HYDROLOGY OF EARLY MARS: EVIDENCE FROM LAKE OVERFLOW AND VALLEY NETWORK INCISION.
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Introduction: Valley networks incised up to several hundred meters into the cratered highlands are ubiquitous on the equatorial crated highlands. Incision of these valley networks required streamflow from precipitation occurring as direct runoff, snowmelt, or groundwater discharge. The majority of the valley networks ceased to incise at about the Noachian-Hesperian boundary, although some valley systems were episodically active until about the Amazonian-Hesperian boundary [*1-4*]. The valley activity near the Noachian-Hesperian boundary may have resulted from a relatively brief climatic optimum [*4*]. The width and meander wavelength of locally-preserved channels within the valley networks suggest formative discharges reached magnitudes equivalent to the mean annual flood in terrestrial drainage networks with the same contributing area [*5*].

The climatic conditions responsible for valley network incision remain uncertain. Simulations of early Martian climate to date have been unable to replicate conditions conducive to an active hydrologic cycle, due to the ease of escape of volatiles due to the lower Martian gravity and the early loss of the magnetic field as well as the lower luminosity of the early Sun. Energy additions from large impacts short-term enhancement of greenhouse gasses due to volcanism have been suggested as causes of short-duration warmer climates.

Methodology: We are constraining the early hydrologic cycle on Mars through analysis of paleolakes and depths of valley incision. The absolute magnitudes of precipitation, runoff, and evaporation on early Mars are uncertain, but evidence from overflowing lakes and relative amounts of channel incision can constrain the ratio of these quantities, the X-Ratio:

$$X=(E-P)/RP \qquad \textbf{[1]}$$

Here E is the yearly depth of evaporation from lakes, P is yearly depth of precipitation, and R is the fraction of precipitation on highlands that enters the channel system through overland flow, throughflow, and groundwater seepage. Low X-Ratios imply humid conditions, and high values reflect desert-like settings. Terrestrial settings with throughflowing drainage generally have X-ratios between -1 to zero. Hot deserts such as in the Great Basin can experience X-ratios exceeding 20. During the last glacial maximum when large lakes (e.g., Bonneville and Lahontan) occupied the Great Basin X-ratios dropped below 4 [*6*].

Results from Analysis of Overflowing Lakes: Using a MOLA-derived digital elevation model we have simulated the relative distribution and sizes of lakes and channel discharges for a wide range of assumed X-Ratios [*7*]. Our analysis focused on determining the value of the X-Ratio that must have occurred in order to create channelized exit breaches in some basins. The majority of exit-breach basins required X-ratios between 3 and 6 to overflow, although there is some regional variation in the required X-ratio. These estimates may over-estimate the required X-ratio because the exit breaches have lowered the required lake levels necessary for overflow. That is, more humid conditions and lower X-ratios may have been required for the initial basin rim breaching.

Valley Incision Analysis: Stream channels occur as two broad classes: alluvial- and bedrock-floored. In the former the rate of channel incision is related to flow discharge, channel gradient, and in many cases abrasion of the bed by sediment in transport. Incision of alluvial channels depends upon the stream transport capacity, which in turn is a function of discharge, stream gradient, and size of sediment. In both cases the relative amount of channel incision within a network of channels should functionally depend upon the spatial distribution of channel gradient and prevailing discharges. We analyze these dependencies in three ways: 1) The maximum X-Ratios (driest conditions) that permitted flow throughout the valley networks are determined; 2) Depth of valley incision is related to valley gradient and assumed values of relative flow intensity; 3) Valley cross-sectional area and eroded volume are related to basin gradient and assumed flow intensity.

X-Ratios at Appreciable Network Flows. We selected sites near the downstream end of 170 large, deeply incised valley networks throughout the Noachian cratered highlands and calculated the relative annual flows at the sites as a function of the assumed X-Ratio for a unit upland runoff depth. At an X-Ratio of -1 all potential upslope areas contribute (all lakes overflow), whereas progressively less of the potential contributing area produces runoff for larger X-Ratios. We plotted the discharges through the network relative to the value at X=-1 (Qmax) as a function of the X-Ratio and noted when discharges reached 5%, 10%, and 50% of the maximum flow. Fig. 1 is a cumulative plot of the fraction of the 170 networks exceeding these discharge thresholds as a function of X-Ratio. It is likely that flows derived from more than 5-10% of the potential upstream contributing area were required to form integrated valley networks. The majority of valley networks would have required X-Ratios less than ~3 to 5 to reach those relative contributing areas, in accord with our analysis of overflowing lakes.

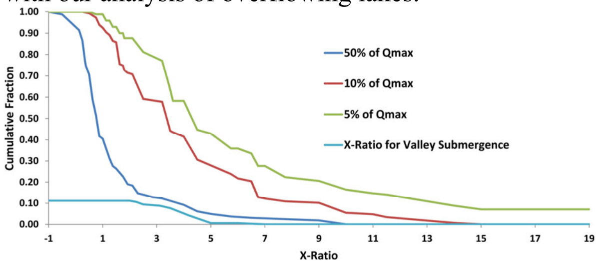

Figure 1

Analysis of Depth of Valley Incision. We utilized a digitized database of valley networks in the Martian highlands compiled by the authors to analyze the depth of incision of valley networks as a function of valley gradient and modeled relative discharges. A methodology was used similar to [*4*] to estimate valley incision depth from MOLA PEDR data by utilizing the 75th percentile of relative elevations within an 8 km radius to define the surface into which valleys were incised. Only relatively constant-gradient valley segments longer than 10 km were chosen in an automated analysis, resulting in 12,043 sample reaches. Gradients were measured directly from the digitized valley centerline. Relative discharges for each sample reach were determined as a function of assumed X-Ratio. Channel incision would have occurred during high discharges superimposed upon the mean annual flow. We assume that the degree to which the drainage network is integrated is a function of which basins are at overflow conditions based upon the mean annual balance of lake evaporation and upland runoff, because large lakes typical of the Martian highlands require hundreds of years to fill to overflowing conditions. We then route flood flows through the network defined by the assumed X-Ratio, with the further assumption that large lakes can attenuate the flood flows routed through them. The incision depth, Z, is related to the local valley gradient, S and the estimated flood discharge, Q in a power law relationship: $Z=KQ^mS^n$. Here we make the assumption that in incising valley networks the amount of incision should correlate with flow magnitude and valley gradient for both the case where the channel might be bedrock or alluvial. We find that incision depths correlate strongly with valley gradient (n~0.57) and weakly with modeled flood discharge (m~0.03), and that the multiple regression R^2 is about 0.44. The value of the exponent m is highest for $X \leq 4$. Assuming floods are attenuated by lakes has only a modest influence on these results.

Analysis of Valley Volume. Vast quantities of sediment were transported across the Martian highlands during the incision of the valley networks. The valley networks generally are sharply incised into broad upland surfaces [*4*]. We utilize the above approach of identification of the upland surface as the 75th percentile elevation in a radius of 16 km to estimate the valley cross sectional area, A_v. This eroded valley cross-section is routed downstream through the valley network to estimate a total eroded volume, V_T, moving through each location in the valley network. We assume that depressions hosting lakes are efficient sediment traps, so that no sediment outflows from the depression, although attenuated flood discharges do pass through overflowing lakes. We apply a threshold ratio of lake volume to throughflowing discharge to distinguish between 'real' lakes and 'accidental' lakes resulting from DEM artifacts and post-Noachian valley modifications, with no sediment volume attenuation for accidental lakes. The analysis of cross sectional area, A_v, as a function of discharge and local gradient unsurprisingly gives results similar to that of incision depth. The total eroded volume was related to estimated discharge and to the average upstream valley gradient, S_B, in a power function relationship: $V_T=KQ^pS_B{}^q$. This regression had high explanatory power (R^2~0.7) with p~1.2 and q~0.4. Although a correlation between V_T and estimated discharge Q is almost inevitable because both are routed downstream, the high degree of explanatory power in the fitted relationship is a result of the strong integration of valley incision throughout individual valley networks. Here also the highest R^2 values occur for low values of the X-Ratio.

Discussion: We have conducted additional analyses not reported here, including the effect of runoff being positively correlated with local relative elevation (as in the southwestern US) and regional variations in depth of incision and eroded volume. All of our hydrological analyses point to the necessity for climatic conditions on early Mars requiring a climate at least as moist in terms of the balance of runoff and lake evaporation as occurred in the Great Basin region of the US during the late Pleistocene when large lakes were present. This climate would have had to be maintained for hundreds and probably hundreds of thousands of years to create the observed valley networks, many of which extend for thousands of kilometers with well-developed tributary systems.

References: [1] Fassett, C. I., Head, J. W. (2008) *Icarus 198* 61-89; [2] Fassett, C. I., Head, J. W. (2008) *Icarus* 198 37-56; [3] Howard, A. D., Moore, J. M. (2011) *JGR 116*, doi:10.1029/2010JE003782; [4] Howard, A. D. *et al.* (2005) *JGR 110*, doi:10.1029/ 2005JE002459; [5] Irwin, R. P. I. *et al.* (2005) *Geol. 33*, 489-92;[6] Matsubara, Y., Howard, A. D. (2009) *WRR45*, W0425, doi:10.1029/2007WR005953;[7] Matsubara, Y. *et al.* (2011) *JGR 116*, E04001, doi:10.1029/2010JE003739.