KEY PARAMETERS FOR EARLY MARS CLIMATE RESEARCH.

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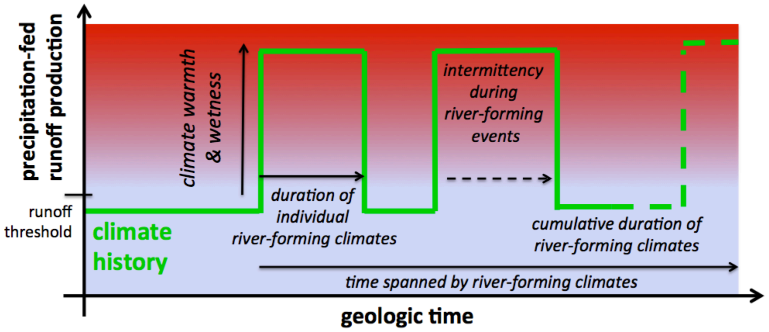

Introduction: In the last few years, published explanations for rivers and lakes on early Mars have ranged from intermittent $<10^2$-yr-duration volcano/impact-triggered transients to $>10^6$-yr-duration humid greenhouse climates. As a set, these models represent an embarrassment of riches for the Mars research community, so geologic data are sorely needed to discriminate between the models. Fortunately, new analyses provide better constraints on the number, duration, intermittency, and intensity of the river-forming climates However, as shown at the October 2017 Early Mars Conference, these geologic constraints have not been summarized in a way that is digestable for the modeling community. Here I focus on physical parameters that can be used as input or test data for numerical models of post-Mid-Noachian climate and atmospheric evolution.

Number of river-forming climates: ≥2 (high confidence). For this abstract, I define a river-forming climate as a >10 yr time interval during which precipitation-sourced water runoff occurred during most years. Valley networks formed in the Late Noachian / Early Hesperian (LN/EH) [1]. Then, after an interval of deep wind erosion indicating dry conditions [2,3], alluvial fans and closed-basin lakes formed in the Late Hesperian and/or Amazonian (LH/A) [4,5]. [3] and [6,7] suggest division of the LH/A climate into 2 or 3 river-forming events. The LN/EH valleys represent an intense, but relatively late and topographically superficial [8] geomorphic event. Pre-LN landscape modification has been interpreted to be fluvial [9].

Final drying-out of the rivers of Mars <3.5 Ga (high confidence). Crater counts indicate rivers at 3.0 Ga [4,10]; (2 Ga on the Robbins chronology [11]). This is consistent with crosscutting relationships [5] and with a K-Ar date at Gale [12]. Because melting snow and ice should be difficult for $P<0.1$ bar [13], these late dates set us the challenge of finding a sink for CO_2 that could be efficient relatively late in Mars history [14].

Duration of longest river-forming climate: >3 kyr (high confidence), $>10^5$ yr (medium confidence). Hydrological analysis using orbiter topography, indicate individual lakes lasted >3 kyr (assuming dilute flow <1%) [15-16]. The Murray mudstone in Gale Crater is water-altered and rhythmically laminated, with mudcracks only near the top of the logged section, and is interpreted as a lake deposit. If mm-thick laminae are interpreted as annual lake varves, then the absence of evidence for drying-up lower in the section suggests lake lifetime $>10^5$ yr [17]. Orbiter data indicate river-forming deposits built up over $>10^6$ yr [18] but hiatuses cannot be excluded. These durations, as well as column runoff production >1 km (medium confidence) [19], mean that runoff could not be directly produced by impact energy [20-21].

Peak runoff production >0.1 mm/yr (high confidence). Hydrologic calculations and width-discharge correlations indicate runoff production > 0.1 mm/yr [19,22,23]. These rates can be explained by either snowmelt or rainfall (but see the new global database of Kite et al., this conf.).

Intermittency during wet events: peak runoff production <10% of the time (high confidence). Many, but not most, lakes during the LN/EH overflowed. Almost no lakes overflowed during the LH/A [24]. To avoid all lakes overflowing, given high peak runoff production and long lake duration, runoff production must have been unsteady during the wet events [25]. Extremely slow average alluvial fan build-up rate during the LH/A wet event [7] further suggests unsteady runoff. Fluvial intermittency need not require intermittent habitability. Life persists in climates too dry for rivers [26].

Paleo-atmospheric pressure, *P*: <1 bar (medium confidence), >0.012 bar (high confidence). The modern atmosphere+ice CO_2 reservoir is 0.012 bar [27]. Small craters interbedded with river deposits indicate thin atmosphere ~(3.6-3.8) Ga; <1 bar according to the bolide burn-up/break-up model of [28]. However, this might correspond to periods of atmospheric collapse interspersed with river-forming climates. P~0.01 bar suggested by ~3.6 Ga bedforms [29] might also record atmospheric collapse. Meteorite noble gas data have been interpreted to require $P>0.5$ bar at 4 Ga, but also $P<0.4$ bar at ~4 Ga [30-31]. There is little direct geological evidence for *instantaneous* $P>0.012$ bar, as opposed to *cumulative* loss/outgassing of >0.012 bar. Gently landing the Littleton meteorite requires P >(0.012 - 0.044) bars [32]. [33] suggests P>0.12 bar ~3 Ga to gently land 1 volcanic bomb sag. The lower bound on the modern C escape-to-space flux is ~0.01 (bars CO_2)/Gyr, or even lower [34].

Years of sediment deposition recorded by sedimentary rocks: >10^8 yr (very high confidence). Sedimentary rocks require less water to form than rivers, but rhythmically-layered sedimentary rocks probably require some liquid water ([35], but see also [36]). Tying of rhythmic bedding to orbital frequencies allows sediment deposition duration to be calculated [37-38]. Counts of craters at one of the many unconformities within sedimentary sequences also yield durations >10^8 yr [6], so the total time spanned by sedimentary-rock build-up was $\gg 10^8$ yr.

Duration of surface liquid water at an "average" place on Mars: <10^7 yr (medium/high confidence). The persistence of minerals that dissolve readily in water show that post-Mid-Noachian aqueous alteration on Mars could not have been both global and long-lasting [39-42].

Maximum ocean size: >1.1×10^6 km^2 (high confidence). Geomorphological evidence indicates a sea in Eridania [43]. Explaining the Eridania sea is even more challenging than explaining the (disputed, putative) Oceanus Borealis, because Oceanus Borealis (but not an Eridania-sized sea) is somewhat self-sustaining in climate models.

Peak warmth: >270K (very high confidence), >298 K (medium confidence). The aqueous deposits of Mars required liquid water to form. Salinity is unlikely to permite much lower temperatures; for example, Mg-sulfate deposits are common, and the MgSO4-H2O eutectic is 270K. Meteorite evidence for >298K is compelling [44], but might correspond to lake-waters warmed by a solid-state greenhouse effect beneath ice cover.

Peak mean annual temperature: >250K (high confidence). Thicker atmospheres that are suspected to be required for rivers and lakes on Mars damp out diurnal temperature oscillations. The lack of evidence for icy conditions along the MSL traverse hints at ice-free lakes [45]. Groundwater circulation occurred, but might be sustained through permafrost by advection, or in steady state beneath taliks.

Duration of valley-network-forming climate episode: >10^5 yr (medium confidence). Sediment transport calculations indicate >10^5 yr are needed to form the valley networks [46]. If the Mars valley networks were cut into weakly-indurated sediment, then shorter formation durations are possible [47], but in-place Mars rock strength is similar to adobe bricks or weak concrete on Earth, *not* a loose sand-pile (high confidence) [48]. When modern estimates of systematic error for counts are folded in, published THEMIS crater counts [1] are consistent with all VNs forming in a short time. Future work might seek craters interbedded during the VNs.

Surface-formed phyllosilicates – the key to early Mars climate? With some exceptions, the above-summarized data are consistent with a fairly cold (snow/ice-melt) climate [49,50]. In contrast, the simplest interpretation of the clay profiles (e.g. Mawrth) is >$10^{(4-5)}$ yr of clement (~300K) climate [51]. One possibility is that Mawrth is a window into a climate that predates the VNs. Alternatively, pedogenic clays could be formed by cold, acidic waters [52].

Wrap-up: In the early 2000s, geomorphic data were used to argue for a wet early Mars; mineralogical data were more ambiguous. In 2018, these roles have perhaps reversed - the orbiter-geomorphic lower limits summarized above may be less constraining than the phyllosilicate evidence! MSL traverse data have been reported by the MSL sedimentology team as supporting warmer/wetter climates than are required by the orbiter-geomorphic lower limits. At the conference, I will graphically summarize available constraints, and discuss how climate models – such as the recently proposed Limit Cycle idea [53] – hold up when confronted with these constraints.

References. (Many great papers are omitted from this abstract due to space limits.) [1] Fassett & Head 2008, Icarus v.195 [2] Palucis et al., 2016, JGR [3] Irwin et al. 2004, JGR v.109(E9) [4] Grant & Wilson 2011, GRL [5] Wilson et al., 2016, JGR [6] Kite et al. 2015, Icarus [7] Kite et al. 2017, GRL [8] Luo et al. 2017, Nature Comm. [9] Irwin et al. 2013, JGR [10] Dickson et al. 2009, GRL [11] Robbins 2014, EPSL [12] Martin et al. 2017, JGR [13] Hecht 2002, Icarus [14] M. Mansfield et al., in review JGR [15] Irwin et al. 2015, Geomorphology [16] Williams & Weitz 2014, Icarus [17] Hurowitz et al. 2017, Science [18] Kite et al. 2013, Icarus [19] Dietrich et al., *in* Tsutsumi & Laronne, *Gravel Bed Rivers* 2017 [20] Turbet et al 2017, 4th Conf. on Early Mars [21] Steakley et al. 2017, 4th Conf. on Early Mars. [22] Palucis et al. 2014, JGR Geology [23] Irwin et al. Geology 2005 [24] Goudge et al. 2016, [25] Barnhart et al. 2009, JGR [26] Amundson et al. 2012, GSA Bull. [27] Bierson et al. 2016 GRL [28] Kite et al. 2014, Nature Geosci. [29] Lapôtre et al. 2016, Science [30] Cassata et al. 2012, Icarus [31] Kurokawa et al. 2018, Icarus [32] Chappelow et al. 2016, LPSC [33] Manga et al. 2012, GRL [34] Lundin et al. 2013, GRL [35] McLennan et al. 2005, EPSL [36] Niles et al. 2017, Nat. Comm. [37] Lewis et al. 2008, Science [38] Lewis & Aharonson 2014, JGR [39] Stopar et al. GCA 2006 [40] Tosca & Knoll EPSL 2009 [41] Elwood Madden et al. 2009, Geology [42] Ruff & Hamilton 2017, Am. Mineral [43] Irwin et al. 2002, Science [44] Halevy et al. 2011, PNAS [45] Grotzinger et al., Science 2015 [46] Hoke et al. 2011, EPSL [47] Rosenberg & Head 2015, P&SS [48] G.H. Peters et al. 2017, GRL [49] Wordsworth et al. 2016, AREPS [50] Head 2017, 6th Conf. on Mars Atmosphere [51] Bishop & Rampe 2016, Icarus [52] Louizeau et al 2018, Icarus. [53] Batalha et al. 2016 EPSL.