WHY DID MARS DRY OUT?

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Summary: Billions of years ago, Mars had rivers and lakes; today it lacks both. Possible causes are loss of atmosphere (mostly CO_2), loss of H_2O (to deep burial or to space), or loss of the capacity for non-CO_2 warming (e.g. [1,2]). We hypothesize that clues to the cause of Mars' final drying out are encoded in shifts in the distribution of water-involved features on Mars' surface as surface liquid water waned (e.g. [3,4]). For example, the lower elevation (after correcting for resurfacing) of Mars' late-stage alluvial-fan sourcing catchments relative to the elevation of the catchments that fed Mars' earlier valley networks might be explained as the result of (i) a reduction in pCO_2; (ii) a reduction in the strength of Mars' greenhouse effect; or (iii) a shift from surface runoff to groundwater control, marking an intermediate stage in loss of H_2O from Mars (Fig. 1) (e.g. [5]). Preliminary results are used to illustrate this approach.

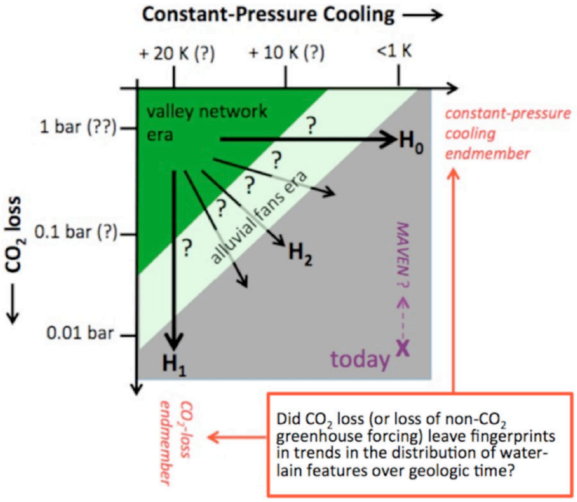

Fig. 1. *Although Mars has lost atmosphere over time, it is not clear if Mars' late-stage rivers formed under high atmospheric pressure (H_0), or if late-stage rivers record atmospheric loss (H_1). This is because CO_2 is important, but not enough to explain Early Mars rivers and lakes. Therefore loss of non-CO_2 greenhouse forcing, alongside (H_2) or instead of (H_0) loss of CO_2, is a possible explanation for the decline in Mars surface habitability Combining improved understanding of the effect of pCO_2 on the elevation+latitude distribution of surface liquid water with geologic proxy data can constrain pCO_2 versus time and thus constrain the causes of the drying-out of Mars.*

Methods: Using existing catalogs [4, 6, 7] and geologic maps [8, 9], we calculated marginalized distributions with latitude and elevation of Mars water-associated geologic features of different ages (Fig. 2). Using the MarsWRF GCM [10], we calculated the annual-peak diurnal mean temperature and the annually-integrated sublimation potential (a proxy for snowpack stability; [11,12]) at a range of atmospheric pressures. (We also plan to carry out gray-gas experiments to represent the effect of non-CO_2 greenhouse forcing). Initial MarsWRF results are consistent with previous GCM work (e.g. [12]).

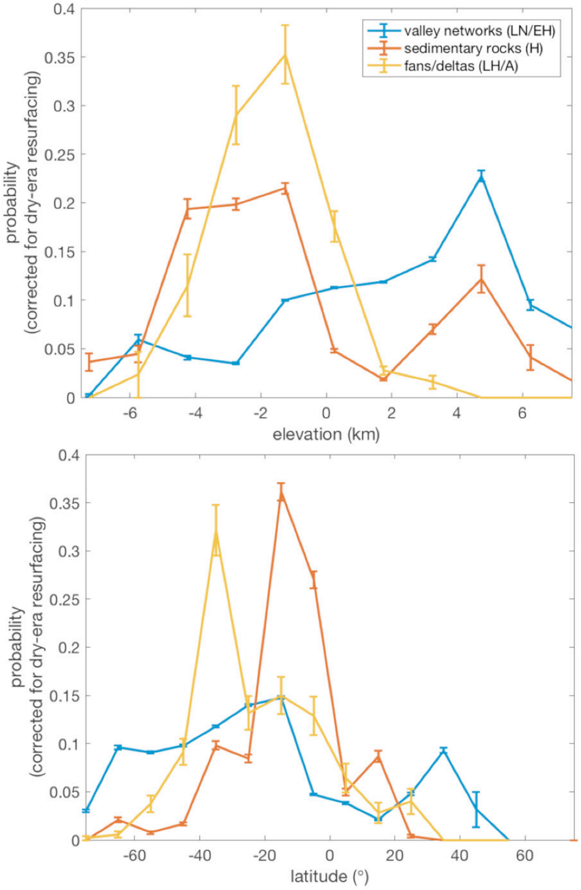

Fig. 2 *Marginalized results for the distribution of water-associated geologic features with (top) elevation and (bottom) latitude. Preliminary results (bootstrapping on outcrops, valleys, and fans). Normalized to wet-era terrain abundance. 1σ error bars are shown. LN/EH = Late Noachian / Early Hesperian. H = Hesperian. LH/A= Late Hesperian / Amazonian.*

Results and interpretation:

So strongly does pCO_2 affect Mars paleoclimate that changes in pCO_2 between ~10 mbar and 1000 mbar are seen, in GCMs, to bring changes in the elevation and latitude distribution of both peak temperature, and snow/ice stability, which (in non-groundwater scenarios for late-stage alluvial fans) jointly control surface liquid water potential on Mars [10-12]. (For example, high pCO_2 is an essential ingredient of the Late Noachian Icy Highlands hypothesis; [13]). The physical basis for this transition is clear: very thin atmospheres "[play] a small role for the heat budget of the surface" [14], so (flat-)surface temperature is set by latitude alone. But, for a very thick atmosphere, winds even out latitudinal temperature gradients, and surface isotherms increasingly correspond to topographic contours. Thus, as pCO_2 goes up, $\partial T_{surf}/\partial z$ becomes more negative [15]. It is tempting to connect this effect with the shifts over geologic time shown in Fig. 3. This would imply a major drop in atmospheric pressure (pCO_2) during the Hesperian, from >0.3 bar to <0.1 bar [2]. However, multiple working hypotheses remain consistent with the data. For example, if Mars cooled at constant pressure, liquid water runoff would be increasingly confined to lower elevations. Moreover, systematic bias is not yet fully captured by the bootstrap procedure we used to generate Fig. 3 (for example, we have not yet taken account of post-fluvial erosion in North-West Arabia Terra [16]). Finally, our current understanding of the effect of pCO_2 on latitude and elevation distribution of rivers and lakes is imprecise, so more modeling in addition to more careful data analysis will be needed in order to fully exploit the global geologic record of Mars' wet-to-dry transition.

Linking orbiter surveys with MAVEN and *Curiosity* results: MAVEN data are consistent with high water loss rate but only slow CO_2 loss (e.g. [1]). Combining 3.5-Gyr integrated isotopic constraints from *Curiosity* with MAVEN data also suggest limited CO2 escape to space since 3.5 Gyr (Heard & Kite, this conference & ref [17]). However, CO_2 sequestration as carbonate is not directly constrained by this procedure.

Conclusion. Mars is the only planet known to have become uninhabitable. With improving whose surface is time resolution thanks to CTX-based crater counts, and combined with the results of morphological studies (e.g. [18-19]), we are getting a better handle on the patterns and the paleoclimatic underpinnings of Mars' drying-out.

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References: [1] Jakosky et al. 2019 *Icarus.* [2] Kite 2019 *Space Sci. Rev.* [3] Kraal et al. 2008 *Icarus*. [4] Morgan & Wilson 2019 *LPSC*. [5] Andrews-Hanna & Lewis 2011 *JGR*. [6] Malin et al. 2010 *Mars Journal.* [7] Hynek et al. 2010 *JGR.* [8] Tanaka et al. 2014 https://dx.doi.org/ 10.3133/sim3292. [9] Nimmo & Tanaka 2005 *AREPS* [10] Mischna et al. 2013 *JGR.* [11] Kite et al. 2013 *Icarus.* [12] Wordsworth et al. 2015 *JGR* [13] Head et al. 2017 *4^{th} Intl. Conf. on Early Mars*. [14] Haberle, R. M.; Catling, D. C.; Carr, M. H.; Zahnle, K. J., 2017, The Early Mars Climate System, in The atmosphere and climate of Mars, Edited by R.M. Haberle et al. ISBN: 9781139060172. Cambridge University Press, 2017, 497-525 [15] Wordsworth 2016, *Annual Reviews*. [16] Hynek et al. 2003 *Geology.* [17] Heard & Kite 2020 *EPSL.* [18] Mangold et al. 2012 *Icarus.* [19] Goudge et al. 2016 *Geology.* [20] Grotzinger & Millilken 2012, chapter in in Sedimentary Geology of Mars. SEPM Special Publication, v. 102.

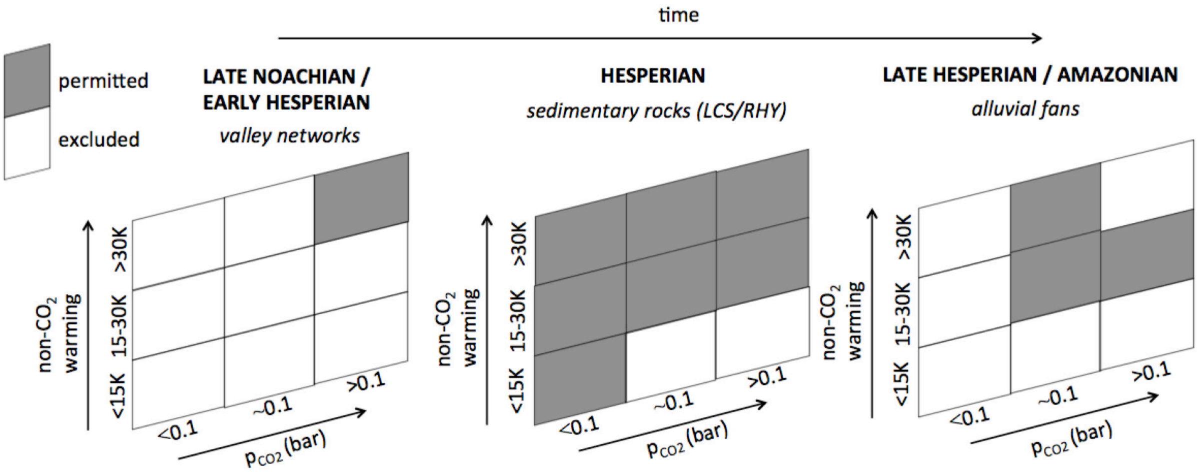

Fig. 3. *Climate evolution inferred here. LCS/RHY = Laterally Continuous Sulfate / Rhythmite facies of [19].*