MARS’ NOACHIAN-HESPERIAN INTENSIVE FLUVIAL ACTIVITY DRIVEN BY ATMOSPHERIC COLLAPSE. P. B. Buhler. Planetary Science Institute (pbuhler@psi.edu).

Introduction: Mars’s surface was modified by liquid water flow in roughly three epochs: a modest Noachian (~3.6 Ga) river-forming period, intensive Late Noachian-Early Hesperian (~3.6 Ga) valley-network-forming period, and later (~3.5 Ga) localized flows [1-3]. The intensive valley network formation period is particularly enigmatic because it follows the less intense, earlier Noachian style of fluvial erosion [3], even though most processes (e.g., volcanism, impacts, thicker atmosphere) typically invoked to sustain surface water were waning by that time [1]. Climate models predict that most of Mars’ water inventory was frozen in southern ice sheets at ~3.6 Ga [4], seemingly at odds with the emergence of an optimal period of fluvial erosion. However, I use numerical modeling to show that insulation from an extensive CO₂ ice sheet atop a south polar H₂O ice sheet [5] due to collapse of Mars’ CO₂ atmosphere at ~3.6 Ga [6, 7] would trigger extensive basal ice sheet melting, leading to global-scale flooding and an attendant period of enhanced fluvial erosion (Fig. 1).

Methods: A regolith adsorption and atmospheric equilibration model [12] is used to calculate the CO₂ ice cap mass \( m_{\text{CO}_2\text{cap}} \) collapsed on a pre-existing south polar H₂O ice cap [5]. Ice column thermal structure and H₂O basal melting is modeled using a 1-D thermal conduction scheme accounting for geothermal heat \( F_{\text{geo}} \) [13], strain heating in the H₂O ice, latent heats of sublimation and fusion, mass balance, the formation of structure-I CO₂ hydrate clathrate (a cage-like structure of H₂O enclosing CO₂ guest molecules), and glacial flow. The model has appropriate temperature bounds at the surface, base, and interface between ices and clathrate. Modeled collapse initiates at 30° obliquity from an inflated 600 mbar atmosphere to a collapsed pressure of 11 mbar at the CO₂ ice cap surface (set by vapor pressure equilibrium) in 10⁴ yr [6, 7], accounting for CO₂ adsorbed in the regolith [12]. Collapse occurs onto the south pole, the favored location in Noachian climate models [4] and in the modern climate [14].

In the column model, CO₂ accumulates to thickness \( h_{\text{CO}_2} \), set by the onset of basal CO₂ melting because model deposition far exceeds glacial flow subsidence. Clathrate forms at the CO₂-H₂O ice boundary, where it is thermodynamically favored. Column thermal profiles are calculated iteratively using temperature-dependent CO₂, H₂O, and clathrate thermal conductivities [15-17]. H₂O ice strain heating \( F_{\text{strain}} = 2A_T\sigma^4 \), with shear strain \( \sigma \) and empirical constant \( A_T \) ranged across low to high values from [18], is also calculated iteratively. Maximum H₂O ice column thickness \( h_{\text{H}_2\text{O}} \) is set by the onset of basal H₂O melting. Modeled bare H₂O ice column \( h_{\text{H}_2\text{O}} = 2-4 \) km, depending on assumed \( F_{\text{geo}} \) so initial H₂O column thickness \( h_{\text{H}_2\text{O},\text{init}} \) is set to 2-4 km, consistent with prior 3-D models [5, 10]. Basal melt volume \( V_{\text{melt}} \) is calculated from the difference in \( h_{\text{H}_2\text{O},\text{init}} \) and \( h_{\text{H}_2\text{O}} \) after CO₂ deposition, multiplied by collapse area \( A_{\text{CO}_2} \). Melt flux is calculated from available column heat flux and latent heat of H₂O melting once the basal temperature reaches the melt point. The model does not include the effects of dust, salts, H₂O basal sliding heating, or CO₂ strain or sliding heating—any of which would enhance H₂O basal melting.

Results: Atmospheric Collapse. Accounting for uncertainty in parameters relevant to regolith adsorption [12], \( m_{\text{CO}_2\text{cap}} = 3.4^{±0.8}_{-0.3} \times 10^{18} \) kg. Nominal \( h_{\text{CO}_2} = 660 \) m for 50 mW m⁻² heat flux. Nominal \( A_{\text{CO}_2} = 3.2^{±0.8}_{-0.6} \times 10^{12} \) m². Across all models, heat flux varies from ~45—100 mW m⁻², yielding a factor of ~3 variance in \( h_{\text{CO}_2} \) and \( A_{\text{CO}_2} \).

Fig. 1: MOLA [8] elevation map (blue, low = -5000 m; red, high = +6000 m) in Mars south polar projection. Map units from [9] and esker distribution from [10]. “Channel 1” is nomenclature from [11]. CO₂ ice sheet extent assumes nominal model parameters and constant 660 m depth.
Fig. 2: Model-predicted volume of H$_2$O basal melt. Subpanels show low, nominal, and high CO$_2$ collapse mass models. Colors indicate $h_{\text{H}_2\text{O}_{\text{init}}}$. Shaded regions indicate melt range for $F_{\text{geo}} = 40, 50$, and 60 mW m$^{-2}$ (labeled) bounded by assumptions of low and high shear heating. Argyre volume up to 0 m breach contour (pink in Fig. 1) provided for reference.

Water Melt Volumes and Fluxes. Model-predicted $V_{\text{melt}}$ generally ranges from $10^{15}$–$10^{16}$ m$^3$ (Fig. 2), i.e., $\sim 0.2 \div 2.0 \times$ Mars’ present-day estimated global inventory or 4-40% of the likely maximum Late Noachian inventory [4]. $V_{\text{melt}}$ increases with larger $h_{\text{H}_2\text{O}_{\text{init}}}$, more clathration, higher $F_{\text{geo}}$, and higher $A_T$. Model melt flux spans $3.3 \times 10^2$–$3.0 \times 10^3$ m$^3$ s$^{-1}$, consistent with basal melt production estimated from Hesperian Polar Unit eskers [10, 11] (Fig. 1, 3). Collapse-triggered basal melting is also consistent with the lack of association between eskers and volcanic edifices [10]. For all model runs, complete column melt times are a few $\times 10^5$ yr. Atmospheric collapse likely lasted $\sim 10^4$–$10^7$ yr, for collapse driven by a dip to low ($\sim 30^\circ$) obliquity during a generally high obliquity state or entry into a persistently low ($\sim 30^\circ$) obliquity state, respectively [19], so complete melting may or may not occur during a given collapse.

Discussion: Several 100s-km sinuous valleys leading from the Hesperian Polar Unit (Fig. 1) have been previously proposed to record melt water flow from a Noachian-Hesperian ice cap into a lake in Argyre Crater [11, 20]. Argyre paleolake has been proposed to have breached, sourcing flow into the Uzboi-Ladon-Marova system, and delivering water at least as far equatorward as Margaritifer Basin [21] (Fig. 1). Such delivery could potentially seeding a previously proposed cycde of Hesperian outflow megaflooding in Chryse Planitia [23]. Argyre overflow has been criticized primarily because no plausible mechanism for delivering sufficient water to cause breaching has previously been identified, although morphologic evidence is consistent with such an overflow [20]. Modeled $V_{\text{melt}}$ indicates that polar basal melting triggered by atmospheric collapse could provide water sufficient for breaching (Fig. 2).

Fig. 3: Basal H$_2$O melt rate as a function of H$_2$O column thickness for various scenarios. Green, blue, and red regions indicate range of melting rates from low to high shear heating for $F_{\text{geo}} = 40, 50$, and 60 mW m$^{-2}$, respectively. Melt rate estimate from eskers [10] is provided for reference.

Conclusions: Water delivery from cyclic collapse events modeled here has timescales consistent with inferred valley network formation from episodic runoff over $\gtrsim 10^6$ yr followed by abrupt cessation of fluvial activity [1]. Over $\sim 10^6$ yr, the effectiveness of polar basal melting would decrease due to the decline in Mars’ volatile inventories [22] and $F_{\text{geo}}$ [13]. These model results indicate that Mars’ period of intensive fluvial activity near the Noachian-Hesperian boundary may have occurred in a collapsed-atmosphere climate similar to modern Mars, permitted principally by the formation of large CO$_2$ and H$_2$O polar deposits.