning have been cited to support the interpretation of a "warm and wet" early Mars climate [e.g., 3,4], but this evidence has also been challenged [5,6]: 1) Significant parts of the phyllosilicates in the Noachian crust (Fe, Mg clays) appear to be due to hydrothermal (subsurface) alteration [7]; 2) Noachian degradation/erosion rates are very low by terrestrial standards [8]; 3) Poor integration of valley networks and open-basin lakes (despite increased valley network density) [9] could suggest shorter-term fluvial, rather than long-term pluvial activity; 4) Regional ice deposits at all latitudes in the Amazonian [1] provide perspective on the possibility of regional ice deposits in the Noachian; 5) A Late Noachian south circumpolar ice sheet [10] suggests that Noachian and mid-latitude atmospheric mean annual temperatures (MAT) were below freezing [11]; 6) Valley network-related precipitation might be snowfall (nivial), not rainfall (pluvial) [12]; 7) The Mars-like Antarctic Dry Valleys [13] show that meltwater-related fluvial activity can occur when MATs are well below freezing; 8) Punctuated volcanic outpourings can lead to transient atmospheric warming and extensive melting of surface ice [14]; 9) New estimates of water loss rates to space are much lower [15]; 10) Martian meteorites [16] suggest that paleoatmospheric pressures were <400 mbar by 4.16 Ga; 11) Atmospheric modelers have always encountered difficulty in producing and maintaining an atmosphere conducive to Noachian warm and wet pluvial environments due to a faint young Sun and insufficient greenhouse gases [17].

Recent Progress: The Late Noachian Icy Highlands Model: Recently, significant progress has been made in the modeling of the early Mars atmosphere by Forget, Wordsworth and colleagues. A complete 3-D General Circulation Model (GCM) [18] including revised spectroscopic properties for CO_2, and a full water cycle [19], has been developed. Simulations of an early Mars climate assumed a faint young Sun and a CO_2 atmosphere with surface pressures between 0.1 and 7 bars. One of the most fundamental findings of the model is that for atmospheric pressures greater than a few hundred millibars, surface temperatures vary with altitude because of the onset of atmosphere-surface thermal coupling, and adiabatic cooling and warming of the atmosphere as it moves vertically. This *adiabatic cooling effect* results in the deposition of snow and ice at high altitudes (Fig. 1), in contrast to the conditions at present and throughout the Amazonian. Exploration of parameter space for the Noachian atmosphere-surface thermally coupled climate regime [18,19] found that, in the absence of other warming mechanisms, no combination of parameters could lead to mean annual surface temperatures consistent with widespread melting and flow of liquid water anywhere on the planet. Inclusion of a complete water cycle with clouds and precipitation [18] permitted the modeling of the location and evolution of water and ice on the surface of early Mars. The addition of a water cycle, combined with the adiabatic cooling effect, causes southern highland region temperatures to fall significantly below the global average (Fig. 1). These conditions lead to the scenario of a "Noachian Icy Highlands": Water is transported to the highlands from low-lying regions due to the adiabatic cooling effect and snows out to form an extended H_2O ice cap at the southern pole, and altitude-dependent snow and ice deposits down to lower southern latitudes [18-19]. Meteorite impacts and volcanism could potentially cause intense episodic melting [19], with ice migration to higher altitudes being a robust mechanism for recharging highland water sources. Could the predictions of this "Noachian Icy Highlands" model (Fig. 1) be consistent with the many lines of evidence traditionally cited for a "warm, wet" early Mars and also address the contradictions cited above?

Testing the Late Noachian Icy Highlands Model: A simple reconstruction of an icy Noachian Mars [18,19] shows the effects of the adiabatic cooling effect (Fig. 2**):** first, the Dorsa Argentea Formation would surround the south circumpolar region, and snow would concentrate at high altitudes (high southern latitudes) accumulating and forming ice deposits; a value of +1.0 km is adopted for the surface ice stability line (ISL). Below this altitude, snow and ice could accumulate on local highs depending on local and regional topography and atmospheric circulation patterns [12]. In a steady-state situation, any transient low-altitude (equatorial and northern lowlands) surface liquid water would rapidly freeze, sublimate, and be transported to the southern high altitudes (Fig. 1), forming a cover of cold-based ice and snow (Fig. 2). Any regolith exposed below the ice stability line would show a dry surface layer over a shallow ice table, the depth of which would be determined by diffusive equilibrium with the atmosphere (Fig. 3). Spin-axis/orbital perturbations [2] would modulate, but not radically change, this configuration.

Perturbing this predominant Noachian environment with punctuated impacts and volcanism/greenhouse gases could lead to the raising of global surface temperatures toward the melting point of water. Four factors would be important: 1) the adiabatic cooling effect would control the distribution of snow and ice (the surface ice stability line); 2) the greenhouse effect would determine the level and duration of temperature changes; 3) latitude dependent insolation would modulate temperatures (cold at the south pole, 'warmer' toward equator); 4) general circulation patterns further influence air temperatures and local ice accumulation. To investigate further the effects of punctuated global warming, we assume current topography, spin-axis/orbital parameters, atmospheric circulation patterns, and a Noachian icy highlands climate [18-19]. Raising Noachian Mars equatorial MAT to +5°C (typical of central Canada and Scandinavia on Earth today) could produce the following regional, perhaps seasonal, consequences (Fig. 2): 1) ice above the surface ice stability line would undergo rapid altitude/latitude dependent warming during each Mars summer (about 6 Earth months); 2) meltwater runoff from the continuous 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 around and into craters, forming closed-basin and open-basin lakes and extensive, but poorly integrated fluvial drainage systems; 3) local snow and ice accumulations below the ISL could also undergo melting, producing a more integrated drainage system controlled by the presence of snow; sometimes these two systems integrate; 4) seasonal top-down heating and melting of the top tens of meters of continuous ice would produce a volume of water well in excess of the total volume interpreted to have occupied open-basin/closed basin lakes [20]; 5) this meltwater would initially erode into the dry regolith down to the top of the ice table (Fig. 3), producing a perched aquifer and more efficient erosion than infiltration alone; 6) time periods above 0°C would be long enough to cause extensive melting and runoff, but too short to cause significant differences in the depth to the top of the ice table; 7) at the end of the annual melting period, temperatures would return to below 0°C, meltwater would freeze and sublime, returning to the high altitudes as snowfall to replenish the snow and ice deposit (Fig. 1); 8) this Noachian icy highlands, adiabatic cooling effect-dominated water cycle would persist until MAT dropped to below 0°C; 9) once MAT returned to normal values well below 0°C at the end of punctuated warming, lower altitude snow and ice would return to high altitudes to reestablish the nominal Noachian icy highlands climate.

In summary, the icy Noachian highlands and punctuated volcanism scenario (Figs. 1,2) appears to be able to account for: 1) the source and volume of water required for valley networks; 2) the presence of closed-basin lakes and open-basin lakes; 4) evidence for recurring phases of activity over millions of years; 5) the generally small amounts of net erosion; 6) areas of both significant trunk streams and more distributed runoff; 7) relatively poor stream integration and lower order than typical of pluvial activity on Earth; 8) abrupt cutoff in valley networks and open-basin lake activity based on delta characteristics; 9) apparent short duration of individual phases of activity; 10) the presence of a surface hydrological cycle that can replenish the source area and cause recurring activity with a small total budget of water; and 11) the presence of melting and runoff in a Late Noachian climate compatible with other constraints (e.g., faint young Sun, low atmospheric pressure).

As outlined here, the contrasting "warm and wet" and "cold and icy" Noachian climate regime models make important predictions that can be tested with current and future data, experiments and missions and point out key locations for the return of samples.

Antarctic Terrestrial Analogs: Can insight into these factors and predictions [18-19,21] be gained using analogous terrestrial environments? Noachian valley networks and open basin lakes have been cited as key evidence for a "warm and wet" early Mars. We investigate fluvial and lacustrine processes in the Mars-like Antarctic McMurdo Dry Valleys (MDV) [4] to assess whether such processes, which take place in the absence of pluvial activity and with mean annual temperatures (MAT) well below zero, can serve as informative proxies for Noachian Mars [21].

Fluvial Processes: Fluvial processes in temperate climates dominate the evolution of the landscape due to the abundance of pluvial activity and the consequence of its drainage, chemical and physical erosion and transport, and its influence on a host of other processes. In the hyperarid, hypothermal MDV, however, there is no pluvial activity. Delivery of water to the surface environment is by direct snowfall in very small amounts (3-50 mm a^{-1} water equivalent in the MDV [23]) and from snow transported laterally off the polar plateau by katabatic winds. Snowfall can drift and be sequestered in topographic traps and wind shadows. Long-term snow and ice accumulation results in the formation of glaciers, and their seasonal melting represents the major source of liquid water for fluvial activity. Melting occurs only seasonally and all streams are ephemeral on seasonal and sometimes daily time scales. Due to localized sources and the immature topography of the MDV, stream order is very low, and streams tend to form ice-covered, closed-basin lakes.

The range of microenvironments in the MDV results in significant variation in the state and activity of water *within* the MDV [22]. In the *stable upland zone* (SUZ), temperatures are sufficiently cold both annually and seasonally that fluvial activity does not occur. In the *inland mixed zone* (IMZ), streams are minimal in number, drainage basins are by definition small, and streams are virtually all of first order. The shallow substrate (Fig. 3) is characterized by permafrost with an ice table at 15-40 cm depth beneath a regionally dry active layer. Recharge zones are limited to perennial and annual snow patches, some of which are trapped in alcoves and gully channels that undergo top-down melting. Initially, meltwater percolates vertically downward, wetting the dry active layer below, and then also migrates laterally to create a wetted zone along the margins of channels (the *hyporheic zone*).

Significant volumes of meltwater that infiltrate down from the surface may flow downslope along the top of the ice table (15-40 cm depth), wicking up and feeding the advancing hyporheic zone. Flow in the hyporheic zone along ephemeral streams occurs at three scales: 1) locally in the stream bed, flux may be insufficient to overcome the infiltration capacity of the channel sediment, and meltwater percolates into the substrate only to re-emerge a few meters down-channel in springs at a topographic step caused by the presence of rocks; 2) at the bases of slopes and near valley bottoms, wet-topped polygons form in topographic lows, creating a "swampy" spongy area where patches of water can be seen to emerge to the surface; 3) water may continue to travel along the ice table in the valley floor until it can intersect the surface, forming a local pond [24,37].

In the *coastal thaw zone* (CTZ), seasonal temperatures exceed the melting point of snow and ice in soils. Alpine and piedmont cold-based glaciers extend down into the CTZ and can undergo significant surface melting, creating the meltwater that feeds the vast majority of ephemeral streams and associated hyporheic zones, and ultimately drains into lakes. Meltwater generation is significantly influenced by the geometry of the glacier relative to solar insolation [25-26]. There is also evidence that significant melting can take place below the solid surface in the upper meter of glacial ice by absorption of solar radiation along crystal boundaries [25]. Glacial meltwater cascades off the edge of the ice, often in waterfalls, and drains downslope in streams. Streamflow is quite variable [27], depending on melting in the source region [25], and streams are of low order. Most streams flow into closed-basin lakes [28]. Since there is no pluvial activity, streamflow is restricted to the meltwater fluvial channel and associated hyporheic zone [24]. Chemical weathering is highly concentrated, especially in stream channels [29], and the large areas of terrain between channels are largely unaffected and unmodified by fluvial activity (Fig. 3).

In some cases, epiglacial lakes [28] can serve as the source of streams and, because of short-term storage of liquid water next to the source, these can form longer streams and even rivers that flow for most of the summer season. Meltwater from Wright Lower Glacier is impounded behind a moraine complex, forming Lake Brownsworth. Drainage from Lake Brownsworth forms the ~35 km long Onyx River that flows into Lake Vanda, a closed-basin lake toward the western end of Wright Valley. The immature nature of the Onyx River retains a memory of recent antecedent climatic events and can thus be used to compare fluvial histories between valleys [30].

In summary, in contrast to temperate climates, fluvial processes in the MDV (and thus a host of weathering, erosion and transport processes there) are severely limited by the lack of rainfall. Fluvial activity is absent in the stable upland zone, seasonal and intermittent in the inland mixed zone, and often seasonally continuous, but ephemeral in the coastal thaw zone [22]. The limited sources of meltwater provide very local streams and hyporheic zones, serving to concentrate chemical weathering processes and biological ecosystems. The horizontally stratified hydrologic system means that localized meltwater is constrained to flow in a very shallow and narrow aquifer perched on top of the ice table aquiclude (Fig. 3).

Lacustrine Processes: More than 20 permanent lakes and ponds occur in the MDV [28] and, in contrast to temperate lakes, almost all are characterized by perennial ice cover up to 6 m thick, overlying liquid lake water. Ice cover serves to: 1) limit exchange of gases between the lake and the atmosphere, 2) restrict sediment deposition in the lake, 3) reduce light penetration, and 4) minimize wind-generated currents [31]. Lake levels have been rising in the recent past at about 15 cm a^{-1} [28], a trend interpreted to be due to a corresponding increase in summertime surface air temperature [32].

Chinn [28] subdivided lakes in the Dry Valleys into several hydrological types: 1) *Wet-based* lakes do not freeze to the ground during austral winter and have either permanent, seasonal or no ice cover; summer inflow of meltwater beneath the ice cover causes lake levels to rise seasonally and they lower from sublimation of the ice cover and evaporation of the summer meltwater moat. 2) *Dry-based lakes* include ice-block lakes that are permanently frozen through to the lake bed; ice thicknesses may far exceed those in wet-based lakes and such lakes rise by addition of meltwater by flooding on top of the ice surface, and fall by ablation of the surface. Some dry-based lakes may have a thin film of highly saline water at their base. 3) *Ice-free lakes*, such as Don Juan Pond, are very highly saline, and usually do not freeze even in winter. Chinn [28] further subdivided MDV lakes on the basis of their openness and associations: 1) *Enclosed lakes* have no surface outflow (*closed-basin* lakes); summer inflow is balanced by annual sublimation and evaporation and such lakes are usually warm, saline, and meromictic. 2) *Lakes with throughflow* overflow into outlet streams (*open-basin* lakes), have relatively stable levels, and are commonly not saline. 3) *Epiglacial lakes* are on or against glaciers.

How do these lakes differ from temperate lakes? First, MDV lakes lie on top of a 200-300 m thick permafrost layer; intuitively, one might imagine that these lakes should freeze solid due to mean annual surface air temperature of ~<-20°C. However, very finely-tuned conditions lead to the present characteristics in MDV wet-based lakes. Stratification results from saline density gradients and the ice cover prevents wind mixing of lake water.

Where does the lake water come from and under what conditions is excess meltwater produced to cause modifications in their levels? The dominant means of supply (meltwater) and loss (ablation) are clearly seasonally and climatically controlled. Throughout their recent history it is clear that small perturbations to the climate can result in large changes in the lake systems, often in non-intuitive ways [28]. Clearly, the main source of meltwater supply in the MDV is from surface melting of glaciers and snowbanks, but this is not a simple function of increasing MDV surface air temperature [28]. The observed positive correlation between increased lake levels and streamflow is thought to represent a complex relationship with the climate-related behavior of glaciers, specifically depending on the distribution of glacier area with elevation in the watershed [28,33]. As the H_2O melting temperature rises seasonally in altitude, glaciers are encountered and melting of their fronts will begin in a complex non-linear manner [25,34], feeding streamflow. The rate of streamflow will increase as seasonal warming brings the melting temperature up to the specific elevation that represents the maximum glacier area per elevation contour in the ablation zone [25,28,33,34,37].

Summary: Lakes and ponds in temperate areas are largely of pluvial origin and characterized by abundant vegetation, large drainage basins and higher order streams delivering rainwater. In contrast, the hyperarid, hypothermal conditions in the MDV mean that there is no rainfall, water sources are limited primarily to meltwater from the surface of cold-based glaciers, and drainage into lakes is seasonal and highly variable, being related to changing and sluggish response to surface ice hypsometry, itself a function of changing climate. Lake surface level fluctuations are caused by imbalances between meltwater input and sublimation from the lake surface ice and this sensitive balance tends to magnify even minor climate signals.

This framework of seasonal melting and fluvial/lacustrine processes in an otherwise hyperarid, hypothermal Mars-like Antarctic cold-based non-pluvial environment [22,25,26,28,37] provides a baseline of environmental conditions to test the hypothesis that a "cold and icy" Noachian Mars [18,19] might produce the observed fluvial and lacustrine features [e.g., 20,35] during transient warming periods [21]. The wide range of fluvial and lacustrine processes and features seen in the MDV strongly suggests that observed Late Noachian features on Mars could be consistent with the "Icy Highlands" climate model [19,36) for Late Noachian Mars.

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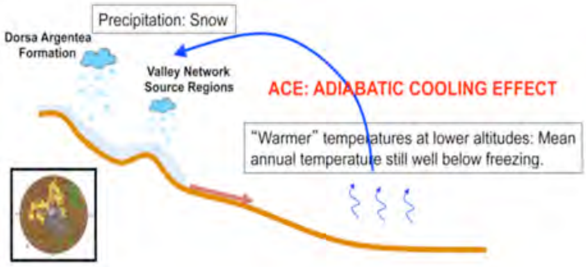

Fig. 1. *Noachian icy highlands climate regime* (18-19); snow at high elevations, a MAT well below 0°C, and a horizontally stratified hydrologic system. Inset map: extensive Dorsa Argentea Formation south polar cap.

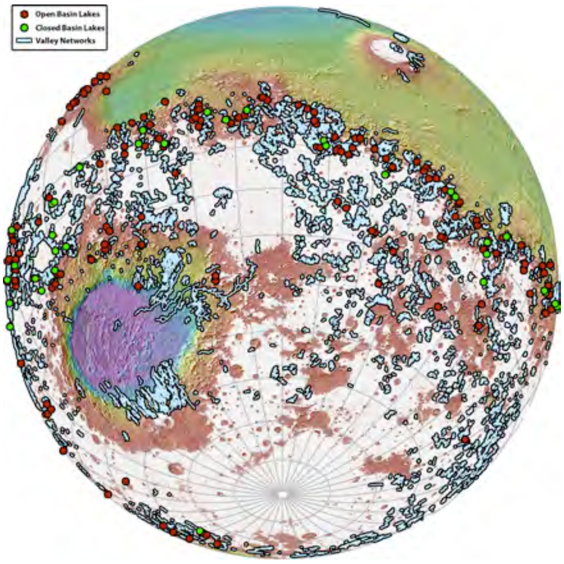

Fig. 2. Global view of the *Noachian icy highlands* (white areas above the surface ice stability line) [19,36]. Kilometers-thick Dorsa Argentea Formation ice cap near bottom; tens to hundreds of meters thick ice cover (white) extends to the vicinity of the dichotomy boundary. Valley networks (blue), closed-basin lakes (green dots), and open-basin lakes (red dots) are shown. Punctuated volcanism [14] is predicted to cause global warming and transient melting of the icy highlands (white) creating sufficient meltwater to form valley networks and associated lake systems.

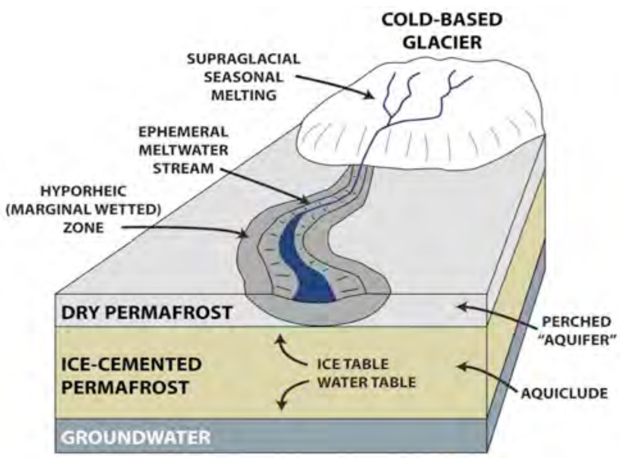

Fig. 3. *Antarctic MDV Hydrological System* [22,37]. Meltwater formation is localized to limited areas of snow and ice supply and then confined to the perched aquifer above the ice table in the dry active layer; dehydration is rapid and intervening areas are unaffected [37].