LATE NOACHIAN CLIMATE OF MARS: CONSTRAINTS FROM VALLEY NETWORK SYSTEM FORMATION TIMES AND THE INTERMITTENCIES (EPISODIC/PERIODIC AND PUNCTUATED).

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Introduction: The formation of valley network systems (VNS) in the Late Noachian-Early Hesperian (LN-EH) signaled the presence of warm and wet conditions and has generated a variety of hypotheses for climates permissive of these conditions (ranging from ambient warm and wet, to cold and icy). In order to constrain options for the ambient Noachian climate, we examine the range of estimates for the amount of water required to form the VNS, the time required to carve channels, form deltas and fill lakes, and the total duration implied by plausible types of intermittencies. Useful definitions include: *duration*, length of time that a process operates or condition exists; *continuous*, uninterrupted, sustained activity; continuity may show variability (deviation from the average condition) and fluctuation (irregular variation in number or amount); *intermittent*, not continuous or steady but recurring at some interval; *intermittency*, the display of discontinuous activity and an estimate of its recurrence; *sustained*, continuing without interruption for an extended period; *episodic*, recurring at irregular intervals; *periodic*, recurring at fixed intervals; and *punctuated*, forceful interruption at uncertain intervals.

Total Volumes of Water Required: The cumulative volume of water required to erode the VN has been estimated at 3-100 m GEL (global equivalent layer) [1], a value ~0.1-3 times the current surface/near surface water inventory [2]. Because all climate models call on precipitation recycling, the actual volume could be much less. The volume required to fill all open-basin lakes (OBL) simultaneously is 0.45 GEL [3].

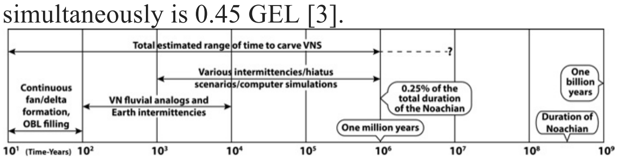

Fig. 1. Durations.

Formation Times for VN, OBL, Deltas, Fans: A synthesis of the timescales required for these features [4] (Fig. 1) showed minima of $<10^1$-10^2 Earth years for continuous alluvial fan/delta formation and OBL filling, 10^2-10^4 assuming various terrestrial fluvial analogs and intermittencies, and for VN formation 10^3-10^6 assuming various intermittencies (e.g., flow every 10^2 years) and hiatus scenarios (e.g., flow 1% of the total time), different VN examples, and computer simulations. Even with the longest estimated continuous duration of VN formation [1] (10^4) and intermittencies of 10^1 or 10^2, the total time to carve the VN does not exceed 10^6 years, a value less than ~0.25% of the total length of the Noachian (Fig. 1). Could the VN systems themselves be forming not simultaneously, but at different times in different places? Crater size-frequency distributions (CSFD) have been interpreted to imply that total VN activity was limited to the LN-EH [5-8], a duration not exceeding ~10^8 years [8] (<25% of the total Noachian) and that each VN was active intermittently for 10^5-10^7 years [5], both relatively short periods of time. What do these numbers (Fig. 1) mean for VNS processes and climates? Assumptions about intermittency and episodicity are climate-model dependent (e.g., most workers use Earth-like fluvial activity and intermittency [9]). Thus we review the major LN-EH climate models.

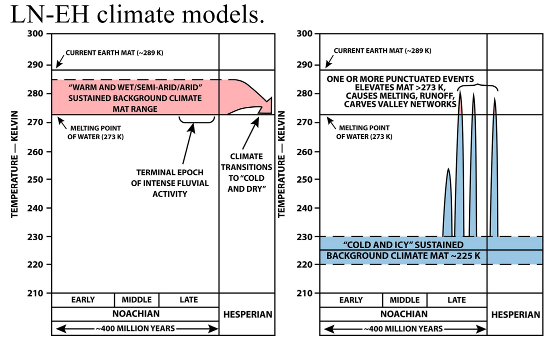

Fig. 2. Climate models.

Noachian-Early Hesperian Climate Models: Three background climate states have been proposed (Fig. 2):

1) Warm and wet/semiarid/arid climate: In this model (Fig. 2a), sustained background MAT is >273 K, the hydrological system is vertically integrated, and rainfall occurs to recharge the aquifer. Two subtypes of this sustained "warm and wet/semiarid/arid" climate have been proposed: a) *"Rainfall/Fluvial Erosion-Dominated Warm and Wet Model"*: In [10] "rainfall and surface runoff" persist throughout the Noachian [10] to explain the state of ancient crater degradation and infilling, and a LN-EH short and rapidly ending terminal epoch of intense fluvial activity [11] is required to form the VNS. b) *"Recharge Evaporation/Evaporite Dominated Warm and Wet Model"*: Here [12] a sustained period of equatorial and mid-latitude precipitation and a vertically integrated hydrological system driven by evaporative upwelling and fluctuating shallow water table playa environments account for the sulfate evaporate environments at the Meridiani Planum MER landing site. Sustained temperatures >273 K are required for extended periods (10^7-10^8 years) [12] to account for the thickness of the Meridiani deposits.

2) Cold and icy climate: In this model (Fig. 2b) [13], sustained background temperatures are extremely low (MAT is ~225 K; ~50 K below the melting point of water), the cryosphere is globally continuous, the hydrological system is horizontally stratified, separating the groundwater system from the surface, and no combination of spin-axis/orbital perturbations can raise the MAT to 273 K. Atmospheric pressure in excess of tens to a few hundred millibars causes atmosphere/surface ther-

mal coupling, inducing adiabatic cooling effects that transfer water to high altitudes to deposit as snow and ice, leading to the "Late Noachian Icy Highlands Model" [13-14], where snow and ice dominate the southern uplands and the south pole. VNS cannot form in this nominal climate environment without special circumstances (e.g., impacts or volcanic eruptions to cause elevation of temperatures by at least ~50 K to induce melting and fluvial/lacustrine activity).

3) Cold and Icy climate warmed by greenhouse gases: In this model, the climate is the sustained cold and icy model (Fig. 2b), but greenhouse gases of unspecified nature, amount and duration elevate MAT by several tens of Kelvins (say 25 K, to MAT 250 K), bringing the annual temperature range into the realm where peak seasonal temperatures (PST) exceed 273 K. In this climate environment, analogous to the Antarctic McMurdo Dry Valleys (MDV)[14], seasonal summer temperatures above 273 K are sufficient to melt snow/ice and to form fluvial and lacustrine features, but MAT is well below 273 K (253 K). As in the MDV, VNS are predicted to form by moderate elevation of MAT to between 225 K and 273 K for a sufficient period to permit multiple years of intermittent peak seasonal melting to form the VNS.

Revisiting Intermittency: What is the total duration of VNS activity? What types of variability in the system might cause different intermittencies? We define two types of intermittency: 1) *Episodic/Periodic Intermittency* is of two scales: a) *Normal atmospheric system variability*: These are seasonal, annual and decadal weather and short-term climate fluctuations (*episodic* on annual, decadal, century and millennial, 1-10^3 year timescales (years) that determine maximum precipitation and runoff in different catchment areas, stream flux, effluence and influence, and groundwater levels. b) *Externally forced climate cycles*: This variability derives from the influence of spin axis-orbital variations (obliquity, eccentricity and precession) that influence patterns of solar insolation and its influence on the climate system. This *periodic* intermittency operates on 10^3-10^6 year timescales. 2) *Punctuated Intermittency* is of two types: a) *Variability in effusive/explosive volcanic processes*: Volcanism is likely to be punctuated and can occur at all timescales and intervals and is likely to be more episodic than periodic, with uncertain intermittency. b) *External stochastic variability: Impact cratering*: Typical impact cratering events are episodic and punctuated (but vary in magnitude); durations of atmospheric effects are estimated at 10^2-10^3 years [15].

Key Factors in Assessing Climate Models: What do these two types of intermittency, *episodic/periodic* and *punctuated* mean for the interpretation of the estimated timescales? 1) For the "warm and wet" climate, there is no problem accomplishing fluvial erosion and for the duration of the Noachian, as required [10], but the problem is finding a climate model that can sustain a MAT >273 K for >0.4 x 10^9 years in order to accomplish this; this requires oceans and long term vertical hydrological system integration for recharge, and then a special case for the short terminal climate optimum for VN incision and rapid cessation [11]. 2) For the "cold and icy" climate, climate models have no problem achieving sustained MAT ~225 K (faint young Sun). The problem is how to find mechanisms that will provide punctuated intermittency sufficient to exceed 273 K to cause the volume of melting required to form the VN systems. A positive aspect of this model is that the location of the snow and ice [13-14] provide a ready source for the VN systems, located at the ice edges, should a mechanism for melting be found. Punctuated intermittencies offer a solution. Only a few of these are required, and high volume, short duration events would be consistent with the data; there is potentially no need for Earth-like fluvial intermittencies, and activity should decrease rapidly when these special conditions terminate. Candidate punctuated events include impact events [15] and volcanism [16]. 3) For the cold and icy climate model with MAT elevated with "greenhouse gases", the intermittency is yearly (PST exceeding 273 K) and the problem is to provide both 1) a sufficient duration of elevated baseline temperatures and 2) peak seasonal melting to explain the VN systems. This mechanism is much more plausible than raising the MAT to >273 K for long durations (>0.4 x 10^9 years) (Fig. 2a) and places considerably less stringent requirements on the production and maintenance of greenhouse gases [17]. It requires, however, PSTs that are sufficient to sustain valley network systems that are more than an order of magnitude larger than those in the MDV.

Conclusions: Fluvial systems driven by *episodic/periodic intermittency* typically involve short intermittency time-scales (10-10^6 years) but require a warm climate (MAT >273 K) to be sustained for >0.4 x 10^9 years. Fluvial systems driven by *punctuated intermittency* typically involve short duration time-scales (10-10^5 years) but only require a warm climate (MAT >273 K) for the very short duration of the climatic impact of the punctuated event (10^2-10^5 years). We conclude that a *cold and icy background climate with punctuated intermittency of warming and melting events* (Fig. 2b) is consistent with (Fig. 1): 1) the estimated durations of continuous VN formation (<10^5 years) and 2) VN system estimated recurrence rates (10^6-10^7 years) [5,7,8].

References: 1) Rosenberg & Head, 2015, PSS 117, 49; 2) Carr & Head, 2015, GRL 42, 1; 3) Fastook & Head, 2015, PSS 106, 82; 4) Buhler et al., 2014, Icarus 124, 130; 5) Hoke et al., 2011, EPSL 312, 1; 6) Fassett & Head, 2008, Icarus 195, 61;7) Hoke & Hynek, 2009, JGR, 114, EO8002; 8) Hoke et al., 2014, Icarus 228, 1; 9) Wolman & Miller, 1960, Jour Geo. 68, 54; 10) Craddock & Howard, 2002, JGR 107, 5111; 11) Irwin et al., 2005, JGR 110, 212; 12) Andrews-Hanna et al., 2010, JGR, 115, E06002; Icarus 195, 61;13) Wordsworth et al., 2013, JGR 120, 1201; 14) Head & Marchant, 2014, Ant. Sci, 26, 774; 15) Horan & Head, 2017, MAPS, in review; 16) Halevy & Head, 2014, Nat. Geosci. 1; 17) Wordsworth et al., 2017, GRL, GL071766.