


Geologic Constraints on Early Mars Climate

Edwin S. Kite¹ 

Received: 17 June 2018 / Accepted: 29 December 2018
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Abstract Early Mars climate research has well-defined goals (MEPAG 2018). Achieving these goals requires geologists and climate modelers to coordinate. Coordination is easier if results are expressed in terms of well-defined parameters. Key parameters include the following quantitative geologic constraints. (1) Cumulative post-3.4 Ga precipitation-sourced water runoff in some places exceeded 1 km column. (2) There is no single Early Mars climate problem: the traces of ≥ 2 river-forming periods are seen. Relative to rivers that formed earlier in Mars history, rivers that formed later in Mars history are found preferentially at lower elevations, and show a stronger dependence on latitude. (3) The duration of the longest individual river-forming climate was $> (10^2 - 10^3)$ yr, based on paleolake hydrology. (4) Peak runoff production was > 0.1 mm/hr. However, (5) peak runoff production was intermittent, sustained (in a given catchment) for only $< 10\%$ of the duration of river-forming climates. (6) The cumulative number of wet years during the valley-network-forming period was $> 10^5$ yr. (7) Post-Noachian light-toned, layered sedimentary rocks took $> 10^7$ yr to accumulate. However, (8) an “average” place on Mars saw water for $< 10^7$ yr after the Noachian, suggesting that the river-forming climates were interspersed with long globally-dry intervals. (9) Geologic proxies for Early Mars atmospheric pressure indicate pressure was not less than 0.012 bar but not much more than 1 bar. A truth table of these geologic constraints versus currently published climate models shows that the late persistence of river-forming climates, combined with the long duration of individual lake-forming climates, is a challenge for most models.

Keywords Atmospheric evolution · Mars · Planetary habitability · Paleoclimate

1 Introduction

Explaining rivers and lakes on Early Mars is difficult. The chief difficulty is that Mars 3.5 Ga received just $\frac{1}{3}$ of the modern Earth’s insolation (Haberle 1998; Bahcall et al. 2001). Such

✉ E.S. Kite
kite@uchicago.edu

¹ University of Chicago, Chicago, IL 60637, USA

low insolation puts Early Mars outside the circumstellar habitable zone—at least according to basic forward models of habitable-planet climate (Kasting et al. 1993; Kopparapu et al. 2013). Those basic models combine the greenhouse effect of CO_2 and $\text{H}_2\text{O}_{(\text{v})}$. But maximum $\text{CO}_2 + \text{H}_2\text{O}_{(\text{v})}$ warming is too cold for $\text{H}_2\text{O}_{(\text{l})}$ rivers (Forget et al. 2013; Wordsworth et al. 2013; Turbet and Tran 2017). Thus, data for Early Mars—the only geologic record that can give an independent test of Earth-derived models of planetary habitability (Ehlmann et al. 2016)—shows that those models do not work (Grotzinger et al. 2014; Dietrich et al. 2017; Vasavada 2017; Haberle et al. 2017). Because basic models do not work, recent explanations for rivers and lakes on Early Mars span a wide range of trigger mechanisms, timescales, and temperatures (e.g. Wordsworth 2016; Kite et al. 2013a; Urata and Toon 2013; Ramirez et al. 2014; Halevy and Head 2014; Kerber et al. 2015; Batalha et al. 2016; Wordsworth et al. 2017; Kite et al. 2017a; Haberle et al. 2017; Palumbo and Head 2018; Tosca et al. 2018). This is an embarrassment of riches. To test these ideas, we need more constraints than just the existence of rivers.

Fortunately, recent work gives better constraints on the climates that caused river flow on early Mars. The new work constrains the number, spatial patchiness, hydrology, and timescales of past wet climates. The new geologic target is no longer “how could Mars be warm enough for lakes?” (Squyres 1989; Carr 2006) but instead “what mechanisms best explain the trends, rhythms and aberrations in Early Mars climate that are recorded by Mars’ geology?” There are also new estimates of paleo-atmospheric pressure, and steps towards paleo-temperature constraints. All these constraints are summed up in Table 1.

In this paper, I focus on quantitative summary parameters that can be used as input or test data for numerical models, both of Mars climate and also of Mars climate evolution (e.g. Armstrong et al. 2004; Wordsworth et al. 2015; von Paris et al. 2015; Manning et al. 2006; Kurahashi-Nakamura and Tajika 2006; Hu et al. 2015; Pham and Karatekin 2016; Manning et al. 2019; Mansfield et al. 2018). For each constraint, I state a subjective confidence level. Despite progress, today’s data are still not enough to pick out one best-fit model (Table 2). Perhaps the true explanation has not yet been dreamt of.

2 River-Forming Climates

Sediment transport by precipitation-sourced water runoff marks Mars history’s wettest climates. These wettest climates are the most challenging parts of Mars climate history to explain.

2.1 Precipitation-Sourced Water Runoff: >1 km Column Post-3.4 Ga (High Confidence)

A lot of the runoff on Early Mars came from rain/snowmelt (precipitation). Observations at Harris crater (Fig. 1, Fig. 2), and at many other sites on Mars, show channel heads <1 km from a ridge (Hynek and Phillips 2003; Williams et al. 2011; Malin et al. 2010). At 24.1 °S 28.2 °E, 22.7 °S 73.8 °E, and 19.9 °S 32.7 °W, channel heads are located close to a ridge-line and on both (opposite) sides of a ridge. These data are inconsistent with spring discharge, but consistent with precipitation-sourced runoff (Mangold et al. 2004, 2008; Weitz et al. 2010). The existence of rain/snowmelt is a constraint on past climate. A wetter climate, with $T > 0$ °C at least seasonally, is required to explain these observations. A rain- or snowmelt-permitting climate almost certainly requires atmospheric pressure higher than the ~6 mbar atmospheric pressure on today’s Mars, because evaporitic cooling efficiently

Table 1 Summary of key parameters for Early Mars climate research

Parameter	Confidence level*	Constraint	Method/notes
<i>River-forming periods</i>			
Post-3.4 Ga precipitation-sourced water column (rain and/or snowmelt)	High	>1 km	Sect. 2.1, Fig. 2. Eroded-sediment thickness \times minimum water/sediment ratio.
Time spanned by river-forming climates	High	$\gg 10^8$ yr	Sect. 2.2, Fig. 3. Differences in crater retention age.
Number of river-forming periods	High	≥ 2	Sect. 2.2, Fig. 3. Crosscutting relationships; crater counts.
Ocean size at maximum extent	Very high	$>1.1 \times 10^6$ km ²	Sect. 2.9. Eridania sea; geomorphology.
Last year of global climate permitting river flow	High	<3.4 Ga	Sect. 2.2. Uncommon supraglacial channels formed <1 Ga (e.g. Dickson et al. 2009).
Trends between wet periods (Sect. 2.3)	Medium/high	Sect. 2.3, Figs. 4–5	
<i>τ-R-I-N parameters</i>			
Duration of individual river-forming climates (τ)	Medium	$>(10^2\text{--}10^3)$ yr for longest climate	Sect. 2.5, Fig. 7. Lake hydrology.
	Low/medium	$>2 \times 10^4$ yr for longest climate	Sect. 2.5. mm-scale laminations, interpreted as annual varves.
Peak runoff production (R)	High	>0.1 mm/hr	Sect. 2.6. River discharge (inferred from paleo-channel dimensions), divided by catchment drainage area.
Intermittency during wet events (I)	High	Peak runoff production <10% of the time	Sect. 2.7, Fig. 8. To avoid over-topping closed basin lakes.
Cumulative wet years during valley-network-forming climate episode ($\tau \times N$)	Medium	$>10^5$ yr	Sect. 2.8. Sediment transport calculations constrained by paleochannel dimensions.
<i>Sedimentary-rock-forming climates</i>			
Duration of post-Noachian surface liquid water for “average” Mars	Medium/high	$<10^7$ yr	Sect. 3.3, Fig. 7. Persistence of easily-dissolved minerals, such as olivine.
Years of sediment deposition in sedimentary rock record	High	$>10^7$ yr	Sect. 3.1. Counts of orbitally-paced rhythmite layers.
Time span of deposition for layered, indurated, equatorial sediments	High	$\gg 10^8$ yr	Sect. 3.1. Sediment deposition need not have been continuous.
Water column required to indurate sedimentary rocks	Medium/high	>20 km	Sect. 3.2. Geochemical reaction-transport models. >1 km column-H ₂ O-equivalent H content in sedimentary rocks today.
<i>Pressure and temperature</i>			
Paleo-atmospheric pressure	Low/medium	>0.01 bar, $<(1\text{--}2)$ bar	Sect. 4.1. High uncertainty.
Peak annual-mean warm-climate temperature at river locations (T_{av})	Low	-18 °C to 40 °C	Sect. 4.2. Poorly constrained.

* Confidence levels are subjective

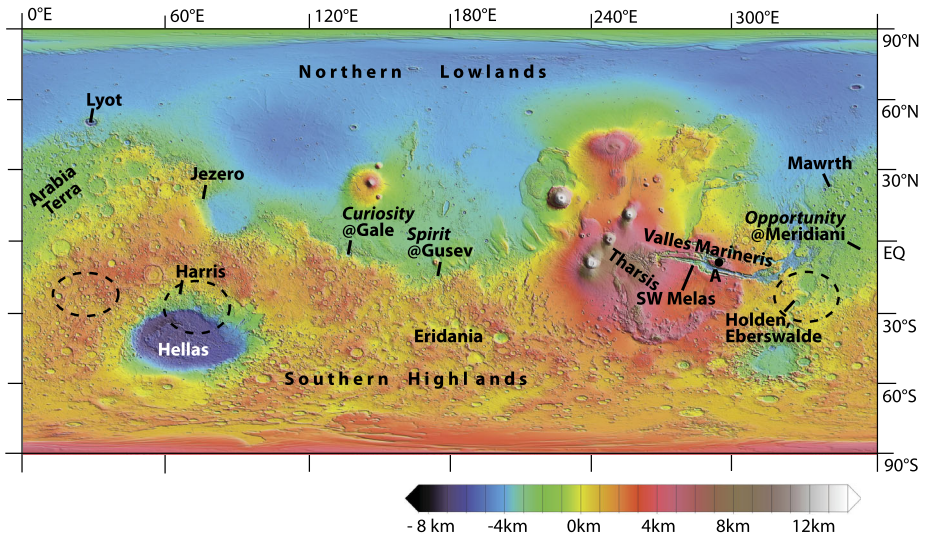


Fig. 1 Map of Mars showing places named in this paper. Dashed ellipses contain most of the large alluvial fans (Kraal et al. 2008a). A = thickest known sedimentary rock accumulation on Mars (easternmost mound within East Candor Chasma, 8 km thick, 8 °S 66 °W). Background is Mars Orbiter Laser Altimeter (MOLA; Smith et al. 2001) topography draped over shaded relief. 1° latitude \approx 59 km

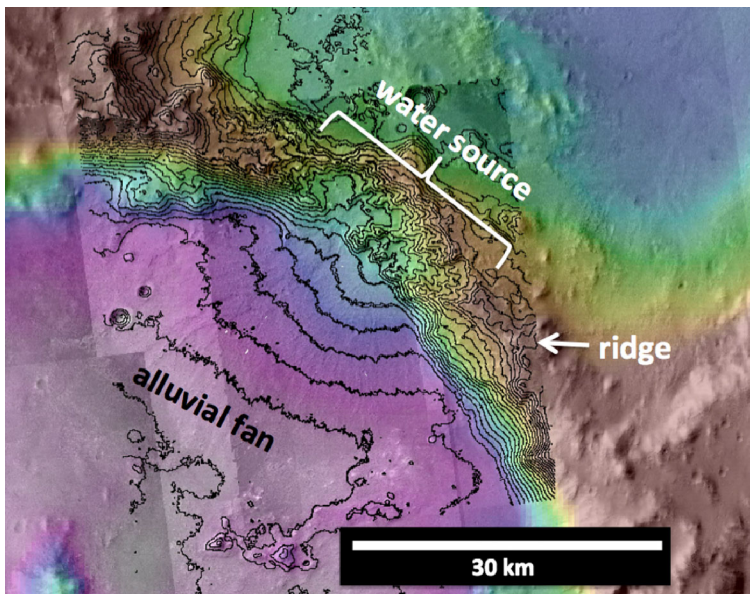


Fig. 2 NE rim of Harris crater (21.5 °S 67 °E), showing an Early Mars alluvial fan that was fed by precipitation-sourced runoff (Williams et al. 2011). 100 m contour spacing on Digital Terrain Models (DTMs) generated by David P. Mayer using the Ames Stereo Pipeline (Moratto et al. 2010) and images from Context Camera (CTX; Malin et al. 2007). Background is MOLA topography overlain on THEMIS (Thermal Emission Imaging System; Christensen et al. 2004) visible-light mosaic (Edwards et al. 2011)

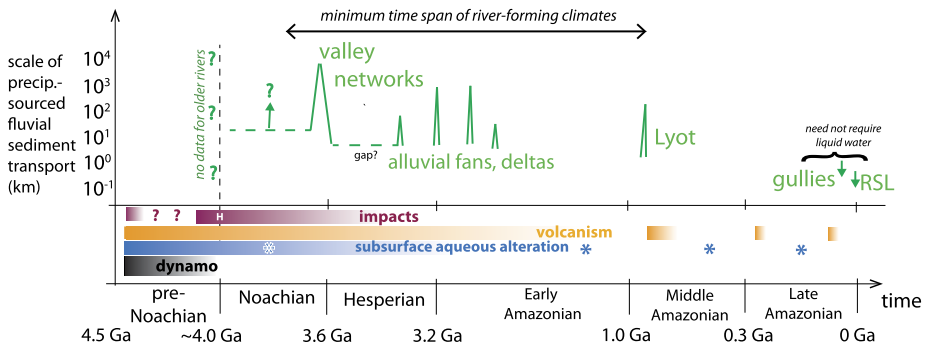


Fig. 3 History of Mars’ river-forming climates (modified after Kite et al. 2017b). Y-axis corresponds to the map-view scale of the landforms shown. Neither the durations of geologic eras, nor the durations of river-forming climates, are to scale. Data are consistent with long globally-dry intervals. Dynamo timing is from Lillis et al. (2013). H = Hellas impact event. * = subsurface aqueous alteration as recorded by Mars meteorites (Borg and Drake 2005; Nemchin et al. 2014)

suppresses runoff at 6 mbar (Hecht 2002; Mansfield et al. 2018). Therefore, this paper will focus on these precipitation-sourced runoff sites.

How much rain/snowmelt is required? Cumulative rain/snowmelt is estimated by first dividing fluvial sediment-deposit volume by the area of the sediment source region. That gives eroded-sediment thickness. Eroded-sediment thicknesses of ~1 km are widespread, with most km-thick alluvial fan deposits being <3.4 Ga in age (Grant and Wilson 2011; Morgan et al. 2014; Kite et al. 2017a). This result is multiplied by water:sediment ratio (Williams et al. 2011). Fan morphology indicates water:sediment volume ratio >1:1. The result is a conservative lower bound on post-3.4 Ga column runoff production: >1 km (Williams et al. 2011; Dietrich et al. 2017).

This paper will focus on precipitation-sourced fluvial activity. However, runoff from precipitation was not the only cause of fluvial sediment transport on Mars. Indeed, impact-initiated volatile release cut valleys and moved sediment on Mars (e.g. El-Maarry et al. 2013; Grant and Wilson 2018). Some canyons were cut by discharge from a subsurface water source (e.g. Gulick 2001; Leask et al. 2007; Burr et al. 2009). Some stubby-headed canyons have a disputed origin, with arguments in favor of formation by surface runoff (e.g. Lapôtre and Lamb 2018; Lamb et al. 2008), and arguments in favor of a subsurface water source (e.g. Kraal et al. 2008b). Discharge of water from the subsurface is much easier when surface temperature is >0 °C, because frozen ground traps water. However, this preference for >0 °C is not absolute. To the contrary, groundwater discharge may continue—thanks to salinity and heat advection—even when the surface is cold and otherwise dry (Andersen et al. 2002; Grasby et al. 2014; Scheidegger and Bense 2014; Ward and Pollard 2018; Mellon and Phillips 2001). Therefore, groundwater discharge does not, by itself, place strong constraints on climate.

2.2 There Is No Single Early Mars Climate Problem: Rivers Formed During ≥2 Distinct Periods (High Confidence)

A river-forming climate is defined in this paper as a >10 yr interval during which precipitation-sourced runoff occurred during most years. With this definition, on Early Mars there were multiple river-forming climates (Figs. 3–4).

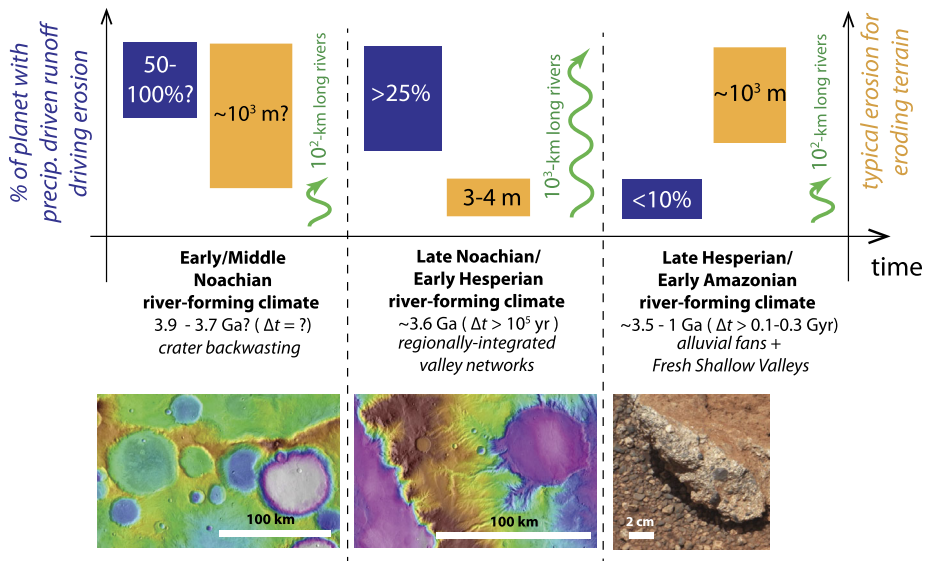


Fig. 4 Distinct river-forming periods show different spatial coverage, different river lengths, and different amounts of erosion by fluvial sediment transport. *Early/Middle Noachian image*: Crater backwasting. Centered near 43.5° E, 20.3° S. Image is 185 km across and color scale runs from +0.8 km (white) to +3.5 km (red) (same region as in Craddock and Howard 2002, their Fig. 8). *Late Noachian/Early Hesperian image*: Image is 137 km across and color scale runs from +1 km (white) to +2.5 km (red) (for discussion see Howard 2007, his Fig. 14). Centered near 60° E, 12.5° S. *Late Hesperian/Amazonian image*: Fluvial conglomerate at Gale crater, seen close-up by *Curiosity* (Williams et al. 2013)

Early/Middle Noachian (3.9 Ga–3.7 Ga?)¹ The first occurred after the Hellas impact,² but before the valley networks. In this time window, craters were modified by erosion and deposition. Craters could not have been modified in one short pulse, in part because the most degraded craters tend to be older than slightly less degraded craters (Craddock and Howard 2002; Forsberg-Taylor et al. 2004; Quantin-Nataf et al. 2019). The erosion and deposition must be at least partly due to rivers and streams, and may be mostly due to rivers and streams (Craddock and Maxwell 1993; Forsberg-Taylor et al. 2004). The simplest explanation is a global climate that permitted snowmelt or even rain (Craddock and Howard 2002). This first river-forming period (Early/Middle Noachian) is clearly distinct in the geologic record from the later period of valley network formation around the Noachian/Hesperian boundary (Irwin et al. 2005a; Howard et al. 2005; Fig. 4).

Late Noachian/Early Hesperian (~3.6 Ga) Across the Mars highlands around the Noachian/Hesperian boundary, regionally-integrated valley networks formed (Fassett and Head 2008a; Hynek et al. 2010; Fassett and Head 2011). These valley networks are

¹ Absolute date estimates in this paper are given in the [Appendix](#). That chronology is based on radiometrically-dated Lunar samples, extrapolated using crater counts to Mars. But these ages have big error bars (e.g. Robbins 2014; Robbins et al. 2018). In-situ radiometric ages for Mars samples are now being acquired using the *Curiosity* rover (Farley et al. 2014). However, so far, these ages have not been securely correlated to the crater-density age of any terrain.

² We take the start point for Mars' legible-from-orbit record of climate change to be the Hellas impact (Smith et al. 1999). Pre-Hellas climate history may be found in megabreccia, rare chunks of uplifted ancient crust, and possibly in meteorites (Humayun et al. 2013; Cannon et al. 2017).

the most obvious evidence for a warmer, wetter past on Mars (Masursky 1973). Valleys connect paleolakes over water flow paths $>10^3$ km long, which thread most of the Southern Highlands (Irwin et al. 2005a; Howard et al. 2005; Fassett and Head 2008b; Goudge et al. 2012). This regional integration of Mars watersheds, which involved $>10^5$ yr of wet climate (Sect. 2.8), was never repeated.

Late Hesperian/Amazonian (~ 3.4 Ga– ~ 1 Ga) Instead, following an interval of deep wind erosion indicating dry conditions (Zabrucky et al. 2012), the Late Hesperian and Amazonian saw runoff forming closed-basin lakes and alluvial fans (Howard et al. 2005; Kraal et al. 2008a; Grant and Wilson 2011, 2012; Morgan et al. 2014; Palucis et al. 2016; Mangold et al. 2012; Milliken et al. 2014; Goudge et al. 2016; Kite et al. 2015). Fans formed over a time span of $>(100\text{--}300)$ Myr (Kite et al. 2017b), but fan sediment deposit thickness locally reach ~ 1 km. Dividing ~ 1 km sediment thickness by time span $>(100\text{--}300)$ Myr gives average fan accumulation rate $\lesssim 10$ $\mu\text{m}/\text{yr}$. Such a slow rate suggests that (even at sites that were spatial maxima in fluvial sediment transport) there were many dry years during the time span of fan accumulation. Fans today have inverted channels on their surfaces, recording dry-climate wind erosion. Perhaps in synch with alluvial fan formation in the low latitudes, Fresh Shallow Valleys formed within latitude bands ($25\text{--}42$) $^\circ\text{N}$ and ($30\text{--}42$) $^\circ\text{S}$ (Howard and Moore 2011; Mangold 2012; Wilson et al. 2016). The Fresh Shallow Valleys formed over $\gg 10^8$ yr, but moved relatively little sediment (Wilson et al. 2016). A younger runoff episode is recorded by uncommon supraglacial or proglacial channels, best seen at Lyot crater < 1 Gya (Dickson et al. 2009; Fassett et al. 2010).

Runoff at Lyot crater—either ice-melt or snowmelt—marks the youngest definite climate-driven water runoff on Mars. Shallow < 100 $^\circ\text{C}$ groundwater at 0.1–1.7 Ga is recorded by meteorites, but it is not clear if this shallow groundwater required a wet climate (Borg and Drake 2005; Bridges et al. 2001; Swindle et al. 2000; Nemchin et al. 2014). Alluvial fans formed close to (and within) a few mid-sized impact craters $\ll 1$ Ga (e.g. Williams and Malin 2008), but this was caused either by localized precipitation or by dewatering of impact ejecta (Goddard et al. 2014), and not by global climate change. Rovers find evidence for $\ll 100$ Ma surface aqueous alteration (Sect. 3). This would require aqueous fluids to infiltrate rocks/regolith, but does not require surface runoff. It is not clear whether or not $\lesssim 5$ Ma surface features (gullies and Recurring Slope Lineae) record water flow (Leask et al. 2018; Dundas et al. 2017a, 2017b).

In summary, the number of distinct river-forming climates required by the data is ≥ 2 (e.g. Mangold et al. 2012).

The distinct periods of river-forming climate show different spatial coverage, different river lengths, and different amounts of fluvial sediment transport and corresponding erosion. These differences are summarized in Fig. 4 and discussed below.

1. The Early/Middle Noachian may be the most erosive time in Mars history—with 1 km of column-averaged sediment transport inferred (Robbins et al. 2013; Irwin et al. 2013). However, rivers were only $\sim 10^2$ km long, and lakes did not overspill. Lack of overspill implies that climate was arid; that individual wet events did not last long enough to overspill craters; or both. Earth's Holocene average erosion rate was $\sim 5 \times 10^{-5}$ m/yr (Milliman and Syvitski 1992). Therefore, if all of the inferred Early/Middle Noachian sediment transport was associated with fluvial erosion, then this is equivalent to $\sim 2 \times 10^7$ yr of fluvial sediment transport at Holocene Earth rates.

2. The Late Noachian/Early Hesperian valleys represent an intense, but relatively late and topographically superficial, erosion episode. Valleys cut $\sim 10^2$ m deep, but valleys are wide-spaced (Williams and Phillips 2001; Carr and Malin 2000; Hynek et al. 2010). As a result, dividing valley volume by the area of Noachian terrain (as mapped by Tanaka et al. 2014) yields just 3–4 m areally-averaged erosion (Irwin et al. 2005a; Ansan and Mangold 2013; Luo et al. 2017). This corresponds to only 10^5 yr of Earth-average fluvial sediment transport. This erosion was not enough for rivers to consistently form smooth convex-up profiles of elevation versus downstream distance (Aharonson et al. 2002; Som et al. 2009; Penido et al. 2013). Many but not all lakes overspilled at this time (e.g. Goudge and Fassett 2018; Fassett and Head 2008b), which was the only time in Mars history when we see a record of pervasive and regionally-integrated valley networks.
3. The Late Hesperian and Amazonian fluvial erosion is spatially more focused. During this time, low-latitude overflow of large lakes was much less probable than during the Late Noachian/Early Hesperian (Goudge et al. 2016). Overall, planet-median time-averaged erosion in the Late Hesperian and Amazonian was 3×10^{-10} – 2×10^{-8} m/yr (Golombek et al. 2006, 2014). Nevertheless, some locations (e.g. Fig. 2) saw > 1 km erosion—these focused erosion zones covered only a small fraction of the planet. Deep erosion occurred preferentially on slopes that face either N or S (Morgan et al. 2018). Lake (playa?) deposits are seen at the toes of some fans (e.g. Morgan et al. 2014).

In summary, the time spanned by all river-forming climates on Mars was $\gg 10^8$ yr (Fig. 3). But the total sediment moved by rivers corresponds to $\lesssim 10^7$ yr at Earth Holocene rates (Matsubara et al. 2018). This contrast suggests that river-forming climates were intermittent.

2.3 Relative to Rivers that Formed Earlier in Mars History, Rivers that Formed Later in Mars History Were Preferentially at Lower Elevations (High Confidence), and Show a Stronger Dependence on Latitude (Medium Confidence)

The latitude-elevation distribution of rivers and lakes suggests trends over time (Fig. 5).

- A proxy for Early/Middle Noachian crater modification, which included fluvial resurfacing, is the spatial distribution of the Middle Noachian highland and Late Noachian highland units (Fig. 5a) (Tanaka et al. 2014). Those units are found over a wide range of latitudes, and mainly at locally lower elevations (Craddock and Maxwell 1993; Irwin et al. 2013).
- The Late Noachian/Early Hesperian valleys are under-abundant at low elevation, although this may be a preservation artifact (Fig. 5b) (Sect. 5.2) (Hynek et al. 2010). After correcting for the availability of non-resurfaced terrain, the data suggest a preference for low latitude (Williams and Phillips 2001).
- In the Hesperian/Early Amazonian (Fig. 5c), the elevation preference is for low elevation. $\sim 3/4$ of large alluvial fan apices are below 0 m. $\sim \frac{4}{5}$ of light-toned layered sedimentary rock occurrences in the Malin et al. (2010) catalog are below 0 m. Even after correcting for the availability of non-resurfaced terrain, light-toned layered sedimentary rock occurrences in the Malin et al. (2010) catalog are found most frequently at low elevations (Kite et al. 2013a).
- Strong latitude preferences are obvious in the Hesperian/Early Amazonian (Fig. 5c). $> 3/4$ of large alluvial fans apices are at latitude (30–15) °S (Kraal et al. 2008a), and $\sim \frac{2}{3}$ of light-toned layered sedimentary rocks in the Malin et al. (2010) catalog are within 10° of

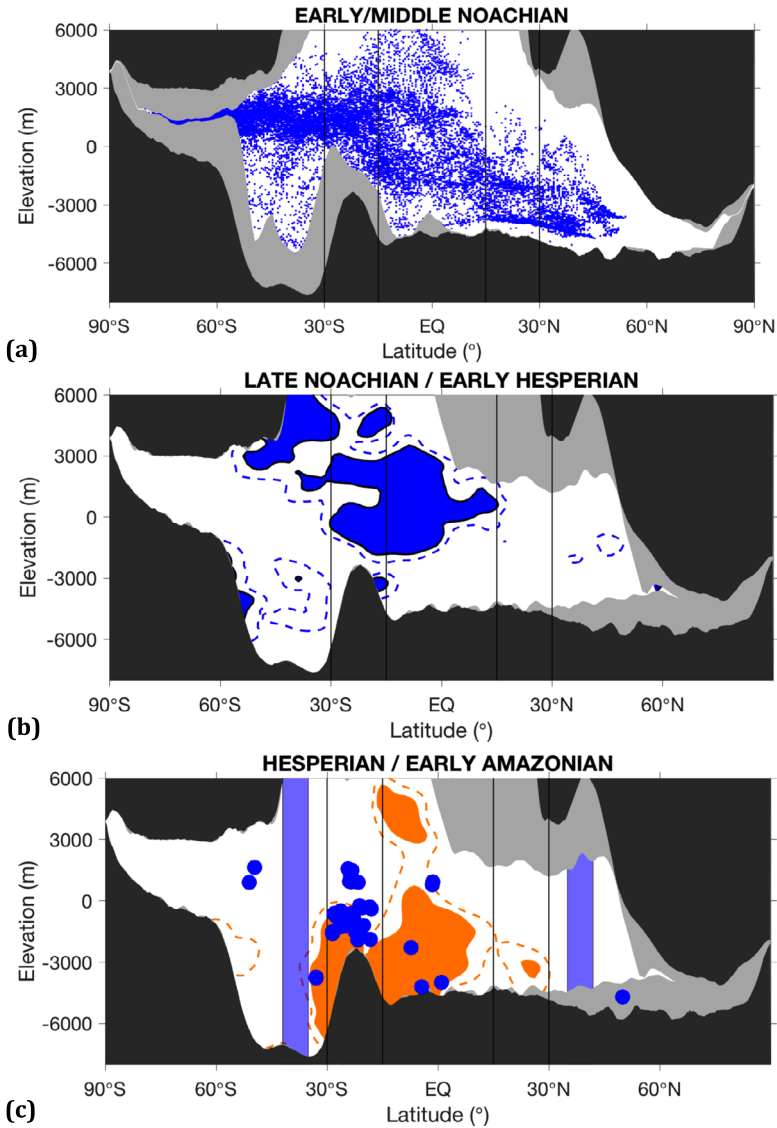


Fig. 5 Latitude-elevation plots of climate-relevant geologic activity for each period of river-forming climate. The black regions have no data, and the gray regions correspond to terrain that was geologically reset after the time slice in question. Vertical black lines highlight latitudes $\pm 15^\circ$ and $\pm 30^\circ$. Figure 12 shows more detail. (a) *Early/Middle Noachian time slice*: Blue dots correspond to Middle Noachian highland materials (Tanaka et al. 2014). These materials are the major Noachian geologic terrains to have been affected by gravity-driven resurfacing (Irwin et al. 2013). (b) *Late Noachian/Early Hesperian time slice*: Blue corresponds to the latitude/elevation zones that contain $\frac{2}{3}$ of the valleys (Hynek et al. 2010), after correcting for the nonuniform distribution of latitude/elevation (Fig. 12). Blue dashed line is the same, but for 9/10 of the valleys. (c) *Late Hesperian/Amazonian time slice*: Blue disks mark large alluvial fans (combining catalogs of Howard et al. 2005 and Kraal et al. 2008a). Pale blue stripes mark latitude range of Fresh Shallow Valleys (Wilson et al. 2016). Orange shading corresponds to the latitude/elevation zones that contain $\frac{2}{3}$ of the light-toned layered sedimentary rocks (Malin et al. 2010), after correcting for the nonuniform distribution of latitude/elevation (Fig. 12). Orange dashed line is the same, but for 9/10 of the light-toned layered sedimentary rocks

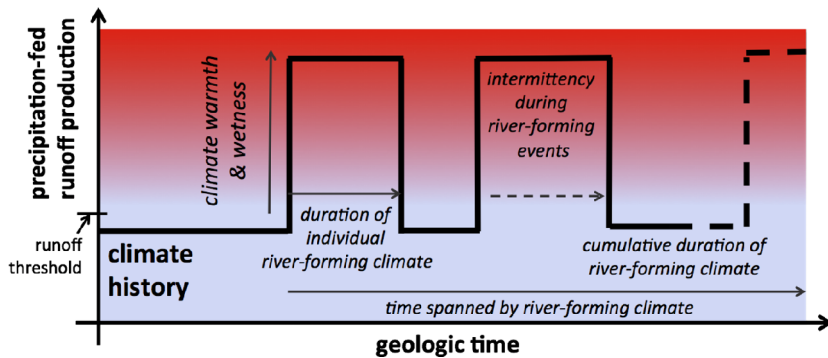


Fig. 6 Anatomy of a single river-forming period on Mars

the equator (Kite et al. 2013a). Fresh Shallow Valleys are also confined to latitude belts (Mangold 2012; Wilson et al. 2016).

To sum up, Fig. 5 suggests a shift over time with increasing control of fluvial sediment transport by latitude. These trends are consistent with theoretical expectations for atmospheric decay (Wordsworth et al. 2013; Wordsworth 2016). Theory predicts that ≥ 0.3 bar atmospheric pressure would cause surface temperature—and thus the potential for above-freezing temperatures needed for snowmelt and/or rainfall—to be strongly influenced by elevation (Wordsworth 2016). Theory predicts that as pressure dropped below ~ 0.1 bar, surface temperature would become more sensitive to direct insolation, which is a function of latitude (Kite et al. 2013a; Toon et al. 1980). Combining data and theory hints that—during the Hesperian—the atmospheric pressure fell from >0.3 bar to <0.1 bar.

2.4 τ - R - I - N framework

For each river-forming period, we can sum up the climate using four numbers (Fig. 6). These are:

τ —*Duration of wet climate* (yr). How long did the wet climate persist (without a drought that lasted centuries or longer)?

R —*Peak runoff production* (discharge/area, units mm/hr). How wet was it during the wettest day of the year? R is related to climate warmth, because warm conditions are needed for rain and storms.

I —*Intermittency* (peak runoff production \times hours in year/annual runoff; dimensionless). Relative to peak runoff, how wet was it on average during the wet years? This is closely related to the “flashiness” and seasonality of the wet climate.

N —*Number of wet events during climate episode* (e.g., number of orbital peaks). A single runoff-producing period may consist of alternations between periods with some runoff in most years, and periods with many consecutive years of zero runoff. For example, wet-dry cycles may be paced by orbital variations (Metz et al. 2009a). How often were the cycles of wet and dry repeated?

Constraints for these $\tau - R - I - N$ parameters are discussed below (Sect. 2.5–Sect. 2.8).

The time spanned by river deposits at a given site is also of interest (Fig. 6). This is constrained for one site of unknown age to $\gtrsim (1-20)$ Myr (Kite et al. 2013b).

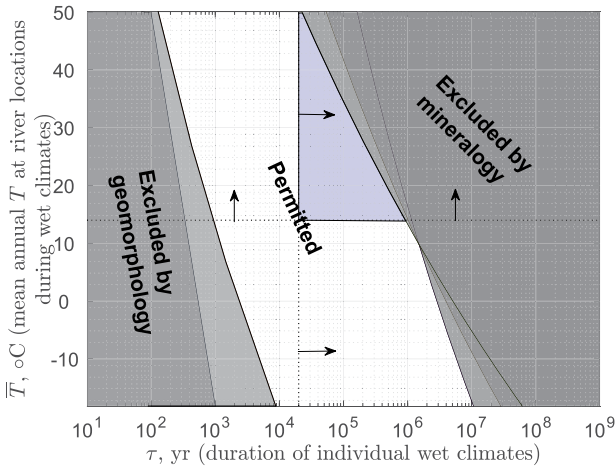


Fig. 7 Constraints on the temperature and timescale of post-Noachian river-forming climates on Mars. The blue-tinted region is not disfavored by any geologic data. The geomorphic constraint boundaries are for water:sediment volume ratio = 10^2 . These boundaries are at smaller durations at higher temperatures because of the T -dependence of evaporation (Irwin et al. 2015). The less permissive geomorphic boundary slope is drawn using the equation of Eagleman (1967) for a relative humidity of 50%. The more permissive geomorphic boundary slope is adjusted to pass through the evaporation rate 0.8 m/yr at $-18\text{ }^\circ\text{C}$ (Dugan et al. 2013) and an evaporation rate of 10 m/yr at $50\text{ }^\circ\text{C}$. The mineralogy constraint boundary is at smaller durations for higher temperatures because of the T -dependence of olivine dissolution (Olsen and Rimstidt 2007). The three different mineralogy constraint boundaries correspond to the full range (42 kJ/mol, and 79.5 kJ/mol) and average of (63 kJ/mol) of activation energies for olivine dissolution reported by Olsen and Rimstidt (2007). Lifetimes are for 1 mm grainsize and a pH of 5.5. The dotted lines correspond to lower confidence constraints. The horizontal dotted line is a lower bound on temperature from ALH 84001 carbonate Δ_{47} (Halevy et al. 2011). The vertical dotted line is a lower bound on lake lifetime from *Curiosity* stratigraphic logs (Sect. 2.5)

2.5 τ : Duration of longest individual river-forming climate: $>(10^2\text{--}10^3)\text{ yr}$ (medium confidence), $>2 \times 10^4\text{ yr}$ (low/medium confidence)

Medium Confidence—Orbiter Data At least some Hesperian closed-basin lakes lasted $>(10^2\text{--}10^3)\text{ yr}$, based on hydrologic analysis (Irwin et al. 2015; Palucis et al. 2016; Williams and Weitz 2014). The analysis starts from measurements of delta volume. (Deltas existed at Eberswalde and Holden, and evidence has been reported for deltas at many other sites—e.g. Lewis and Aharonson 2006; Grant et al. 2008; Metz et al. 2009b; di Achille and Hynek 2010; Goudge et al. 2017; Cardenas et al. 2018; Goudge et al. 2018; Adler et al. 2019). Multiplying delta volume by assumed water:sediment volume ratio $>10^2$ gives (at Eberswalde, SW Melas, and Gale) a cumulative water volume that is far in excess of the paleo-lake volume. This volume excess is inconsistent with the roughly constant lake level recorded by the un-incised delta deposits. Therefore, as the excess water was supplied, it must have been removed. The water removal processes (for closed-basin lakes, for which there is no outlet channel) are infiltration and evaporation. Both these water-removal processes are slow (Irwin et al. 2015). Therefore, water supply must also have been slow, and delta build-out rate would have been slow as well. Dividing delta volume by these slow delta build-out rates gives $>(10^2\text{--}10^3)\text{ yr}$ for the delta at Eberswalde (Irwin et al. 2015; Kite et al. 2017a) (Fig. 7). The main uncertainty is the water:sediment ratio (e.g. Kleinhans 2005; Kleinhans et al. 2010; Mangold et al. 2012). In contrast to the long life inferred for the delta at Eberswalde, formation by brief, low water:sediment ratio floods is inferred for many other

sites that have deltas which show a stepped morphology (Kraal et al. 2008b). This stepped morphology results (in laboratory experiments) from “one-shot” delivery of water and sediment, concurrent with rapid lake-level rise (e.g. de Villiers et al. 2013; Hauber et al. 2013).

During the Late Noachian/Early Hesperian valley-network-forming period, hundreds of exit-breach lakes existed (Fassett and Head 2008a, 2008b; Grant et al. 2011). In order to breach their rims, these lakes had to fill up. Filling up with precipitation-sourced water would have required $> 10^2$ yr; thousands of years in the case of the Eridania sea (Irwin et al. 2004).

Both the lake hydrology lower limit and the lake fill-up duration lower limit are lower limits on the duration of the corresponding river-forming climates.

Low/Medium Confidence—Rover Data The Mars Science Laboratory *Curiosity* rover sampled a mudstone in Gale crater—the Murray—that has rhythmic mm-scale laminations (Grotzinger et al. 2015; Hurowitz et al. 2017). If these laminae are interpreted as annual lake varves, then the 25 m–30 m thickness of stratigraphic sections with mm-thick laminae, and without textural evidence for drying-up (Fedó et al. 2017; Stein et al. 2018), suggests lake lifetime $> 2 \times 10^4$ yr. However, textural evidence for drying-up is observed in the best-studied part of the Murray (Kah et al. 2018), and periodic drying-up might have occurred without leaving textural evidence (Bristow et al. 2018).

The medium confidence $> (10^2\text{--}10^3)$ yr limit is inconsistent with wet climates caused by the direct conversion of impact kinetic energy into water vapor. Post-impact rainout would last < 3 yr (Steakley et al. 2017; Turbet et al. 2017a). The $> (10^2\text{--}10^3)$ yr limit is also inconsistent with wet climates maintained by single, isolated super-volcanic eruptions. Such eruptions would last < 30 yr (Halevy and Head 2014; Kerber et al. 2015).

2.6 R: Peak Runoff Production > 0.1 mm/hr (High Confidence)

Runoff production for river channels draining catchments of known area may be estimated using channel slope, width, and depth. Channel width and slope can be measured from digital terrain models and anaglyphs, exploiting Mars’ tectonic quiescence³ and preservation of channel properties in river deposits (e.g. Hajek and Wolinsky 2012). Channel depth can be estimated for self-formed channels using rover measurements of the grain-size of river-bed material. That is because the channel depth adjusts to move river-bed material downstream: the coarser the river-bed material, the deeper the channel. Unfortunately the four data needed to back out runoff production from first principles—drainage area, plus channel width, slope, and depth—are almost never simultaneously available for Mars rivers. There are two possible work-arounds: (1) Use empirical correlations from Earth rivers, corrected for Mars gravity (Parker et al. 2007; Eaton 2013; Li et al. 2015; Pfeiffer et al. 2017). (2) Guess a grain size based on Earth analogy, or observations made at or beyond the pixel scale of orbiter images (e.g. Morgan et al. 2014). For any individual measurement, both method (1) and method (2) have order-of-magnitude uncertainty (Jacobsen and Burr 2016; Dietrich et al. 2017). Nevertheless, both approaches consistently indicate runoff production > 0.1 mm/hr on Early Mars (Palucis et al. 2014; Fassett and Head 2005; Irwin et al. 2005b; Jaumann et al. 2005; Baratti et al. 2015;

³Although tilting by planetary tectonics has little effect on Mars river slopes, within some sedimentary basins differential compaction and subsidence has tilted layers substantially (e.g. Lefort et al. 2012; Gabasova and Kite 2018).

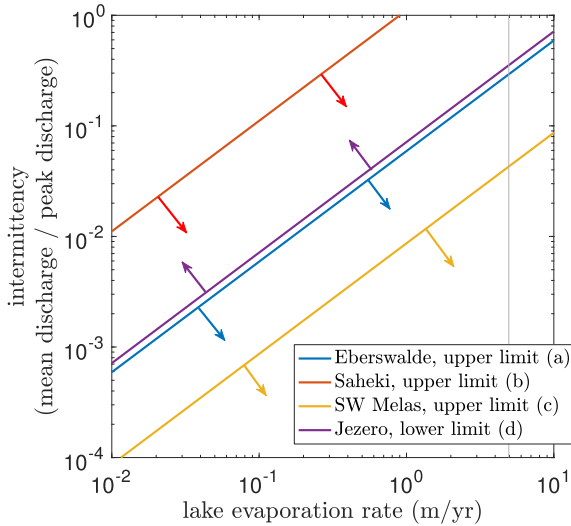


Fig. 8 Intermittency constraints for Early Mars river-forming climates. Example sites: (a) Constant lake level at Eberswalde crater. $Q_{water} = 400 \text{ m}^3 \text{ s}^{-1}$, $A_{lake} = 710 \text{ km}^2$ (Irwin et al. 2015). (b) Non-formation of a deep lake at Saheki crater. $Q_{water} = 30 \text{ m}^3 \text{ s}^{-1}$ (Morgan et al. 2014), $A_{playa} < 10^3 \text{ km}^2$. (c) Constant lake level at SW Melas Chasma. $Q_{water} = 250 \text{ m}^3 \text{ s}^{-1}$, $A_{lake} = 65 \text{ km}^2$ (Williams and Weitz 2014). (d) Overspill of the lake at Jezero crater. $Q_{water} = 700 \text{ m}^3 \text{ s}^{-1}$ (Fassett and Head 2005), $A_{lake} = 1500 \text{ km}^2$. The gray vertical line at $\sim 6 \text{ m/yr}$ marks an energetic upper limit (400 W/m^2) for Early Mars climate-driven evaporation rate. For sites (a)–(c), the main assumption is that the climate event lasted long enough to fill up the lake at continuous flow (e.g., > 7 years for Eberswalde; Irwin et al. 2015). The non-agreement between the Jezero constraint and the SW Melas constraint implies that river-forming climates varied in time, space, or both (Goudge et al. 2016)

Dietrich et al. 2017), with $> 1 \text{ mm/hr}$ suggested at many locations (Kite et al. 2019). This is a conservative lower limit on peak melt/rain rates, for two reasons. (1) Storm runoff peaks are damped as they flow downstream (Dingman 2014). (2) Climate models must produce rain/melt rates in excess not just of runoff production, but rather of (runoff + infiltration + refreezing-within-snowpack + evaporation) (Clow 1987).

Precipitation-fed runoff production is a probe of past Mars temperature. When the air is warm, snow melts faster; when the air is warmer still, rain and storms may occur.

2.7 I: Intermittency During Wet Events: Peak Runoff Production <10% of the Time (High Confidence)

Even during the wettest period in Mars history, not all lakes overflowed. To avoid all lakes overflowing, given $R > 0.1 \text{ mm/hr}$ and $\tau > (10^2\text{--}10^3) \text{ yr}$, runoff production during the wet events must have been intermittent (Fig. 8) (e.g. Barnhart et al. 2009; Matsubara et al. 2011). Here, intermittency is defined as the dimensionless ratio of peak runoff production to annual-mean runoff production. As on Earth, intermittency might correspond to seasonality, or to infrequent storms (Hoke et al. 2011). Intermittency on longer timescales is suggested by extremely slow alluvial fan build-up rate averaged over the Late Hesperian/Amazonian wet event (Kite 2017). This suggests that wet years were intercalated with years too dry for river runoff (Buhler et al. 2014). Years too dry for river runoff need not be too dry for life; life

persists in climates too dry for rivers (Amundson et al. 2012). Moreover, it is possible that alluvial fan activity was not globally synchronous. Therefore, the at-a-site runoff-production intermittency is a lower bound on the fraction of years that saw runoff production somewhere on Mars. The main uncertainty in estimating intermittency is lake evaporation rate (Fig. 8). Taking into account an energetic upper limit on lake evaporation rate, $I < 10\%$ for the rivers that delivered sediment to closed-basin sites (such as SW Melas) during the Late Hesperian/Amazonian.

2.8 $N \times \tau =$ Cumulative Wet Years During Valley-Network-Forming Climate Episode: $> 10^5$ yr (Medium Confidence)

Around the Noachian/Hesperian boundary, $\sim 2 \times 10^5$ km³ sediment moved downstream to form Mars' valley networks (Luo et al. 2017). Dividing the volume of sediment by the sediment flux gives a timescale $> 10^4$ yr to form the valley networks (Hoke et al. 2011; Orofino et al. 2018; Rosenberg et al. 2019). This increases to $> 10^5$ yr if intermittency is considered. The sediment flux is estimated using the relation between sediment flux and water discharge (e.g. Marcelo Garcia 2008; Parker et al. 2007). In turn, water discharge is estimated using channel width and depth. These sediment flux calculations assume that the Mars rivers that cut the valley networks were gravel bedded and/or were incised into bedrock. This is probably a safe assumption. Where measured, in-place Mars clastic rock strength is similar to adobe bricks or weak concrete, not to loose sand (Thomson et al. 2013; Peters et al. 2018). Although shorter valley formation durations are possible if the Mars valley networks were cut into loose, fine-grained sediment (Rosenberg and Head 2015), that set-up does not match in-place measurements of Mars rock strength.

Published THEMIS crater counts do not exclude the hypothesis that all of the regionally-integrated valley networks on the Southern highlands were incised in one brief interval (Fassett and Head 2008a, 2008b; Warner et al. 2015; but see also Hoke and Hynes 2009). This one-pulse hypothesis for valley-network formation might be tested in future by seeking interbedded craters that (based on crosscutting relationships) must have formed during the era of valley-network formation (Hartmann 1974).

2.9 Maximum Lake Size: $> 1.1 \times 10^6$ km² (Very High Confidence)

Very High Confidence. A spillway drained a $> 1.1 \times 10^6$ km² sea in Eridania during the Late Noachian (Irwin et al. 2002, 2004). This Eridania sea would have required at least thousands of years to fill to the > 1 km depths needed to over-top the spillway. Seas with volume $> 10^5$ km³ existed within Valles Marineris (very high confidence) (Warner et al. 2013; Harrison and Chapman 2008). It is not certain that the Valles Marineris seas were precipitation-fed.

Low Confidence. Bigger paleo-seas have been proposed. For example, the Northern Ocean hypothesis is that a $> 1.2 \times 10^7$ km² sea existed in the northern lowlands of Mars (Parker et al. 1993; Clifford and Parker 2001; di Achille and Hynes 2010; Ivanov et al. 2017; Citron et al. 2018). Indeed, if Mars formed with surface H₂O, that water must have pooled in the northern lowlands, at least in the immediate aftermath of Hellas-sized impacts (Early Noachian). However, the Parker et al. (1993) hypothesis posits an ocean in the Late Noachian, or even later. In favor of this hypothesis, it is plausible that Late Noachian—Early Amazonian lakes and rivers in the highlands of Mars should have a counterpart in the lowlands. Moreover, a candidate shoreline exists close to an equipotential (Ivanov et al. 2017). In opposition, high-resolution images of the candidate shoreline are

ambiguous (Malin and Edgett 1999; Carr and Head 2003; Ghatan and Zimbelman 2006; Salvatore and Christensen 2014). Hesperian deposits claimed to record a past ocean tsunami (Rodriguez et al. 2016) might instead be wet ejecta (Grant and Wilson 2018) from the impact that formed Lyot crater. Hundreds of delta candidates exist on Mars (di Achille and Hynek 2010), but few deltas have been definitively identified from orbit. Definitive delta identification requires good outcrop exposure, and analysis of highest-resolution Digital Terrain Models. Of the deltas on Mars for which the strongest evidence exists (e.g. Malin and Edgett 2003; Grant et al. 2008; DiBiase et al. 2013; Goudge et al. 2017; Hughes et al. 2019), none drain into basins that are topographically open to the northern lowlands based on modern topography. Overall, the Parker et al. (1993) hypothesis is not proven.

A Northern Ocean (but not an Eridania-sized sea) would kick-start planet-scale albedo feedbacks and water-vapor feedbacks that might help to warm Mars (Mischna et al. 2013, but see also Turbet et al. 2017b).

3 Climates that Allowed Sedimentary Rocks, Shallow Diagenesis, and Soil Weathering

Ancient sedimentary materials are indurated and strong—“sedimentary rocks” (Malin and Edgett 2000). Rock-making probably involves cementation by aqueous minerals (Gendrin et al. 2005; Murchie et al. 2009; McLennan et al. 2019; Grotzinger and Milliken 2012). Cementation requires transport of ions by some aqueous fluid (McLennan and Grotzinger 2008; Hurowitz and Fischer 2014, but see also Niles et al. 2017). However, the corresponding aqueous fluid supply rate requirement is much lower than for the river-forming climates (e.g. Arvidson et al. 2010). In particular, the aqueous fluids can be supplied by either quickly by rain/snowmelt, or slowly by groundwater (Andrews-Hanna et al. 2010). Because groundwater upwelling can occur in a cold climate, it is not as challenging to explain sedimentary rock formation as it is to explain the river-forming climates. Indeed, acidic or saline fluids can persist at temperatures well below 0 °C (Fairén et al. 2009; Ward and Pollard 2018)—one Antarctic pond stays unfrozen to −50 °C (Toner et al. 2017), and the H₂O–H₂SO₄ eutectic is at −74 °C (Niles et al. 2017; Niles and Michalski 2009). With these caveats, the low-rate aqueous fluid supply might constrain climate models, if its duration were known.

The first sedimentary-rock basins to be catalogued from orbit were light-toned, layered sedimentary rocks (Malin and Edgett 2000). Although these materials mostly postdate the valley networks, the depositional record of later river-forming climates is intercalated within the sedimentary rock record (Kite et al. 2015; Grotzinger et al. 2005; Milliken et al. 2014; Williams et al. 2018). The light-toned, layered sedimentary rocks that have been catalogued from orbit cover <3% of planet surface area (Tanaka et al. 2014). However, this is only a subset of the true distribution of sedimentary rocks on Mars, which is broader in latitude and age (Malin 1976; Edgett and Malin 2002; Grotzinger and Milliken 2012; McLennan et al. 2019). For example, the northwest part of Gale crater’s moat appears bland from orbit, but is a smorgasbord of sedimentary rocks and aqueous weathering at rover scale (Stack et al. 2016; Buz et al. 2017; Grotzinger et al. 2014).

3.1 Years of Sediment Deposition Recorded by Sedimentary Rocks: >10⁷ yr (High Confidence)

Many of the sedimentary rocks show rhythmic bedding (Lewis et al. 2008; Lewis and Aharonson 2014). Rhythmic bedding can be tied to orbitally-paced variations in inso-

lation (at the equator: 2.5×10^4 yr– 1.2×10^5 yr period), allowing the calculation of sediment build-up rate. Sediment build-up rate so determined is 10^{-5} – 10^{-4} m/yr. This build-up rate, combined with the total thickness of rhythmite-containing rock, gives build-up duration (Lewis et al. 2008; Lewis and Aharonson 2014). The resulting duration is $>10^7$ yr. During this $>10^7$ yr period, liquid water does not have to be available every year. To the contrary, the sedimentary rock record could be a “wet-pass filter” of Mars history, only recording those times that produced liquid water (Kite et al. 2013a). If the “wet-pass filter” idea is correct, then long dry periods would correspond to hiatuses or wind-erosion surfaces (unconformities) (Banham et al. 2018; Day et al. 2016; Steele et al. 2018). Indeed, one of the erosion surfaces within one sedimentary sequence has a crater count corresponding to erosion/nondeposition duration $>10^8$ yr (Kite et al. 2015).

The total time spanned by sedimentary-rock build-up was $\gg 10^8$ yr, based on crater counts and crosscutting relationships (Middle Noachian to Amazonian; Kerber and Head 2010; Hynes and Di Achille 2017; Zimbelman and Scheidt 2012).

3.2 Water Column Required to Lithify Sedimentary Rocks: >20 km (Medium/High Confidence)

The thickest known sedimentary rock accumulation on Mars (the easternmost mound within East Candor Chasma; $8^\circ\text{S } 66^\circ\text{W}$) is >8 km thick. It is reasonable to assume that this rock column has approximately the same composition as that of the light-toned sedimentary rocks investigated by Mars Exploration Rover *Opportunity* at Meridiani (5.5 wt% H_2O ; Glotch et al. 2006; Bibring et al. 2007). With this assumption, ~ 1 km column H_2O is bound within the rock as H_2O or as OH (Wang et al. 2016). This mineral-bound water is less than the amount of water involved in cementing these rocks. The needed water is estimated using geochemical reaction models. These models yield estimated water:rock mass ratios of $\gtrsim 1$. The water:rock mass ratio in geochemistry refers to the time-integrated amount of water that participates in reactions with the rock (Reed 1997). This geochemical ratio is distinct from the water:sediment ratio in geomorphology. For example, suppose a flood moves olivine pebbles downstream, and the flood water then quickly evaporates. In this case, the geomorphologist’s water:sediment ratio is high. However, the geochemist’s water:rock ratio need not be high, because—in this case—the olivine does not have enough time to dissolve. As another example, suppose rain water trickles down through a soil profile for Myr. Then, the instantaneous volume ratio of water to sediment is no more than ~ 0.4 (limited by soil porosity). But the time-integrated water:rock mass ratio in this set-up can be $>10^4$.

Water:rock mass ratio $\gtrsim 1$ yields water column >20 km. This water could be supplied either by precipitation (Kite et al. 2013a; Melwani Daswani and Kite 2017) or by deep-sourced groundwater (Andrews-Hanna et al. 2010).⁴ Groundwater, either deep-sourced or locally derived, cemented the sedimentary rocks at shallow depths (McLennan et al. 2005; Siebach et al. 2014; Schieber et al. 2017; Martin et al. 2017), and groundwater transport through fractures occurred after the sedimentary rocks were buried deep enough to be lithified (e.g. Okubo and McEwen 2007; Vaniman et al. 2018). Groundwater circulation could not have been both globally pervasive and long-lasting however, because salts (and other easily-reset minerals in the rocks) have remained in place since the Early Hesperian.

⁴Much more water is indicated by the acid-titration calculations of Hurowitz et al. (2010). Applied to the $8^\circ\text{S } 66^\circ\text{W}$ site, they give water columns of 2000 km (for pH = 2) or 200000 km (for pH = 4).

3.3 Duration of Post-Noachian Surface Liquid Water at an “Average” Place on Mars: $<10^7$ yr (Medium/High Confidence)

Olivine in liquid water dissolves quickly ($<10^7$ yr, usually $\ll 10^7$ yr). Despite this fragility, olivine is widespread in Mars rocks and soil (Hamilton and Christensen 2005; Koepfen and Hamilton 2008; McGlynn et al. 2012; Ody et al. 2013). Olivine’s persistence—alongside other minerals which dissolve or transform readily in water, such as halite, jarosite, and amorphous phases including hydrated amorphous silica—shows that post-Noachian aqueous alteration on Mars could not have been both global and long-lasting (e.g. Osterloo et al. 2010; Stopar et al. 2006; Tosca and Knoll 2009; Elwood Madden et al. 2009; Ruff and Hamilton 2017; Tosca et al. 2008; Olsen and Rimstidt 2007; McLennan et al. 2019). To the contrary, either liquid water was available briefly, or patchily, or both. Although physical erosion can “reset” the mineral-dissolution stopwatch (e.g., Hausrath et al. 2008), this does not explain the persistence of post-Noachian olivine at places that show little evidence for physical erosion. At the *Opportunity* landing site, Fe is mobile but Al is not mobile, suggesting water-limited and time-limited element mobility at water-to-rock mass ratio <300 (Hurowitz and McLennan 2007) and with water available for <20 years per sediment parcel (Berger et al. 2009). These quantitative upper limits are consistent with qualitative inferences about aqueous alteration. In particular, much of the climate-driven surface aqueous alteration uncovered by rovers is cation-conservative (e.g. Ehlmann et al. 2011a; Thompson et al. 2016), although there are open-system exceptions (e.g. Michalski et al. 2015). Cation-conservative alteration is in contrast to Earth and suggests cold conditions with limited liquid water (Milliken and Bish 2010; Ehlmann et al. 2011a). Low water:rock ratio is also inferred at regional scale. At ≥ 300 km scale, soluble K has not separated from insoluble Th (Taylor et al. 2006). Moreover, aqueous alteration younger than 3.5 Ga is minor on Mars (e.g. Yen et al. 2005; Salvatore et al. 2014). For example, surface wetting $\lesssim 10^8$ yr is limited to surface salt precipitation and near-surface vertical transport of salts (Knoll et al. 2008; Wang et al. 2006; Arvidson et al. 2010; Squyres et al. 2009; Amundson 2018). A largely dry history is also recorded by the soil and dust (Goetz et al. 2005; Yen et al. 2005; Pike et al. 2011; Cousin et al. 2015; McCubbin et al. 2016).

In summary, climate-driven surface aqueous alteration on Mars had shut down in most places by ~ 3.4 Ga (Ehlmann et al. 2011a; Ehlmann and Edwards 2014). During the post-3.4 Ga river-forming climate (>1 km column runoff production) that produced the alluvial fans, much of the planet’s surface apparently evaded aqueous alteration. This contrast between the evidence for alluvial fans, lakes and rivers (Sect. 2 of this paper), and mineralogical/chemical evidence for low water-rock ratios (Sect. 3 of this paper), has been described as “[a] fundamental paradox” (McLennan 2012). To resolve this paradox will require climate modelers to consider one or more of low temperatures, intermittency, patchiness, strong positive feedbacks, or bistability (Head 2017; Ehlmann et al. 2016; Ehlmann and Edwards 2014; McLennan 2012).

3.4 Example Rover Observations of Ancient Sediments

Surface conditions inferred from rover data for Early Mars are consistent with slow water-limited alteration interspersed with $<10^6$ -yr-long pulses of abundant water.

For example, *Opportunity* at Meridiani Planum found rocks derived from siliciclastic sulfate-rich sediments, that had been reworked by wind and deposited and cemented in association with a shallow, fluctuating groundwater table (McLennan et al. 2005; McLennan

and Grotzinger 2008). The persistence of the easily-dissolved mineral olivine, combined with the lack of evidence for Al mobility, indicates rapid formation with only minor exposure to liquid water after deposition (Hurowitz and McLennan 2007; McLennan 2012; Berger et al. 2009; Elwood Madden et al. 2009).

Mars Exploration Rover *Spirit* was sent to Gusev, which is a crater downstream along the flow-path carved by the spill-over of the Eridania sea. *Spirit* found water-altered deposits (impact ejecta and wind-transported material) that appear to drape hills (Ming et al. 2006; Squyres et al. 2006; McCoy et al. 2008; Crumpler et al. 2011). These rocks have been interpreted to record two endmember styles of top-down weathering. The first endmember style involves water-limited weathering at rates slower than exist anywhere on today's Earth (Ruff and Hamilton 2017; Bandfield 2017). The second endmember style involves rapid alteration by brief pulses of water that deposited abundant salts (sulfates in some rocks, carbonates in others), but that did not last long enough to dissolve all of the olivine (Squyres et al. 2006; Ruff et al. 2014).

Most rocks sampled by *Curiosity* at Gale crater show >15 wt% clays (Bristow et al. 2018). At Gale, persistence of ferrihydrite shows that the rocks were not buried deeply, nor permeated by hydrothermal fluids (Dehouck et al. 2017; Borlina et al. 2015). Rocks sampled early in the mission show near-isochemical alteration (McLennan et al. 2014; Thompson et al. 2016; Siebach et al. 2017; but see also Schieber et al. 2017), and rocks sampled later in the mission show evidence consistent with open-system alteration (Mangold et al. 2019; Bristow et al. 2018; see also Bedford et al. 2019). The high abundance of amorphous phases is consistent with cold conditions, low water-rock ratio diagenesis, or both.

All three rovers found that at least some early Mars sedimentary rocks experienced acid alteration (Hurowitz and McLennan 2007; Hurowitz et al. 2006; Ming et al. 2006; Hurowitz et al. 2010; Berger et al. 2017; Rampe et al. 2017).

4 Atmospheric Pressure and Surface Temperature

4.1 Paleo-Atmospheric Pressure, P : 0.012–1 bar (Low/Medium Confidence)

There are few firm constraints on Mars paleo-atmospheric pressure (Fig. 9). Today's Mars atmosphere is 95% CO₂ (Webster et al. 2013). The modern atmosphere + (ice cap) CO₂ reservoir is 0.012 bar (Bierson et al. 2016; Phillips et al. 2011). That CO₂ reservoir was probably larger in the past: the spacecraft-era CO₂ escape-to-space flux is ≤ 0.02 bars/Gyr (Jakosky et al. 2018), but $\gtrsim 10^{-4}$ bars/Gyr (Barabash et al. 2007). Past escape rates were higher, because the drivers of escape (solar wind and solar UV) had greater flux in the past. Modelers of past escape can use spacecraft-era measurements for calibration (Lundin et al. 2013; Lillis et al. 2015; Ramstad et al. 2018). These calibrated models output that post-Hellas atmospheric escape-to-space “would have been as much as 0.8 bar CO₂ or 23 m global equivalent layer of H₂O” (Jakosky et al. 2018; Lillis et al. 2017). However, because the partitioning between CO₂ and H₂O escape is not known, the lower bound on the post-3.4 Ga CO₂ escape-to-space flux remains small: $\gtrsim 10^{-3}$ bar (Fig. 9). Moreover, escape-to-space measurements do not constrain sequestration of CO₂ in the subsurface, as carbonate or as CO₂-clathrate (Wray et al. 2016; Kurahashi-Nakamura and Tajika 2006; Longhi 2006). Finally, escape-to-space models constrain the atmosphere + (ice cap) CO₂ reservoir, but what matters for climate is atmospheric CO₂. Therefore, in order to reconstruct Mars' atmospheric-pressure history, we need both continued observations/analyses of Mars atmospheric escape (Jakosky et al. 2018; Lee et al. 2018) and also paleo-proxy data.

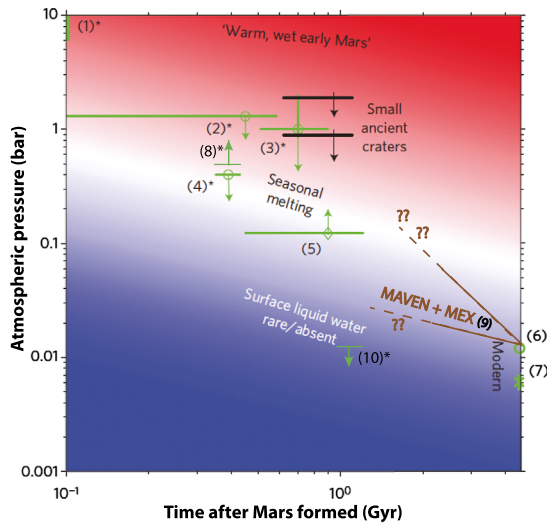


Fig. 9 Paleo-atmospheric pressure figure, updated from Kite et al. (2014). Black symbols show result of Kite et al. (2014). * = indirect estimate. (1*) estimate of initial atmospheric pCO₂ based on cosmochemistry; (2*) prehnite stability (Ehlmann et al. 2011b; Kite et al. 2014); (3*) carbonate Mg/Ca/Fe (Van Berk et al. 2012); (4*) ⁴⁰Ar/³⁶Ar (Cassata et al. 2012); (5) bomb sag (Manga et al. 2012; single data point); (6) modern atmosphere; (7) modern atmosphere + buried CO₂ ice; (8*) meteorite trapped-atmosphere isotopic ratios (Kurokawa et al. 2018); (9—range spanned by brown dashed lines) modern escape-to-space measured by Mars Atmosphere and Volatile Evolution Mission (MAVEN) and Mars Express (MEX) spacecraft, extrapolated into past (Barabash et al. 2007; Lillis et al. 2017; Jakosky et al. 2018); (10*) bedform wavelengths (Lapôtre et al. 2016). Approximate and model-dependent implications for climate are shown by background colours

After ~4.0 Ga, geologic proxy data constrain atmospheric pressure. Atmospheric pressure ~ (3.6–3.7) Ga is constrained by river deposits that cocoon small impact craters. The presence of small hypervelocity impact craters within the river deposits shows that the atmosphere was thin around the time the rivers were flowing, because thick atmospheres would slow down and/or disintegrate small impactors (Vasavada et al. 1993). These small-ancient-crater observations give $P < (1-2)$ bar according to one bolide burn-up/break-up model (Kite et al. 2014; Williams et al. 2014). However, this might correspond to periods of atmospheric collapse interspersed with river-forming climates (Soto et al. 2015). $P \sim 0.01$ bar suggested by ~3.6 Ga bedforms (Lapotre et al. 2016) might also record times of atmospheric collapse. Claims for low pCO₂ in the Hesperian based on the nondetection of carbonates in ancient sediments (Bristow et al. 2017) are not supported by experiments (Tosca et al. 2018; Gaudin et al. 2018). Given that higher-than-modern atmospheric pressure is considered essential to river-forming climates on Mars (Hecht 2002; Wordsworth 2016), there is remarkably little direct geological evidence for instantaneous $P > 0.012$ bar. An exception is the Littleton meteorite at Gale crater. This meteorite is intact, implying dissipation of most of the impactor’s kinetic energy in the atmosphere and thus $P > (0.012-0.044)$ bar (Chapelow et al. 2016). A single volcanic bomb sag observed by the Spirit rover gently deflected underlying layers (~3 Ga?), suggesting $P > 0.12$ bar (Manga et al. 2012).

Meteorite noble gas data have been interpreted to require $P > 0.5$ bar at ~4.1 Ga, but also $P < 0.4$ bar at ~4.1 Ga (Cassata et al. 2012; Kurokawa et al. 2018).

According to isotopic proxy data from Mars samples, modeling, and analogy to the Lunar record, processes that would tend to reduce Mars’ atmospheric pressure were most vigorous

before $\sim(3.9\text{--}4.0)$ Ga (Lammer et al. 2013; Niles et al. 2013). Most of Mars' initially-at-the-surface volatile content escaped to space (Catling 2009; Jakosky and Phillips 2001; Jakosky and Jones 1997; Catling and Kasting 2017; Jakosky et al. 2017; Shaheen et al. 2015). However, the most vigorous escape is thought to predate the Hellas impact (Cassata 2017; Catling and Kasting 2017; Webster et al. 2013). The wet-to-dry climate transition occurred long after the Hellas impact (Fig. 3). It is not clear how much CO_2 escape-to-space occurred after the Hellas impact. Therefore, it is also not clear whether or not CO_2 escape-to-space was the major driver of Mars' wet-to-dry climate transition.

4.2 Peak Warmth: $> -4^\circ\text{C}$ (Very High Confidence), $>14^\circ\text{C}$ (Medium Confidence). Peak Mean-Annual Warm-Climate Temperature: -18°C to 40°C (Low/Medium Confidence)

Early Mars rivers and aqueous minerals required liquid water to form. Pure liquid water implies temperatures $>0^\circ\text{C}$. Temperatures $\gtrsim -4^\circ\text{C}$ are needed even taking into account salinity; for example, the most-commonly-detected sulfates on Mars are Mg-sulfates, and the $\text{MgSO}_4\text{--H}_2\text{O}$ eutectic is -4°C . $\gtrsim(-4^\circ\text{C})$ peak temperatures are consistent with mean annual temperatures (T_{av}) of -18°C (Doran et al. 2002). At T_{av} of -18°C in the McMurdo Dry Valleys, Antarctica, lakes are permanently covered with an ice layer. Ice thickness is only <10 m (McKay et al. 1985). The thin ice cover is sustained despite low T_{av} , because freezing of melt-water supplied during a brief melt season warms the deep parts of the lakes (McKay et al. 1985). Beneath long-lived, perennially-ice-covered lakes, unfrozen ground develops and can allow deep groundwater to exchange with near-surface lake waters even in a cold climate (e.g. Mikucki et al. 2015). Subglacial water flow near the South Pole of Mars ~ 3.6 Ga requires polar surface temperatures $>(-73^\circ\text{C})$, warmer than today's polar temperature but consistent with low-latitude $T_{av} < 0^\circ\text{C}$ (Fastook et al. 2012). An upper limit on post-4.0 Ga long-term mean temperatures of $(22_{-\infty}^{+8})^\circ\text{C}$ has been obtained from Ar diffusion kinetics in ALH 84001 (Cassata et al. 2010). Remanant magnetization in ALH 84001 implies that meteorite never got hotter than 313 K (Weiss et al. 2000). These limits all permit peak mean annual temperatures (T_{av}) = 255–313 K, which is a wide range.

Within this wide range, there are few firm constraints on Early Mars paleo-temperature. Meteorite evidence indicates >298 K at ~ 3.9 Ga from ALH 84001 isotopologue data (Halevy et al. 2011). This data point could mark a warm early climate, or alternatively an impact induced heating event (Niles et al. 2009). Consistent with colder temperatures at later times, possible pseudomorphs after meridianiite ($\text{MgSO}_4 \bullet 11\text{H}_2\text{O}$) have been observed in ~ 3.6 Ga rocks by *Opportunity* (Peterson et al. 2007). Because meridianiite turns into slurry at 275K, this is evidence for annual average temperatures below 275K. *Curiosity* data shows multiple episodes of burial-diagenetic groundwater alteration at Gale (e.g. Nachon et al. 2017; Yen et al. 2017; Frydenvang et al. 2017). Burial-diagenetic groundwater alteration does not preclude near-surface permafrost, because temperatures increase with depth below the surface.

The lack of evidence for icy conditions along the *Curiosity* rover traverse hints at ice-free Hesperian lakes (Grotzinger et al. 2015). These *Curiosity* observations are not decisive however, because it is difficult to distinguish the deposits of perennially-ice-covered lakes from the deposits of ice-free lakes in the sedimentary rock record (Rivera-Hernandez et al. 2018; Head and Marchant 2014).

An important piece of evidence in favor of $T_{av} > 0^\circ\text{C}$ on Early Mars is a globally distributed Noachian-aged weathering profile revealed by orbiter data (Carter et al. 2015). This profile is typically several meters thick, and 200 m thick at Mawrth (Loizeau et al. 2012;

Carter et al. 2015; Loizeau et al. 2018). The profile includes an Al-phyllsilicate, likely formed by leaching of basaltic-composition materials. The Al-phyllsilicate overlies smectite clay. This weathering profile suggests a warm climate. The simplest interpretation of the smectite clay profiles (e.g. Mawrth) is $\sim 10^6$ yr of warm climate, with summer maxima of (30–40) °C (Bishop and Rampe 2016; Bishop et al. 2018). This stratigraphic interval (or intervals) might correspond to the warmest/wettest climate in Mars' stratigraphically-legible history (Bibring et al. 2006; Carter et al. 2015; Le Deit et al. 2012). No rover has systematically explored the Noachian weathering profiles. Mawrth could be a window into a climate that might predate the valley networks, and might have been more habitable (or habitable for longer) even than the valley-network-forming climate (Bishop et al. 2018; Bishop et al. 2013; Sect. 6.2). However, this interpretation might be wrong: acid alteration can form Al-phyllsilicates from basalt at 273K (Zolotov and Mironenko 2007; Zolotov and Mironenko 2016; Peretyazhko et al. 2018; Loizeau et al. 2018). Moreover, clays exist in the Coastal Thaw Zone of the McMurdo Dry Valleys (Kaufman et al. 2018).

To sum up, we know little about Early Mars paleotemperature. $T_{av} > 0$ °C is supported by the weathering profiles that feature Al-phyllsilicates, the isotopologue data from ALH 84001, and the ubiquitous evidence for groundwater flow. However, when the data are considered together, the alternative hypothesis of $T_{av} \leq -13$ °C is no less likely.

5 Data-Model Comparison

Table 1 sums up the geologic constraints, and Table 2 compares constraints to models.

5.1 Challenges and Opportunities for Models (Table 2)

Explaining rivers and lakes on Early Mars is difficult. Only in the past few years have models emerged that can self-consistently account for rivers and lakes on Early Mars. However, also in the last few years, new geologic constraints have been published (Table 1). No single published model can match all the geologic constraints without special circumstances (Table 2). For example,

- The lower bound on post-3.4 Ga runoff, combined with the fact that almost all large impacts on Mars predate 3.4 Ga (Irwin 2013), means that direct conversion of impact kinetic energy into latent heat of water melting/vaporization gives too little liquid water to explain the data (Steakley et al. 2017; Turbet et al. 2017a; Segura et al. 2013).
- Single, isolated super-volcanic eruptions would last < 30 yr (Halevy and Head 2014), giving warming pulses too short to match the lake-lifetime constraint.
- Many models assume ≥ 1 bar of CO_2 to provide a baseline of greenhouse warming (e.g. Wordsworth et al. 2017). It is not clear whether or not such a thick atmosphere existed by the time Gale crater sediments formed. If atmospheric pressure was $\lesssim 0.1$ bar by the time Gale crater sediments formed, then of currently proposed global models, most would not explain the Gale data. Melting snow and ice should be especially difficult for $P < 0.1$ bar (Hecht 2002). Therefore, more constraints on paleopressure would be valuable.
- Wet climates on Mars existed $\lesssim 3.4$ Ga. Post-3.4 Ga persistence is a challenge for models, because a thin atmosphere is expected and a thin atmosphere makes melting difficult (e.g. Wordsworth et al. 2017; Ramirez 2017).

Therefore, explaining rivers and lakes on Early Mars remains difficult. This difficulty, however, also creates opportunities for models. For example,

- Surface temperatures $>0\text{ }^{\circ}\text{C}$ are not enough! To be compared to the “wet-pass filtered” geologic record (Sect. 3.1), models should account for evaporitic cooling, evaporative removal of snowpack, and meltwater infiltration and refreezing (e.g. Clow 1987; Woo 2012; Dingman 2014; Williams et al. 2009).
- Mars could have had a climate with global average annual average $T_{av} > 0\text{ }^{\circ}\text{C}$. However, the persistence of easily-dissolved minerals rules out a globally $T_{av} > 0\text{ }^{\circ}\text{C}$, wet climate having occurred for more than a few percent of Mars’ post-Noachian history. The data are consistent with no such climate ever having occurred except for a couple of years after very large impacts. Indeed, the data can be matched with $T_{av} \lesssim -13\text{ }^{\circ}\text{C}$ (Fairén 2010). This relaxed target is easier to match in models. A globally warm, but very arid, climate is also not ruled out (Ramirez and Craddock 2018).
- The cumulative duration of river-forming climates could be $<10^7\text{ yr}$. Indeed a $\gg 10^8\text{-yr}$ long Earth-like climate would overpredict both weathering and erosion. This opens the door to warming mechanisms that rely on infrequent, but expected, triggers.
- Different warming mechanisms may have been active at different times. For example, H_2 outgassing was likely more potent in the Early/Mid Noachian than in the Late Hesperian/Amazonian. The $\{T_{av}-P-\tau-R-I-N\}$ target for the Noachian/ Hesperian boundary is not the same as the $\{T_{av}-P-\tau-R-I-N\}$ target for the Late Hesperian/Early Amazonian.
- The H_2O -ice cloud greenhouse model is not rejected by any geologic data (Table 2).

5.2 “False Friends”: Ambiguous Proxies

Some geologic data are valid on their own merits, but easy to over-interpret when translating between data and models of Early Mars climate. These “false friends” include:

(1) *Large gaps in the latitude-longitude distribution of valley networks in THEMIS and MOLA databases may be preservation artifacts.* Most large gaps in the latitude-longitude distribution of valley networks in THEMIS and MOLA databases (Hynek et al. 2010; Luo et al. 2017) correspond to post-fluvial resurfacing (i.e., by Amazonian lava or Amazonian ice-rich mantling deposits). The biggest exception, Arabia Terra, has numerous river deposits at scales too fine to be detected in THEMIS or MOLA (Hynek et al. 2010; Davis et al. 2016; Williams et al. 2017). Given that large gaps in the valley network distribution are mostly preservation artifacts, conclusions that rest on large gaps in the valley network distribution (e.g., Bouley et al. 2016) are questionable. However, a climate model that predicts zero precipitation in a zone where data show that precipitation-fed rivers did occur can be ruled out (as done by Wordsworth et al. 2015). Moreover, other aspects of the spatial distribution of valleys are potentially useful constraints. For example, valleys are deepest near the equator (Williams and Phillips 2001). Moreover, clumps in the distribution of large alluvial fans (Fig. 1, Kraal et al. 2008a) are not a preservation artifact. These clumps remain completely unexplained.

(2) *There is no unambiguous geologic evidence for post-Hellas True Polar Wander (TPW).* For example, ice-cap offset (Kite et al. 2009) can be explained by atmospheric dynamics instead of TPW (Scanlon et al. 2018). Deflection of candidate shorelines (Perron et al. 2007) can be explained by flexure instead of TPW (Citron et al. 2018).

(3) *Neither high drainage density, nor softened crater rims, need imply rainfall.* High drainage density ($>5\text{ km}^{-1}$ of total channel length per unit area) is sometimes observed on Mars. High drainage density has been claimed to be “a gun, although not a smoking gun” for past rainfall (Malin et al. 2010). However, high drainage density can be seen in

Table 2 Comparison of Early Mars geologic constraints to selected models. ✓ = this model can explain this observation; ? = special, but plausible circumstances may be required to produce this observation from this model; × = this model does not plausibly explain this observation.

	Confidence level (VH = very high, H = high, M = medium, L = low)	CO ₂ + H ₂ O _(v) greenhouse + orbital forcing (a)	Lower surface albedo (b)	MEGA-OUTFLO (c)	Direct impact energy to H ₂ O vapor (d)	Localized Palimpsest (e)	Volcanic eruptions/ SO ₂ (f)	H ₂ O-ice cloud greenhouse (g)	Bursty release of CH ₄ or H ₂ from subsurface (h)	Impact delivery of CH ₄ or H ₂ (i)	Steady release of H ₂ (±CH ₄) from subsurface (with limit cycling) (j)	Steady release of H ₂ (±CH ₄) from subsurface (no limit cycling) (k)
Post 3.4 Ga-precipitation-sourced water column > 1 km	H (Sect. 2.1)	×	×	?	×	×	?	✓	?	×	?	?
Time spanned by river-forming climates ≥10 ⁸ yr	H (Sect. 2.2)	×	×	✓	?	✓	✓	✓	?	?	✓	✓
Number of river-forming periods ≥2	H (Sect. 2.2)	×	×	✓	✓	✓	✓	✓	?	✓	✓	×
Ocean size at maximum extent > 1.1 × 10 ⁶ km ²	VH (Sect. 2.9)	×	×	✓	?	×	×	?	✓	✓	✓	✓
Last year of flow in the rivers of Mars < 3.4 Ga	H (Sect. 2.2)	×	×	✓	×	✓	✓	✓	?	?	×	×
Duration of longest individual river-forming climate > (10 ² –10 ³) yr	M (Sect. 2.5)	×	×	?	×	×	×	✓	✓	✓	✓	✓
Peak runoff production (R) > 0.1 mm/hr	H (Sect. 2.6)	×	×	✓	✓	✓	?	?	?	✓	✓	✓
Intermittency during wet events (J); peak runoff production < 10% of the time	H (Sect. 2.7)	?	?	?	?	×	✓	✓	✓	✓	✓	✓
Cumulative wet years during valley-network-forming climate episode (τ × N) > 10 ⁵ yr	M (Sect. 2.8)	×	×	?	×	×	?	✓	?	?	✓	✓
Duration of surface liquid water for “average” post-Noachian Mars < 10 ⁷ yr	M/H (Sect. 3.3)	✓	✓	✓	✓	✓	✓	✓	✓	✓	?	×

Table 2 (Continued)

	Confidence level (VH = very high, H = high, M = medium, L = low)	CO ₂ + H ₂ O(v) greenhouse + orbital forcing (a)	Lower surface albedo (b)	MEGA- OUTFLO (c)	Direct conversion of impact energy to H ₂ O vapor (d)	Localized Palmipst (e)	Volcanic eruptions/ SO ₂ (f)	H ₂ O-ice cloud greenhouse (g)	Bursty release of CH ₄ or H ₂ from subsurface (h)	Impact delivery of CH ₄ or H ₂ (i)	Steady release of H ₂ (±CH ₄) from subsurface (with limit cycling) (j)	Steady release of H ₂ (±CH ₄) from subsurface (no limit cycling) (k)
Years of sediment deposition in sedimentary rock record > 10 ⁷ yr	H (Sect. 3.1)	?	?	×	×	×	✓*	?	×	×	✓	✓
Time span of deposition for layered, indurated, equatorial sediments ≥ 10 ⁸ yr	H (Sect. 3.1)	?	?	✓	?	?	✓	✓	?	×	?	?
Water column required to indurate sedimentary rocks > 20 km	M/H (Sect. 3.2)	?	?	?	×	×	✓	✓	?	?	?	?
Paleo-atmospheric pressure < (1–2) bar	L/M (Sect. 4.1)	?	✓	✓	?	✓	?	✓	?	?	?	?
Peak annual-mean warm-climate temperature at river locations (T ₀₁) > -18 °C	L (Sect. 4.2)	?	?	✓	✓	?	?	?	?	?	✓	✓

Table notes: *a*: Pollack et al. (1987), Fogget et al. (2013), Kite et al. (2013a), Mansfield et al. (2018), *b*: Fairén et al. (2012), *c*: Baker et al. (1991). Assuming massive CH₄ release during outflows: H₂O alone is not sufficient—see Turbet et al. (2017b), *d*: Segura et al. (2008), Toon et al. (2010), *e*: Gulick and Baker (1989), Kite et al. (2011a, 2011b), *f*: Tian et al. (2010), Halsey and Head (2014), Kerber et al. (2015), *g*: e.g. Uraia and Toon (2013), Ramirez and Kasting (2017), Kite et al. (2018). Possibly impact-triggered. *h*: Kite et al. (2017a), Tosca et al. (2018), *i*: Haberte et al. (2018), *j*: Batalha et al. (2016), *k*: Ramirez (2017), *aa*: For post-Noachian climates. *; See Niles et al. 2017

some snowmelt landscapes (Kite et al. 2011b). Therefore, high drainage density does not constrain the phase of precipitation (rain versus snow/ice melt). Some workers assert that the softened appearance of ancient crater rims implies rainfall (Craddock and Lorenz 2017; Ramirez and Craddock 2018). This is not correct: rainsplash may soften hillslopes under some circumstances (Dunne et al. 2016), but rounded hill-crests can form due to non-rainfall processes (Melosh 2009). Therefore, the phase of precipitation (rain vs snow/ice melt) cannot be “read” from rounded hill-crests alone. Rainfall can be proven by fossilized rainsplashes—but these have not yet been observed at Mars.

(4) *Km-deep precipitation-fed canyons can form in $<10^6$ yr.* Many precipitation-fed Mars river valleys are cut $>10^2$ m deep into bedrock; some are 10^3 m deep. The only 10^3 m deep and $>10^2$ km long bedrock canyon exposed on Earth—the Grand Canyon of the Colorado—took 5–70 Myr to carve—implying a rate of 10^{-4} m/yr (Flowers and Farley 2012; Darling and Whipple 2015). However, it is incorrect to infer that Mars’ bedrock river canyons must also have taken 10^7 yr to form. To the contrary, much faster fluvial erosion of bedrock occurs both in the laboratory and in the field (Whipple et al. 2000; Dethier 2001; Anderson and Anderson 2010; Hildreth and Fierstein 2012; Gallen et al. 2015). This is especially true for basin breach flooding events (Baker and Kale 1998; Burr et al. 2009). To figure minimum Mars canyon erosion timescales, it is better to drop the Earth analogy approach, and instead use timescales for sediment-transport-limited erosion (Lamb et al. 2015). This is a better approach because sediment transport is better understood than bedrock erosion. Using the sediment-transport-limited estimation procedure, Mars valley formation timescales can be as short as 10^4 yr (Hoke et al. 2011; Rosenberg et al. 2019). Taking into account intermittency constraints (Sect. 2.7 of this paper), this rises to 10^5 yr.

(5) *More H_2O need not imply a wetter climate.* Mars climate need not be sensitive to gradually-imposed factor-of-a-few increases in the amount of H_2O substance on Mars’ surface. The modern Mars atmosphere + (ice cap) system has ~ 34 m Global Equivalent Layer of H_2O ice (Carr and Head 2015), 10^{-5} m Global Equivalent Layer of H_2O vapor (Smith 2002), and no liquid water. D/H of 3.3 ± 0.3 Ga rocks shows that H corresponding to ~ 60 m Global Equivalent Layer of H_2O has been lost to space since 3.3 ± 0.3 Ga (Mahaffy et al. 2015).⁵ The implication, consistent with glacial geologic data (Scanlon et al. 2018), is that Mars in the Hesperian had H_2O -ice sheets that were thicker. Counterintuitively, this does not imply a wetter climate. The tiny fraction of H_2O in Mars’ atmosphere is regulated by lag-deposit formation and by ice-cap albedo (Mischna and Richardson 2005). Ice sheet size is only a secondary factor. Volatile abundance does become important for climate when ice sheets spread under their own weight to cover the planet (Turbet et al. 2016), but even >700 m Global Equivalent Layer of water is not enough to put Mars into that regime (Kite and Hindmarsh 2007; Fastook and Head 2015). To sum up, tripling the amount of H_2O substance on the surface of Mars—with no other changes—would just lead to thicker ice caps, and not a liquid ocean.

For many Early Mars data, the data allow for multiple interpretations: one that is familiar from Earth experience, and alternatives that (while consistent with basic theory and with experiments) would require processes to operate differently on Mars than on Earth. These alternative, strange explanations can turn out to be true. For example, High Resolution Imaging Science Experiment (HiRISE; McEwen et al. 2007) monitoring of active gully-shaping processes shows that the currently active agent is CO_2 (Diniiega et al. 2013;

⁵This suggests that most of the 3-Gyr-integrated O loss inferred from MAVEN (Lillis et al. 2017) was “paired” with H, and therefore that CO_2 escape from Mars over the last 3.5 Gyr was $\ll 0.8$ bar.

Dundas et al. 2017a). CO₂-driven gully modification would not have been anticipated from Earth analogy. Gully-shaping processes on modern Mars are a case where Earth analogy led to premature conclusions. This is one reason why the method of Earth analogy is a questionable method for testing the hypothesis that an Earth-like climate existed on Early Mars.

5.3 Key Parameters for Early Mars Climate: Unifying Frameworks in Time and Space

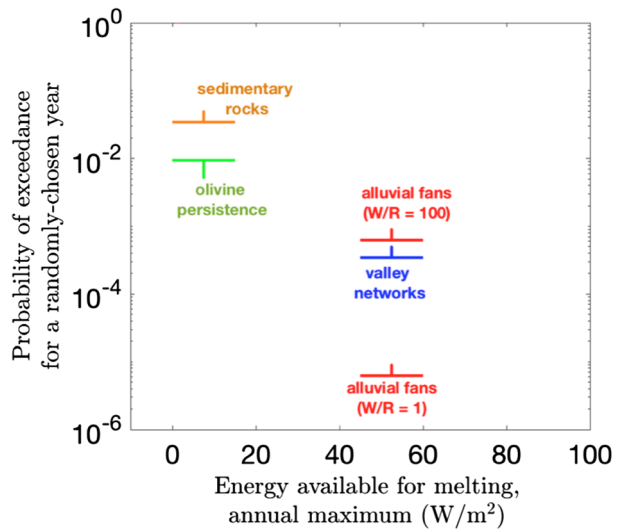
Unifying Frameworks in Space. For a given time slice, climate-driven geologic activity for Early Mars can be plotted using latitude/elevation coordinates (Figs. 5, 12). In Fig. 5, we plot precipitation-fed rivers and alluvial fans. We also plot light-toned layered sedimentary rocks, which are generally believed to record warmer and/or wetter past climates (Malin and Edgett 2000; Grotzinger et al. 2005; Kite et al. 2013a; Andrews-Hanna and Lewis 2011; but see Niles et al. 2017). The data indicate latitude-elevation preferences, and suggest trends over time (Sect. 2.3). These observations can be related to past climate, as follows. Latitude and elevation are key parameters for models of Early Mars climate-driven geologic activity. Snow or ice will melt if they get warmed above 0 °C. Warming can be supplied by (1) insolation and (2) by turbulent exchange with the air. Insolation (for a prescribed slope and aspect) is mainly controlled by latitude. Insolation is the main warming agent on Mars today, because the air is so thin. But for atmospheric pressure $\gtrsim 0.3$ bar, turbulent exchange with the air is the main control on surface temperature (Wordsworth 2016). That is because the turbulent fluxes with that exchange heat between the surface and adjacent air are proportional to air density. Air temperature decreases with elevation, so at high pressure, turbulent fluxes ensure that surface temperature also decreases with elevation. Moreover, at high pressure, greenhouse warming becomes relatively more important (for all elevations), and greenhouse warming is strongest at low elevation. Thus, at high pressure, elevation and latitude are both important for determining surface temperature. This is consistent with data for the Noachian (e.g. Fig. 5b).

Unifying Frameworks in Time. Climate-driven geologic activity for Early Mars can be plotted as a wetness probability distribution function. Suppose we are transported back in time to a random year in Early Mars history. How wet would we expect it to be during that year? How often would the energy available for melting of snow and ice exceed (0–15) W/m²—allowing soil-wetting and olivine dissolution? How often would the energy available for melting of snow and ice be high enough for surface runoff and fluvial sediment transport? (We arbitrarily pick 50 W/m² energy available for melting as the threshold for runoff; see Clow 1987 for more detailed calculations). We plot our expectations, based on the constraints from Table 1, on a “wetness probability distribution function” (Fig. 10).

From the wetness pdf, we deduce the following:

- (1) No data rule out the hypothesis that Early Mars was globally dry for >90% of years.
- (2) The apparent discrepancy between olivine persistence and the time needed for sedimentary-rock build-up (Fig. 10) can be understood as follows. To pile up a sedimentary rock mound, less-weathered minerals are blown in by the wind. This import of less-weathered materials resets the olivine-dissolution stopwatch. Any one sediment layer within the mound “sees water” for $\ll 10^7$ yr. Therefore, each sediment layer can retain olivine. Despite this, the sedimentary rock column as a whole records the availability of water $> 10^7$ yr.

Fig. 10 The wetness probability distribution function (wetness pdf) for Early Mars. The x axis corresponds to energy available for snow/ice melt (i.e., net surface energy balance for a snow/ice surface at 273.15 K). 0.5 m/yr runoff in each year with some runoff is assumed for the build-up of the alluvial fans



- (3) Combining the post-Noachian olivine persistence constraint with the post-Noachian alluvial fan formation constraint indicates that it was not wet very often, but when it was wet, it was often very wet. Surprisingly, this inference from data can be matched by a basic surface energy-balance model of long-term climate evolution that includes only CO_2 , solar luminosity, and chaotic obliquity forcing (Mansfield et al. 2018).

6 Summary

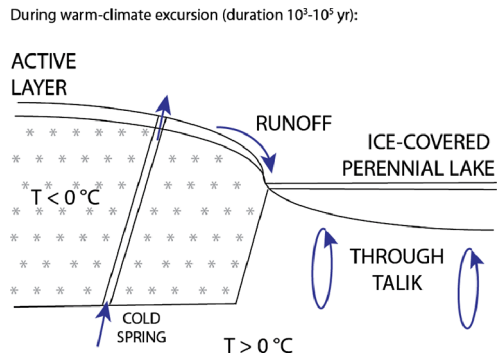
6.1 A Speculative Hypothesis for Early Mars Climate

The data reviewed above are mostly consistent with the following speculative hypothesis for Early Mars climate. This hypothesis follows the ideas of McKay et al. (2005), and is similar to the Late Noachian Icy Highlands hypothesis (Head et al. 2017). This hypothesis is not a consensus statement, it is controversial, and it is intended to spur further work.

“During the middle Noachian through early Amazonian, Mars experienced individually prolonged, but increasingly infrequent excursions to temperatures as warm as places near McMurdo, Antarctica today—perhaps as warm as Central Siberia. During these excursions, perennial lakes, filled by seasonal meltwater runoff, existed beneath thin (<10 m) ice cover. Taliks beneath these lakes, as well as conduits through permafrost that were maintained either by high solute concentration or by advection, permitted surface-interior hydrologic circulation (Scheidegger and Bense 2014). Warmer-than-Central-Siberia temperatures occurred only in the immediate aftermath ($<10^2$ yr) of basin-forming impacts—these impact-generated transients were too brief to permit interior-to-surface groundwater flow.”

The above hypothesis (Fig. 11) matches much, but not all of the data (e.g. Bishop et al. 2018). This hypothesis is acceptable to many palates: many climate models can achieve McMurdo Dry Valleys-like conditions (e.g. Wordsworth et al. 2017; Kite 2017). The above hypothesis can also reproduce the best-understood geologic data. Because of the

Fig. 11 A speculative hypothesis for Early Mars climate (see, e.g. McKay et al. 2005; Head et al. 2017)



key role of sub-lake ‘through taliks,’ the above hypothesis also permits both vertical segregation and vertical integration of the Early Mars hydrosphere (e.g., Head 2012). On the other hand, many climate models predict climates that were intermittently (or stably) warmer than the McMurdo Dry Valleys (Urata and Toon 2013; Batalha et al. 2016; Ramirez 2017); conversely, some climate models predict that lake-enabling conditions were $<10^2$ yr duration (Segura et al. 2013). Moreover, *Curiosity* data show no evidence in favor of the proposed subzero conditions. Therefore, more tests are needed. These future tests might include runoff production, and a search for evidence of ancient low-latitude snow/ice melt. A particularly useful measurement would be grain-size data for ancient fluvial sediments. Measuring the size of clasts moved by rivers has been a key justification for pushing orbiter imagery to higher resolution in the past (Malin et al. 2010; McEwen et al. 2007). Today, we are frustratingly a factor of a few below orbital detection of the most relevant grain sizes—gravel (Dietrich et al. 2017). Future methods might include active methods for surface roughness characterization (Pitman et al. 2004).

6.2 Implications for the Mars Exploration Program

Most people on Earth have put money towards Mars missions. Mars missions have been initiated by China, India, Europe, Russia, Japan, the United Arab Emirates, and the United States. The United States has supplied the largest investment so far, and all eight of the successful landed missions. NASA objectives for Mars exploration are defined in the Mars Exploration Program Analysis Group Science Goals Document (MEPAG 2018).

Goal II of the Mars Exploration Program is “Understand the processes and history of climate on Mars.” The data reviewed in this paper show great promise for progress on this goal. Mars’ geology records distinct, separable climate regimes spanning billions of years. Therefore, Mars records a rich set of natural experiments for understanding how planets in general behave (Ehlmann et al. 2016). Models of long-term planetary climate evolution can be tested through continued data collection and analysis.

However, Goal I of the Mars Exploration Program is “Determine if Mars ever supported life.” The data reviewed in this paper highlights a major concern for this goal. Specifically:

- Mars’s surface could have supported life during multiple time windows during its history (e.g. Grotzinger et al. 2014; Knoll et al. 2005; Squyres et al. 2008), sprinkled across >1 Gyr. However, the data do not require >1 Gyr of continuous Mars surface habitability. To the contrary, a minimal model in which globally surface-sterilizing conditions occurred $>90\%$ of the time, even on Early Mars, can match data. Gappy and spotty sur-

face habitability would be a challenge for the persistence of surface life (Cockell 2014; Westall et al. 2015).⁶

- Maximizing the probability of finding life beyond Earth, as well as the science value of a negative result, requires investigating rocks that date from Mars' most-habitable period (Mustard et al. 2013). Intermittent surface habitability after ~4.0 Ga may mean that the most habitable times in Mars surface history predate the interpretable-from-orbit geologic record. Most of Mars' crust (and thus most of Mars' volcanic activity) predates the Hellas impact (Taylor and McLennan 2009), and Mars' geodynamo shut down before the Hellas impact (Lillis et al. 2013). Theoretically, Mars should have had abundant liquid water right after the planet formed (e.g., Cannon et al. 2017). However, landing sites for rovers and sample return missions are chosen based on orbiter data. Use of orbiter data biases rovers to land at sites that are easier to interpret from orbit. Sites that are easier to interpret from orbit tend to be relatively young. But the most habitable times on Mars history may simply not leave a record that can be read from orbit today, because the earliest record has been jumbled by impacts and volcanism (Cannon et al. 2017; Botke and Andrews-Hanna 2017). Because the data are consistent with a scenario in which the post-Hellas surface was not continuously habitable, the understandable bias towards post-Hellas geologic targets for landed missions is a serious concern. This concern may be mitigated by including megabreccia samples in a return cache (McEwen et al. 2009; Weiss et al. 2018).

Acknowledgements The results listed above sum up the work of thousands of engineers and scientists. Many great papers are omitted from this review for concision. I am grateful to Chris McKay and Caleb Fassett for formal reviews, and to Tim Goudge, Paul Niles, and Brian Hynek for informal read-throughs. I thank David P. Mayer for generating the CTX DTM used in Fig. 2, and Jack Mustard for sharing a preprint. This paper was stimulated by the Fourth International Conference on Early Mars, and I thank the organizers and participants for that meeting. This work was funded in part by the U.S. taxpayer, via NASA grant NNX16AJ38G.

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Appendix

See Table 3 and Fig. 12.

Table 3 Absolute date estimates used in this paper, reproduced from Table 1 of Michael (2013) which in turn follows the Hartmann (2005) chronology

Epoch	Ages of epoch
Late Amazonian	0.27–0 Ga
Middle Amazonian	1.03–0.27 Ga
Early Amazonian	3.24–1.03 Ga
Late Hesperian	3.39–3.24 Ga
Early Hesperian	3.56–3.39 Ga
Late Noachian	3.85–3.56 Ga
Middle Noachian	3.96–3.85 Ga
Early Noachian	~4.0–3.96 Ga

⁶Research aimed at Goal I is focused on surface life. That is because the search for ancient microbial fossils of Earth's surface biosphere has a >50 year record of developing techniques that may be applied to Mars sediments (McMahon et al. 2018), whereas techniques for finding fossils of deep subsurface life are less well-developed (Onstott et al. 2018).

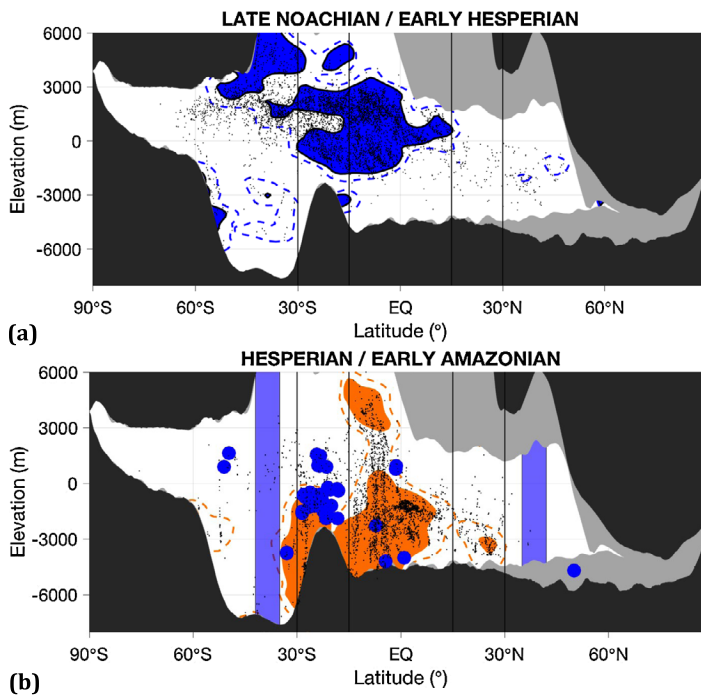


Fig. 12 Latitude-elevation plots of climate-relevant geologic activity for the Late Noachian/Early Hesperian and the Hesperian/Early Amazonian. The black regions have no data, and the gray regions correspond to terrain that was geologically reset after the time slice in question. Vertical black lines highlight latitudes $\pm 15^\circ$ and $\pm 30^\circ$. **(a)** *Late Noachian/Early Hesperian time slice*: Black dots correspond to individual valleys from the catalog of Hynes et al. (2010). Only every 10th valley is plotted, for legibility. The density of black dots reflects the nonuniform distribution of elevation as a function of latitude (for example, there is not much Noachian terrain S of 30° S above +3 km elevation). To correct for this effect, and get the latitude-and-elevation dependent density of valleys, we used a kernel density estimator. The resulting blue zone corresponds to the latitude/elevation zones that have the highest density of valleys, and is drawn to contain $\frac{2}{3}$ of the valleys. Blue dashed line is the same, but for 9/10 of the valleys. **(b)** *Late Hesperian/Amazonian time slice*: Blue disks mark large alluvial fans (combining catalogs of Howard et al. 2005 and Kraal et al. 2008a). Pale blue stripes mark latitude range of Fresh Shallow Valleys (Wilson et al. 2016). Black dots correspond to the sedimentary rocks from the catalog of Malin et al. (2010). The density of black dots reflects the nonuniform distribution of elevation as a function of latitude. To correct for this effect, and get the latitude-and-elevation dependent density of sedimentary rocks from Malin et al.'s (2010) catalog, we used a kernel density estimator. The resulting orange zone corresponds to the latitude/elevation zones that have the highest density of sedimentary rocks, and is drawn to contain $\frac{2}{3}$ of the sedimentary rocks. Orange dashed line is the same, but for 9/10 of the sedimentary rocks

References

- J.B. Adler, J.F. Bell III, P. Fawdon, J. Davis, N.H. Warner, E. Sefton-Nash, T.N. Harrison, Hypotheses for the origin of the Hypanis fan-shaped deposit at the edge of the Chryse escarpment, Mars: is it a delta? *Icarus* **319**, 885–908 (2019)
- O. Aharonson, M.T. Zuber, D.H. Rothman, N. Schorghofer, K.X. Whipple, Drainage basins and channel incision on Mars. *Proc. Natl. Acad. Sci.* **99**(4), 1780–1783 (2002)
- R. Amundson, Meteoric water alteration of soil and landscapes at Meridiani Planum, Mars. *Earth Planet. Sci. Lett.* **488**, 155–167 (2018)

- R. Amundson, W. Dietrich, D. Bellugi, S. Ewing, K. Nishiizumi, G. Chong, J. Owen, R. Finkel, A. Heimsath, B. Stewart, M. Caffee, Geomorphologic evidence for the late Pliocene onset of hyperaridity in the Atacama Desert. *Geol. Soc. Am. Bull.* **124**(7–8), 1048–1070 (2012)
- D.T. Andersen, W.H. Pollard, C.P. McKay, J. Heldmann, Cold springs in permafrost on Earth and Mars. *J. Geophys. Res., Planets* **107**(E3), 5015 (2002). <https://doi.org/10.1029/2000JE001436>
- R. Anderson, S.P. Anderson, *Geomorphology: The Mechanics and Chemistry of Landscapes* (Cambridge University Press, Cambridge, 2010)
- J.C. Andrews-Hanna, K.W. Lewis, Early Mars hydrology: 2. Hydrological evolution in the Noachian and Hesperian epochs. *J. Geophys. Res.* **116**(E2), E02007 (2011)
- J.C. Andrews-Hanna, M.T. Zuber, R.E. Arvidson, S.M. Wiseman, Early Mars hydrology: Meridiani playa deposits and the sedimentary record of Arabia Terra. *J. Geophys. Res.* **115**(E6), E06002 (2010)
- V. Ansan, N. Mangold, 3D morphometry of valley networks on Mars from HRSC/MEX DEMs: implications for climatic evolution through time. *J. Geophys. Res., Planets* **118**(9), 1873–1894 (2013)
- J.C. Armstrong, C.B. Leovy, T. Quinn, A 1 Gyr climate model for Mars: new orbital statistics and the importance of seasonally resolved polar processes. *Icarus* **171**, 255–271 (2004)
- R.E. Arvidson, J.F. Bell, P. Bellutta, N.A. Cabrol, J.G. Catalano, J. Cohen, L.S. Crumpler, D.J. Des Marais, T.A. Estlin, W.H. Farrand, R. Gellert, J.A. Grant, R.N. Greenberger, E.A. Guinness, K.E. Herkenhoff, J.A. Herman, K.D. Iagnemma, J.R. Johnson, G. Klingelhöfer, R. Li, K.A. Lichtenberg, S.A. Maxwell, D.W. Ming, R.V. Morris, M.S. Rice, S.W. Ruff, A. Shaw, K.L. Siebach, A. de Souza, A.W. Stroupe, S.W. Squyres, R.J. Sullivan, K.P. Talley, J.A. Townsend, A. Wang, J.R. Wright, A.S. Yen, Spirit Mars Rover Mission: overview and selected results from the northern home plate winter haven to the side of Scamander Crater. *J. Geophys. Res.* **115**(E12), E00F03 (2010)
- J.N. Bahcall, M.H. Pinsonneault, S. Basu, Solar models: current epoch and time dependences, neutrinos, and helioseismological properties. *Astrophys. J.* **555**(2), 990–1012 (2001)
- V.R. Baker, V.S. Kale, The role of extreme floods in shaping bedrock channels, in *Rivers over Rock: Fluvial Processes in Bedrock Channels*, ed. by K.J. Tinkler, E.E. Wohl. AGU Geophysical Monograph, vol. 107 (1998), pp. 153–166
- V.R. Baker, R.G. Strom, V.C. Gulick, J.S. Kargel, G. Komatsu, Ancient oceans, ice sheets and the hydrological cycle on Mars. *Nature* **352**, 589–594 (1991)
- J.L. Bandfield, Rover observations in Gusev Crater: evidence for a style of weathering unique to Mars? *Am. Mineral.* **102**(2), 233–234 (2017)
- S.G. Banham, S. Gupta, D.M. Rubin, J.A. Watkins, D.Y. Sumner, K.S. Edgett, J.P. Grotzinger, K.W. Lewis, L.A. Edgar, K.M. Stack-Morgan, R. Barnes, J.F. Bell III, M.D. Day, R.C. Ewing, M.G.A. Lapotre, N.T. Stein, F. Rivera-Hernandez, A.R. Vasavada, Ancient Martian aeolian processes and palaeomorphology reconstructed from the Stimson formation on the lower slope of Aeolis Mons, Gale Crater, Mars. *Sedimentology* **65**, 993–1042 (2018)
- S. Barabash, A. Fedorov, R. Lundin, J.-A. Sauvaud, Martian atmospheric erosion rates. *Science* **315**(5811), 501 (2007)
- E. Baratti, M. Pajola, S. Rossato, C. Mangili, M. Coradini, A. Montanari, K. McBride, Hydraulic modeling of the tributary and the outlet of a Martian paleolake located in the Memnonia quadrangle. *J. Geophys. Res., Planets* **120**(10), 1597–1619 (2015)
- C.J. Barnhart, A.D. Howard, J.M. Moore, Long-term precipitation and late-stage valley network formation: landform simulations of Parana basin, Mars. *J. Geophys. Res.* **114**(E1), E01003 (2009)
- N.E. Batalha, R.K. Kopparapu, J. Haqq-Misra, J.F. Kasting, Climate cycling on early Mars caused by the carbonate-silicate cycle. *Earth Planet. Sci. Lett.* **455**, 7–13 (2016)
- C.C. Bedford, J.C. Bridges, S.P. Schwenzer, R.C. Wiens, E.B. Rampe, J. Frydenvang, P.J. Gasda, Alteration trends and geochemical source region characteristics preserved in the fluviolacustrine sedimentary record of Gale crater, Mars. *Geoch. Cosmoch. Acta* **246**, 234–266 (2019)
- G. Berger et al., Evidence in favor of small amounts of ephemeral and transient water during alteration at Meridiani Planum, Mars. *Am. Mineral.* **94**, 1279–1282 (2009)
- J.A. Berger, M.E. Schmidt, R. Gellert, N.I. Boyd, E.D. Desouza, R.L. Flemming, M.R.M. Izawa, D.W. Ming, G.M. Perrett, E.B. Rampe, L.M. Thompson, S.J.V. VanBommel, A.S. Yen, Zinc and germanium in the sedimentary rocks of Gale Crater on Mars indicate hydrothermal enrichment followed by diagenetic fractionation. *J. Geophys. Res., Planets* **122**(8), 1747–1772 (2017)
- J.-P. Bibring, Y. Langevin, J.F. Mustard, F. Poulet, R. Arvidson, A. Gendrin, B. Gondet, N. Mangold et al., Global mineralogical and aqueous Mars history derived from OMEGA/Mars express data. *Science* **312**(5772), 400–404 (2006)
- J.-P. Bibring, R.E. Arvidson, A. Gendrin, B. Gondet, Y. Langevin, S. Le Mouelic, N. Mangold, R.V. Morris, J.F. Mustard, F. Poulet, C. Quantin, C. Sotin, Coupled ferric oxides and sulfates on the Martian surface. *Science* **317**(5842), 1206 (2007)

- C.J. Bierson, R.J. Phillips, I.B. Smith, S.E. Wood, N.E. Putzig, D. Nunes, S. Byrne, Stratigraphy and evolution of the buried CO₂ deposit in the Martian south polar cap. *Geophys. Res. Lett.* **43**(9), 4172–4179 (2016)
- J.L. Bishop, E.B. Rampe, Evidence for a changing Martian climate from the mineralogy at Mawrth Vallis. *Earth Planet. Sci. Lett.* **448**, 42–48 (2016)
- J.L. Bishop, D. Loizeau, N.K. McKeown, L. Saper, M.D. Dyar, D.J. Des Marais, M. Parente, S.L. Murchie, What the ancient phyllosilicates at Mawrth Vallis can tell us about possible habitability on early Mars. *Planet. Space Sci.* **86**, 130–149 (2013)
- J.L. Bishop, A.G. Fairén, J.R. Michalski, L. Gago-Duport, L.L. Baker, M.A. Velbel, C. Gross, E.B. Rampe, Surface clay formation during short-term warmer and wetter conditions on a largely cold ancient Mars. *Nat. Astron.* **2**, 206–213 (2018)
- L. Borg, M.J. Drake, A review of meteorite evidence for the timing of magmatism and of surface or near-surface liquid water on Mars. *J. Geophys. Res.* **110**(E12), E12S03 (2005)
- C.S. Borlina, B.L. Ehlmann, E.S. Kite, Modeling the thermal and physical evolution of Mount Sharp's sedimentary rocks, Gale Crater, Mars: implications for diagenesis on the MSL Curiosity rover traverse. *J. Geophys. Res., Planets* **120**(8), 1396–1414 (2015)
- W.F. Bottke, J.C. Andrews-Hanna, A post-accretionary lull in large impacts on early Mars. *Nat. Geosci.* **10**(5), 344–348 (2017)
- S. Bouley, D. Baratoux, I. Matsuyama, F. Forget, A. Séjourné, M. Turbet, F. Costard, Late Tharsis formation and implications for early Mars. *Nature* **531**(7594), 344–347 (2016)
- J.C. Bridges, D.C. Catling, J.M. Saxton, T.D. Swindle, I.C. Lyon, M.M. Grady, Alteration assemblages in Martian meteorites: implications for near-surface processes. *Space Sci. Rev.* **96**(1–4), 365–392 (2001)
- T.F. Bristow, R.M. Haberle, D.F. Blake et al., Low Hesperian P-CO₂ constrained from in situ mineralogical analysis at Gale Crater, Mars. *Proc. Natl. Acad. Sci.* **114**(9), 2166–2170 (2017)
- T.F. Bristow, E.B. Rampe, C.N. Achilles, D.F. Blake, S.J. Chipera, P. Craig, J.A. Crisp, D.J. Des Marais et al., Clay mineral diversity and abundance in sedimentary rocks of Gale Crater, Mars. *Sci. Adv.* **4**(6), eaar3330 (2018). <https://doi.org/10.1126/sciadv.aar3330>
- P.B. Buhler, C.I. Fassett, J.W. Head, M.P. Lamb, Timescales of fluvial activity and intermittency in Milna Crater, Mars. *Icarus* **241**, 130–147 (2014)
- D.M. Burr, P.A. Carling, V.R. Baker, *Megaflooding on Earth and Mars* (Cambridge University Press, Cambridge, 2009)
- J. Buz, B.L. Ehlmann, L. Pan, J.P. Grotzinger, Mineralogy and stratigraphy of the Gale Crater rim, wall, and floor units. *J. Geophys. Res., Planets* **122**(5), 1090–1118 (2017)
- K.M. Cannon, S.W. Parman, J.F. Mustard, Primordial clays on Mars formed beneath a steam or supercritical atmosphere. *Nature* **552**, 88 (2017)
- B.T. Cardenas, D. Mohrig, T.A. Goudge, Fluvial stratigraphy of valley fills at Aeolis Dorsa, Mars: evidence for base-level fluctuations controlled by a downstream water body. *Geol. Soc. Am. Bull.* **130**(3–4), 484–498 (2018)
- M.H. Carr, *The Surface of Mars* (Cambridge University Press, Cambridge, 2006)
- M.H. Carr, J.W. Head, Oceans on Mars: an assessment of the observational evidence and possible fate. *J. Geophys. Res., Planets* **108**(E5), 5042 (2003). <https://doi.org/10.1029/2002JE001963>
- M.H. Carr, J.W. Head, Martian surface/near-surface water inventory: sources, sinks, and changes with time. *Geophys. Res. Lett.* **42**(3), 726–732 (2015)
- M.H. Carr, M.C. Malin, Meter-scale characteristics of Martian channels and valleys. *Icarus* **146**(2), 366–386 (2000)
- J. Carter, D. Loizeau, N. Mangold, F. Poulet, J.-P. Bibring, Widespread surface weathering on early Mars: a case for a warmer and wetter climate. *Icarus* **248**, 373–382 (2015)
- W.S. Cassata, Meteorite constraints on Martian atmospheric loss and paleoclimate. *Earth Planet. Sci. Lett.* **479**, 322–329 (2017)
- W.S. Cassata, D.L. Shuster, P.R. Renne, B.P. Weiss, Evidence for shock heating and constraints on Martian surface temperatures revealed by ⁴⁰Ar/³⁹Ar thermochronometry of Martian meteorites. *Geochim. Cosmochim. Acta* **74**(23), 6900–6920 (2010)
- W.S. Cassata, D.L. Shuster, P.R. Renne, B.P. Weiss, Trapped Ar isotopes in meteorite ALH 84001 indicate Mars did not have a thick ancient atmosphere. *Icarus* **221**(1), 461–465 (2012)
- D.C. Catling, Atmospheric evolution of Mars, in *Encyclopedia of Paleoclimatology and Ancient Environments*, ed. by V. Gornitz (Springer, Dordrecht, 2009), pp. 66–75
- D.C. Catling, J.F. Kasting, *Atmospheric Evolution on Inhabited and Lifeless Worlds* (Cambridge University Press, Cambridge, 2017)
- J.E. Chappelow, M.P. Golombek, F.J. Calef, Does the Littleton meteorite require a past, denser Martian atmosphere? in *47th Lunar and Planetary Science Conference*, March 21–25, 2016, The Woodlands, Texas. LPI Contribution, vol. 1903 (2016), p. 1662

- P.R. Christensen, B.M. Jakosky, H.H. Kieffer, M.C. Malin, H.Y. McSween Jr., K. Neelson, G.L. Mehall, S.H. Silverman, S. Ferry, M. Caplinger, M. Ravine, The Thermal Emission Imaging System (THEMIS) for the Mars 2001 Odyssey Mission. *Space Sci. Rev.* **110**(1), 85–130 (2004)
- R.I. Citron, M. Manga, D.J. Hemingway, Timing of oceans on Mars from shoreline deformation. *Nature* **555**(7698), 643–646 (2018)
- S.M. Clifford, T.J. Parker, The evolution of the Martian hydrosphere: implications for the fate of a primordial ocean and the current state of the northern plains. *Icarus* **154**(1), 40–79 (2001)
- G.D. Clow, Generation of liquid water on Mars through the melting of a dusty snowpack. *Icarus* **72**, 95–127 (1987)
- C.S. Cockell, Habitable worlds with no signs of life. *Philos. Trans. R. Soc., Math. Phys. Eng. Sci.* **372**, 20130082 (2014)
- A. Cousin, P.Y. Meslin, R.C. Wiens, W. Rapin, N. Mangold, C. Fabre, O. Gasnault, O. Forni, R. Tokar, A. Ollila, S. Schröder, J. Lasue, S. Maurice, V. Sautter, H. Newsom, D. Vaniman, S. Le Mouélic, D. Dyar, G. Berger, D. Blaney, M. Nachon, G. Dromart, N. Lanza, B. Clark, S. Clegg, W. Goetz, J. Berger, B. Barraclough, D. Delapp, Compositions of coarse and fine particles in Martian soils at Gale: a window into the production of soils. *Icarus* **249**, 22–42 (2015)
- R.A. Craddock, A.D. Howard, The case for rainfall on a warm, wet early Mars. *J. Geophys. Res., Planets* **107**(E11), 5111 (2002). <https://doi.org/10.1029/2001JE001505>
- R.A. Craddock, R.D. Lorenz, The changing nature of rainfall during the early history of Mars. *Icarus* **293**, 172–179 (2017)
- R.A. Craddock, T.A. Maxwell, Geomorphic evolution of the Martian highlands through ancient fluvial processes. *J. Geophys. Res., Planets* **98**, 3453–3468 (1993)
- L.S. Crumpler, R.E. Arvidson, S.W. Squyres, T. McCoy, A. Yingst, S. Ruff, W. Farrand, Y. McSween, M. Powell, D.W. Ming, R.V. Morris, J.F. Bell III, J. Grant, R. Greeley, D. DesMarais, M. Schmidt, N.A. Cabrol, A. Haldemann, K.W. Lewis, A.E. Wang, C. Schröder, D. Blaney, B. Cohen, A. Yen, J. Farmer, R. Gellert, E.A. Guinness, K.E. Herkenhoff, J.R. Johnson, G. Klingelhöfer, A. McEwen, J.W. Rice Jr., M. Rice, P. deSouza, J. Hurowitz, Field reconnaissance geologic mapping of the Columbia Hills, Mars, based on Mars Exploration Rover Spirit and MRO HiRISE observations. *J. Geophys. Res., Planets* **116**, E7, E00F24 (2011)
- A. Darling, K. Whipple, Geomorphic constraints on the age of the western Grand Canyon. *Geosphere* **11**(4), 958–976 (2015)
- J.M. Davis, M. Balme, M. Grindrod, R.M.E. Williams, S. Gupta, Extensive Noachian fluvial systems in Arabia Terra: implications for early Martian climate. *Geology* **44**(10), 847–850 (2016)
- M. Day, W. Anderson, G. Kocurek, D. Mohrig, Carving intracrater layered deposits with wind on Mars. *Geophys. Res. Lett.* **43**, 2473–2479 (2016)
- G. de Villiers, M.G. Kleinhans, G. Postma, Experimental delta formation in crater lakes and implications for interpretation of Martian deltas. *J. Geophys. Res., Planets* **118**, 651–670 (2013)
- E. Dehouck, S.M. McLennan, E.C. Sklute, M.D. Dyar, Stability and fate of ferrihydrite during episodes of water/rock interactions on early Mars: an experimental approach. *J. Geophys. Res., Planets* **122**(2), 358–382 (2017)
- D.P. Dethier, Pleistocene incision rates in the western United States calibrated using Lava Creek B tephra. *Geology* **29**(9), 783 (2001)
- G. di Achille, B.M. Hynek, Ancient ocean on Mars supported by global distribution of deltas and valleys. *Nat. Geosci.* **3**(7), 459–463 (2010)
- R.A. DiBiase, A.B. Limaye, J.S. Scheingross, W.W. Fischer, M.P. Lamb, Deltaic deposits at Aeolis Dorsa: sedimentary evidence for a standing body of water on the northern plains of Mars. *J. Geophys. Res., Planets* **118**(6), 1285–1302 (2013)
- J.L. Dickson, C.I. Fassett, J.W. Head, Amazonian-aged fluvial valley systems in a climatic microenvironment on Mars: melting of ice deposits on the interior of Lyot Crater. *Geophys. Res. Lett.* **36**(8), L08201 (2009)
- W.E. Dietrich, M.C. Palucis, R.M.E. Williams, K.W. Lewis, F. Rivera-Hernandez, D.Y. Sumner, Fluvial gravels on Mars: analysis and implications, in *Gravel Bed Rivers: Processes and Disasters*, ed. by D. Tsutsumi, J.B. Laronne (Wiley, New York, 2017), pp. 755–783
- S.L. Dingman, *Physical Hydrology*, 3rd edn. (2014)
- S. Diniega, C.J. Hansen, J.N. McElwaine, C.H. Hugenholtz, C.M. Dundas, A.S. McEwen, M.C. Bourke, A new dry hypothesis for the formation of Martian linear gullies. *Icarus* **225**(1), 526–537 (2013)
- P.T. Doran, C.P. McKay, G.D. Clow, G.L. Dana, A.G. Fountain, T. Nylen, W.B. Lyons, Valley floor climate observations from the McMurdo dry valleys, Antarctica, 1986–2000. *J. Geophys. Res., Atmos.* **107**(D24), 4772 (2002). <https://doi.org/10.1029/2001JD002045>
- H.A. Dugan, M.K. Obryk, P.T. Doran, Lake ice ablation rates from permanently ice-covered Antarctic lakes. *J. Glaciol.* **59**(215), 491–498 (2013)

- C.M. Dundas, A.S. McEwen, S. Diniega, C.J. Hansen, S. Byrne, J.N. McElwaine, *The Formation of Gullies on Mars Today*. Special Publications, vol. 467 (Geological Society, London, 2017a). <https://doi.org/10.1144/SP467.5>
- C.M. Dundas, A.S. McEwen, M. Chojnacki et al., Granular flows at recurring slope lineae on Mars indicate a limited role for liquid water. *Nat. Geosci.* **10**, 903 (2017b)
- T. Dunne, D.V. Malmon, K.B.J. Dunne, Limits on the morphogenetic role of rain splash transport in hillslope evolution. *J. Geophys. Res., Earth Surf.* **121**(3), 609–622 (2016)
- J.R. Eagleman, Pan evaporation, potential and actual evapotranspiration. *J. Appl. Meteorol.* **6**(3), 482–488 (1967)
- B.C. Eaton, Chap. 9.18: hydraulic geometry, in *Treatise on Geomorphology, 9, Fluvial Geomorphology*, ed. by E.E. Wohl (Elsevier, Oxford, 2013)
- K.S. Edgett, M.C. Malin, Martian sedimentary rock stratigraphy: outcrops and interbedded craters of north-west Sinus Meridiani and southwest Arabia Terra. *Geophys. Res. Lett.* **29**(24), 2179 (2002). <https://doi.org/10.1029/2002GL016515>
- C.S. Edwards, K.J. Nowicki, P.R. Christensen, J. Hill, N. Gorelick, K. Murray, Mosaicking of global planetary image datasets: 1. Techniques and data processing for Thermal Emission Imaging System (THEMIS) multi-spectral data. *J. Geophys. Res.* **116**(E10), E10008 (2011)
- B.L. Ehlmann, C.S. Edwards, Mineralogy of the Martian surface. *Annu. Rev. Earth Planet. Sci.* **42**(1), 291–315 (2014)
- B.L. Ehlmann, J.F. Mustard, S.L. Murchie et al., Subsurface water and clay mineral formation during the early history of Mars. *Nature* **479**(7371), 53–60 (2011a)
- B.L. Ehlmann, J.F. Mustard, R.N. Clark, G.A. Swayze, S.L. Murchie, Evidence for low-grade metamorphism, hydrothermal alteration, and diagenesis on Mars from phyllosilicate mineral assemblages. *Clays Clay Miner.* **59**(4), 359–377 (2011b)
- B.L. Ehlmann, F.S. Anderson, J. Andrews-Hanna, D.C. Catling, R. Christensen, B.A. Cohen, C.D. Dressing, C.S. Edwards, L.T. Elkins-Tanton, K.A. Farley, C.I. Fassett, W.W. Fischer, A.A. Fraeman, M.P. Golombek, V.E. Hamilton, A.G. Hayes, C.D.K. Herd, B. Horgan, R. Hu, B.M. Jakosky, J.R. Johnson, J.F. Kasting, L. Kerber, K.M. Kinch, E.S. Kite, H.A. Knutson, J.I. Lunine, R. Mahaffy, N. Mangold, F.M. McCubbin, J.F. Mustard, B. Niles, C. Quantin-Nataf, M.S. Rice, K.M. Stack, D.J. Stevenson, S.T. Stewart, M.J. Toplis, T. Usui, B.P. Weiss, S.C. Werner, R.D. Wordsworth, J.J. Wray, R.A. Yingst, Y.L. Yung, K.J. Zahnle, The sustainability of habitability on terrestrial planets: insights, questions, and needed measurements from Mars for understanding the evolution of Earth-like worlds. *J. Geophys. Res., Planets* **121**(10), 1927–1961 (2016)
- M.R. El-Maarry, J.M. Dohm, G. Michael, N. Thomas, S. Maruyama, Morphology and evolution of the ejecta of Hale Crater in Argyre basin, Mars: results from high resolution mapping. *Icarus* **226**, 905–922 (2013)
- M.E. Elwood Madden, A.S. Madden, J.D. Rimstidt, How long was Meridiani Planum wet? Applying a jarosite stopwatch to determine the duration of aqueous diagenesis. *Geology* **37**(7), 635–638 (2009)
- A.G. Fairén, A cold and wet Mars. *Icarus* **208**(1), 165–175 (2010)
- A.G. Fairén, A.F. Davila, L. Gago-Duport, R. Amils, C.P. McKay, Stability against freezing of aqueous solutions on early Mars. *Nature* **459**, 401–404 (2009)
- A.G. Fairén, J.D. Haqq-Misra, C.P. McKay, Reduced albedo on early Mars does not solve the climate paradox under a faint young Sun. *Astron. Astrophys.* **540**, A13 (2012)
- K.A. Farley, C. Malespin, P. Mahaffy, J.P. Grotzinger, P.M. Vasconcelos, R.E. Milliken, M. Malin, K.S. Edgett, A.A. Pavlov, J.A. Hurowitz, J.A. Grant et al., In situ radiometric and exposure age dating of the Martian surface. *Science* **343**(6169), 1247166 (2014)
- C.I. Fassett, J.W. Head, Fluvial sedimentary deposits on Mars: ancient deltas in a crater lake in the Nili Fossae region. *Geophys. Res. Lett.* **32**(14), L14201 (2005)
- C.I. Fassett, J.W. Head, The timing of Martian valley network activity: constraints from buffered crater counting. *Icarus* **195**(1), 61–89 (2008a)
- C.I. Fassett, J.W. Head, Valley network-fed, open-basin lakes on Mars: distribution and implications for Noachian surface and subsurface hydrology. *Icarus* **198**(1), 37–56 (2008b)
- C.I. Fassett, J.W. Head, Sequence and timing of conditions on early Mars. *Icarus* **211**(2), 1204–1214 (2011)
- C.I. Fassett, J.L. Dickson, J.W. Head, J.S. Levy, D.R. Marchant, Supraglacial and proglacial valleys on Amazonian Mars. *Icarus* **208**(1), 86–100 (2010)
- J.L. Fastook, J.W. Head, Glaciation in the late Noachian icy highlands: ice accumulation, distribution, flow rates, basal melting, and top-down melting rates and patterns. *Planet. Space Sci.* **106**, 82–98 (2015)
- J.L. Fastook, J.W. Head, D.R. Marchant, F. Forget, J.-B. Madeleine, Early Mars climate near the Noachian-Hesperian boundary: independent evidence for cold conditions from basal melting of the south polar ice sheet (Dorsa Argentea formation) and implications for valley network formation. *Icarus* **219**(1), 25–40 (2012)

- C.M. Fedo, J.P. Grotzinger, S. Gupta, N.T. Stein, J. Watkins, S. Banham, K.S. Edgett, M. Miniti, J. Schieber, K. Siebach, K. Stack-Morgan, H. Newsom, K.W. Lewis, C. House, A.R. Vasavada, Facies analysis and basin architecture of the upper part of the Murray formation, Gale Crater, Mars, in *48th Lunar and Planetary Science Conference*. 20–24 March 2017, The Woodlands, Texas. LPI Contribution, vol. 1964 (2017), p. 1689
- R.M. Flowers, K.A. Farley, Apatite $4\text{He}/3\text{He}$ and (U-Th)/He evidence for an ancient Grand Canyon. *Science* **338**(6114), 1616 (2012)
- F. Forget, R. Wordsworth, E. Millour, J.-B. Madeleine, L. Kerber, J. Leconte, E. Marcq, R.M. Haberle, 3D modelling of the early Martian climate under a denser CO_2 atmosphere: temperatures and CO_2 ice clouds. *Icarus* **222**(1), 81–99 (2013)
- N.K. Forsberg-Taylor, A.D. Howard, R.A. Craddock, Crater degradation in the Martian highlands: morphometric analysis of the Sinus Sabaeus region and simulation modeling suggest fluvial processes. *J. Geophys. Res.* **109**(E5), E05002 (2004)
- J. Frydenvang, P.J. Gasda, J.A. Hurowitz, J.P. Grotzinger, R.C. Wiens, H.E. Newsom, K.S. Edgett, J. Watkins, J.C. Bridges, S. Maurice, M.R. Fisk, J.R. Johnson, W. Rapin, N.T. Stein, S.M. Clegg, S.P. Schwenzer, C.C. Bedford, P. Edwards, N. Mangold, A. Cousin, R.B. Anderson, V. Payré, D. Vaniman, D.F. Blake, N.L. Lanza, S. Gupta, J. Van Beek, V. Sautter, P.-Y. Meslin, M. Rice, R. Milliken, R. Gellert, L. Thompson, B.C. Clark, D.Y. Sumner, A.A. Fraeman, K.M. Kinch, M.B. Madsen, I.G. Mitrofanov, I. Jun, F. Calef, A.R. Vasavada, Diagenetic silica enrichment and late-stage groundwater activity in Gale Crater, Mars. *Geophys. Res. Lett.* **44**(10), 4716–4724 (2017). <https://doi.org/10.1002/2017GL073323>
- L.R. Gabasova, E.S. Kite, Compaction and sedimentary basin analysis on Mars. *Planet. Space Sci.* **152**, 86–106 (2018)
- S.F. Gallen, F.J. Pazzaglia, K.W. Wegmann, J.L. Pederson, T.W. Gardner, The dynamic reference frame of rivers and apparent transience in incision rates. *Geology* **43**(7), 623–626 (2015)
- A. Gaudin, E. Dehouck, O. Grauby, N. Mangold, Formation of clay minerals on Mars: insights from long-term experimental weathering of olivine. *Icarus* **311**, 210–223 (2018)
- A. Gendrin, N. Mangold, J.-P. Bibring, Y. Langevin, B. Gondet, F. Poulet, G. Bonello, C. Quantin, J. Mustard, R. Arvidson, S. Le Mouélic, Sulfates in Martian layered terrains: the OMEGA/Mars express view. *Science* **307**(5715), 1587–1591 (2005)
- G.L. Ghatan, J.R. Zimbelman, Paucity of candidate coastal constructional landforms along proposed shorelines on Mars—implications for a northern lowlands-filling ocean. *Icarus* **185**(1), 171–196 (2006). <https://doi.org/10.1016/j.icarus.2006.06.007>
- T.D. Glotch, J.L. Bandfield, P.R. Christensen, W.M. Calvin, S.M. McLennan, B.C. Clark, A.D. Rogers, S.W. Squyres, Mineralogy of the light-toned outcrop at Meridiani Planum as seen by the miniature thermal emission spectrometer and implications for its formation. *J. Geophys. Res.* **111**, E12, E12S03 (2006)
- K. Goddard, N.H. Warner, S. Gupta, J.-R. Kim, Mechanisms and timescales of fluvial activity at Mojave and other young Martian craters. *J. Geophys. Res., Planets* **119**(3), 604–634 (2014)
- W. Goetz, P. Bertelsen, C.S. Binou, H.P. Gunnlaugsson, S.F. Hviid, K.M. Kinch, D.E. Madsen, M.B. Madsen, M. Olsen, R. Gellert, G. Klingelhöfer, D.W. Ming, R.V. Morris, R. Rieder, D.S. Rodionov, P.A. de Souza, C. Schröder, S.W. Squyres, T. Wdowiak, A. Yen, Indication of drier periods on Mars from the chemistry and mineralogy of atmospheric dust. *Nature* **436**(7047), 62–65 (2005)
- M.P. Golombek, J.A. Grant, L.S. Crumpler, R. Greeley, R.E. Arvidson, J.F. Bell, C.M. Weitz, R. Sullivan, R. Christensen, L.A. Soderblom, S.W. Squyres, Erosion rates at the Mars Exploration Rover landing sites and long-term climate change on Mars. *J. Geophys. Res.* **111**(E12), E12S10 (2006)
- M.P. Golombek, N.H. Warner, V. Ganti, M.P. Lamb, T.J. Parker, R.L. Ferguson, R. Sullivan, Small crater modification on Meridiani Planum and implications for erosion rates and climate change on Mars. *J. Geophys. Res., Planets* **119**(12), 2522–2547 (2014)
- T.A. Goudge, C.I. Fassett, Incision of Licus Vallis, Mars, from multiple lake overflow floods. *J. Geophys. Res., Planets* **123**(2), 405–420 (2018)
- T.A. Goudge, J.W. Head, J.F. Mustard, C.I. Fassett, An analysis of open-basin lake deposits on Mars: evidence for the nature of associated lacustrine deposits and post-lacustrine modification processes. *Icarus* **219**(1), 211–229 (2012)
- T.A. Goudge, C.I. Fassett, J.W. Head, J.F. Mustard, K.L. Aureli, Insights into surface runoff on early Mars from paleolake basin morphology and stratigraphy. *Geology* **44**(6), 419–422 (2016)
- T.A. Goudge, R.E. Milliken, J.W. Head, J.F. Mustard, C.I. Fassett, Sedimentological evidence for a deltaic origin of the western fan deposit in Jezero Crater, Mars and implications for future exploration. *Earth Planet. Sci. Lett.* **458**, 357–365 (2017)
- T.A. Goudge, D. Mohrig, B.T. Cardenas, C.M. Hughes, C.I. Fassett, Stratigraphy and paleohydrology of delta channel deposits, Jezero Crater, Mars. *Icarus* **301**, 58–75 (2018)
- J.A. Grant, S.A. Wilson, Late alluvial fan formation in southern Margaritifer Terra, Mars. *Geophys. Res. Lett.* **38**, L08201 (2011). <https://doi.org/10.1029/2011GL046844>

- J.A. Grant, S.A. Wilson, A possible synoptic source of water for alluvial fan formation in southern Margaritifer Terra, Mars. *Planet. Space Sci.* **72**(44), 52 (2012)
- J.A. Grant, S.A. Wilson, The nature and emplacement of distal aqueous-rich ejecta deposits from Hale crater, Mars. *Meteorit. Planet. Sci.*, 839–856 (2018). <https://doi.org/10.1111/maps.1284353>
- J.A. Grant, R.P. Irwin III, J.P. Grotzinger et al., HiRISE imaging of impact megabreccia and sub-meter aqueous strata in Holden Crater, Mars. *Geology* **36**, 195–198 (2008)
- J.A. Grant, R.P. Irwin, S.A. Wilson, D. Buczkowski, K. Siebach, A lake in Uzboi Vallis and implications for late Noachian-early Hesperian climate on Mars. *Icarus* **212**(1), 110–122 (2011)
- S.E. Grasby, B.C. Proemse, B. Beauchamp, Deep groundwater circulation through the High Arctic cryosphere forms Mars-like gullies. *Geology* **42**(8), 651–654 (2014)
- J.P. Grotzinger, R.E. Milliken, The sedimentary rock record of Mars: distribution, origins, and global stratigraphy, in *Sedimentary Geology of Mars*. SEPM Special Publication, vol. 102 (2012), pp. 1–48. ISBN 978-1-56576-312-8
- J.P. Grotzinger, R.E. Arvidson, J.F. Bell, W. Calvin, B.C. Clark, D.A. Fike, M. Golombek, R. Greeley, A. Haldemann, K.E. Herkenhoff, B.L. Jolliff, A.H. Knoll, M. Malin, S.M. McLennan, T. Parker, L. Soderblom, J.N. Sohl-Dickstein, S.W. Squyres, N.J. Tosca, W.A. Watters, Stratigraphy and sedimentology of a dry to wet eolian depositional system, Burns formation, Meridiani Planum, Mars. *Earth Planet. Sci. Lett.* **240**(1), 11–72 (2005)
- J.P. Grotzinger, D.Y. Sumner, L.C. Kah, K. Stack, S. Gupta, L. Edgar, D. Rubin, K. Lewis, J. Schieber, N. Mangold, R. Milliken, G. Conrad, D. DesMarais, J. Farmer, K. Siebach, F. Calef, J. Hurowitz, S.M. McLennan et al., A Habitable Fluvio-Lacustrine environment at Yellowknife bay, Gale Crater, Mars. *Science* **343**(6169), 1242777 (2014)
- J.P. Grotzinger, S. Gupta, M.C. Malin, D.M. Rubin, J. Schieber, K. Siebach, D.Y. Sumner, K. Stack et al., Deposition, exhumation, and paleoclimate of an ancient lake deposit, Gale Crater, Mars. *Science* **350**, 6257 (2015)
- V. Gulick, Origin of the valley networks on Mars: a hydrological perspective. *Geomorphology* **37**(3–4), 241–268 (2001)
- V.C. Gulick, V.R. Baker, Fluvial valleys and Martian palaeoclimates. *Nature* **341**, 514–516 (1989). <https://doi.org/10.1038/341514a0>
- R.M. Haberle, Early Mars climate models. *J. Geophys. Res.* **103**(E12), 28467–28480 (1998)
- R.M. Haberle, D.C. Catling, M.H. Carr, K.J. Zahnle, The early Mars climate system, in *The Atmosphere and Climate of Mars*, ed. by R.M. Haberle et al. (Cambridge University Press, Cambridge, 2017), pp. 497–525. ISBN 9781139060172
- R.M. Haberle, K. Zahnle, N.G. Barlow, Warming early Mars by impact degassing of reduced greenhouse gases, in *49th Lunar and Planetary Science Conference*, 19–23 March, 2018, The Woodlands, Texas. LPI Contribution, vol. 2083 (2018), p. 1682
- E.A. Hajek, M.A. Wolinsky, Simplified process modeling of river avulsion and alluvial architecture: connecting models and field data. *Sediment. Geol.* **257–260**, 1–30 (2012)
- I. Halevy, J.W. Head III, Episodic warming of early Mars by punctuated volcanism. *Nat. Geosci.* **7**(12), 865–868 (2014)
- I. Halevy, W.W. Fischer, J.M. Eiler, Carbonates in the Martian meteorite Allan Hills 84001 formed at 18 ± 4 degrees C in a near-surface aqueous environment. *Proc. Natl. Acad. Sci.* **108**(41), 16895–16899 (2011)
- V.E. Hamilton, P.R. Christensen, Evidence for extensive, olivine-rich bedrock on Mars. *Geology* **33**, 433–436 (2005)
- K.R. Harrison, M.G. Chapman, Evidence for ponding and catastrophic flood in central Valles Marineris. *Icarus* **198**, 351–364 (2008). <https://doi.org/10.1016/j.icarus.2008.08.003>
- W.K. Hartmann, Geological observations of Martian arroyos. *J. Geophys. Res.* **79**, 3951–3957 (1974)
- W.K. Hartmann, Martian cratering 8: isochron refinement and the chronology of Mars. *Icarus* **174**, 294–320 (2005)
- E. Hauber, T. Platz, D. Reiss, L. Le Deit, M.G. Kleinhans, W.A. Marra, T. Haas, P. Carboneau, Asynchronous formation of Hesperian and Amazonian-aged deltas on Mars and implications for climate. *J. Geophys. Res., Planets* **118**, 1529–1544 (2013)
- E.M. Hausrath, A.K. Navarre-Sitchler, P.B. Sak et al., Basalt weathering rates on Earth and the duration of liquid water on the plains of Gusev Crater, Mars. *Geology* **36**(1), 67–70 (2008)
- J.W. Head, Mars planetary hydrology: was the Martian hydrological cycle and system ever globally vertically integrated? in *43rd Lunar and Planetary Science Conference*, March 19–23, 2012, The Woodlands, Texas. LPI Contribution, vol. 1659 (2012), p. 2137
- J.W. Head, Mars climate history: a geological perspective, in *The Sixth International Workshop on the Mars Atmosphere: Modelling and Observation*, January 17–20, 2017, Granada, Spain. Scientific committee: F. Forget, M.A. Lopez-Valverde, S. Amiri, M.-C. Desjean, F. Gonzalez-Galindo, J. Hollingsworth, B. Jakosky, S.R. Lewis, D. McCleese, E. Millour, H. Svedhem, D. Titov, M. Wolff (2017), p. 4301

- J.W. Head, D.R. Marchant, The climate history of early Mars: insights from the Antarctic McMurdo Dry Valleys hydrologic system. *Antarct. Sci.* **26**(06), 774–800 (2014)
- J.W. Head, R. Wordsworth, F. Forget, M. Turbet, Deciphering the Noachian geological and climate history of Mars: part 2: a Noachian stratigraphic view of major geologic processes and their climatic consequences, in *Fourth International Conference on Early Mars: Geologic, Hydrologic, and Climatic Evolution and the Implications for Life, Proceedings of the Conference*. 2–6 October, 2017, Flagstaff, Arizona. LPI Contribution, vol. 2014 (2017), p. 3047
- M.H. Hecht, Metastability of liquid water on Mars. *Icarus* **156**(2), 373–386 (2002)
- W. Hildreth, J. Fierstein, The Novarupta–Katmai eruption of 1912—largest eruption of the twentieth century, centennial perspectives. *U. S. Geol. Surv. Prof. Pap.* **1791**, 259 (2012)
- M.R.T. Hoke, B.M. Hynek, Roaming zones of precipitation on ancient Mars as recorded in valley networks. *J. Geophys. Res.* **114**(E8), E08002 (2009)
- M.R.T. Hoke, B.M. Hynek, G.E. Tucker, Formation timescales of large Martian valley networks. *Earth Planet. Sci. Lett.* **312**(1), 1–12 (2011)
- A. Howard, Simulating the development of Martian highland landscapes through the interaction of impact cratering, fluvial erosion, and variable hydrologic forcing. *Geomorphology* **91**, 332–363 (2007)
- A.D. Howard, J.M. Moore, Late Hesperian to early Amazonian midlatitude Martian valleys: evidence from Newton and Gorgonum basins. *J. Geophys. Res.* **116**(E5), E05003 (2011)
- A.D. Howard, J.M. Moore, R.P. Irwin, An intense terminal epoch of widespread fluvial activity on early Mars: 1. Valley network incision and associated deposits. *J. Geophys. Res.* **110**(E12), E12S14 (2005)
- R. Hu, D.M. Kass, B.L. Ehlmann, Y.L. Yung, Tracing the fate of carbon and the atmospheric evolution of Mars. *Nat. Commun.* **6**, 10003 (2015)
- C.M. Hughes, B.T. Cardenas, T.A. Goudge, D. Mohrig, Deltaic deposits indicative of a paleo-coastline at Aeolis Dorsa, Mars. *Icarus* **317**, 442–453 (2019)
- M. Humayun, A. Nemchin, B. Zanda, R.H. Hewins, M. Grange, A. Kennedy, J.-P. Lorand, C. Göpel, C. Fieni, S. Pont, D. Deldicque, Origin and age of the earliest Martian crust from meteorite NWA 7533. *Nature* **503**, 513–516 (2013)
- J.A. Hurowitz, W.W. Fischer, Contrasting styles of water–rock interaction at the Mars Exploration Rover landing sites. *Geochim. Cosmochim. Acta* **127**, 25–38 (2014)
- J.A. Hurowitz, S.M. McLennan, A ~ 3.5 Ga record of water-limited, acidic weathering conditions on Mars. *Earth Planet. Sci. Lett.* **260**(3–4), 432–443 (2007)
- J.A. Hurowitz, S.M. McLennan, N.J. Tosca, R.E. Arvidson, J.R. Michalski, D.W. Ming, C. Schröder, S.W. Squyres, In situ and experimental evidence for acidic weathering of rocks and soils on Mars. *J. Geophys. Res.* **111**, E2, E02S19 (2006)
- J.A. Hurowitz, W. Fischer, N.J. Tosca et al., Origin of acidic surface waters and the evolution of atmospheric chemistry on early Mars. *Nat. Geosci.* **3**: **5**, 323–326 (2010)
- J.A. Hurowitz, J.P. Grozinger, W.W. Fischer, S.M. McLennan, R.E. Milliken, N. Stein, A.R. Vasavada, D.F. Blake, E. Dehouck, J.L. Eigenbrode, A.G. Fairén, J. Frydenvang, R. Gellert, J.A. Grant, S. Gupta, K.E. Herkenhoff, D.W. Ming, E.B. Rampe, M.E. Schmidt, K.L. Siebach, K. Stack-Morgan, D.Y. Sumner, R.C. Wiens, Redox stratification of an ancient lake in Gale Crater, Mars. *Science* **356**(6341), aah6849 (2017)
- B.M. Hynek, G. Di Achille, Geologic map of Meridiani Planum, Mars (ver. 1.1, April 2017): U.S. Geological Survey Scientific Investigations Map 3356, pamphlet 9 pp., scale 1:2,000,000 (2017). <https://doi.org/10.3133/sim3356>
- B.M. Hynek, R.J. Phillips, New data reveal mature, integrated drainage systems on Mars indicative of past precipitation. *Geology* **31**(9), 757 (2003)
- B.M. Hynek, M. Beach, M.R.T. Hoke, Updated global map of Martian valley networks and implications for climate and hydrologic processes. *J. Geophys. Res.* **115**(E9), E09008 (2010)
- R.P. Irwin, Testing links between impacts and fluvial erosion on post-Noachian Mars, in *44th Lunar and Planetary Science Conference*, March 18–22, 2013, The Woodlands, Texas. LPI Contribution, vol. 1719, (2013), p. 2958
- R.P. Irwin, T.A. Maxwell, A.D. Howard, R.A. Craddock, D.W. Leverington, A large paleolake basin at the head of Ma’adim Vallis, Mars. *Science* **296**(5576), 2209–2212 (2002)
- R.P. Irwin, A.D. Howard, T.A. Maxwell, Geomorphology of Ma’adim Vallis, Mars, and associated paleolake basins. *J. Geophys. Res.* **109**(E12), E12009 (2004)
- R.P. Irwin, A.D. Howard, R.A. Craddock, J.M. Moore, An intense terminal epoch of widespread fluvial activity on early Mars: 2. Increased runoff and paleolake development. *J. Geophys. Res.* **110**(E12), E12S15 (2005a)
- R.P. Irwin, R.A. Craddock, A.D. Howard, Interior channels in Martian valley networks: discharge and runoff production. *Geology* **33**(6), 489–492 (2005b)

- R.P. Irwin, K.L. Tanaka, S.J. Robbins, Distribution of early, middle, and late Noachian cratered surfaces in the Martian highlands: implications for resurfacing events and processes. *J. Geophys. Res., Planets* **118**(2), 278–291 (2013)
- R.P. Irwin, K.W. Lewis, A.D. Howard, J.A. Grant, Paleohydrology of Eberswalde crater, Mars. *Geomorphology* (2015). <https://doi.org/10.1016/j.geomorph.2014.10.012>
- M.A. Ivanov, G. Erkeling, H. Hiesinger, H. Bernhardt, D. Reiss, Topography of the Deuteronilus contact on Mars: evidence for an ancient water/mud ocean and long-wavelength topographic readjustments. *Planet. Space Sci.* **144**, 49–70 (2017)
- R.E. Jacobsen, D.M. Burr, Greater contrast in Martian hydrological history from more accurate estimates of paleodischarge. *Geophys. Res. Lett.* **43**(17), 8903–8911 (2016)
- B.M. Jakosky, J.H. Jones, The history of Martian volatiles. *Rev. Geophys.* **35**(1), 1–16 (1997)
- B.M. Jakosky, R.J. Phillips, Mars' volatile and climate history. *Nature* **412**(6843), 237–244 (2001)
- B.M. Jakosky, M. Sliwski, M. Benna et al., Mars' atmospheric history derived from upper-atmosphere measurements of Ar-38/Ar-36. *Science* **355**, 1408 (2017)
- B.M. Jakosky et al., Loss of the Martian atmosphere to space: present-day loss rates determined from MAVEN observations and integrated loss through time. *Icarus* **315**, 146–157 (2018). <https://doi.org/10.1016/j.icarus.2018.05.030>
- R. Jaumann, D. Reiss, S. Frei, G. Neukum, F. Scholten, K. Gwinner, T. Roatsch, K.-D. Matz, V. Mertens, E. Hauber, H. Hoffmann, U. Köhler, J.W. Head, H. Hiesinger, M.H. Carr, Interior channels in Martian valleys: constraints on fluvial erosion by measurements of the Mars Express High Resolution Stereo Camera. *Geophys. Res. Lett.* **32**(16), L16203 (2005)
- L.C. Kah, K.M. Stack, J.L. Eigenbrode, R.A. Yingst, K.S. Edgett, Syndepositional precipitation of calcium sulfate in Gale Crater, Mars. *Terra Nova* **30**(6), 431–439 (2018). <https://doi.org/10.1111/ter.12359>
- J.F. Kasting, D.P. Whitmire, R.T. Reynolds, Habitable zones around main sequence stars. *Icarus* **101**(1), 108–128 (1993)
- S.V. Kaufman, J.F. Mustard, J.W. Head, Characterization of the alteration of Antarctic ash: the products of a cold and icy environment, in *49th Lunar and Planetary Science Conference*, 19–23 March, 2018, The Woodlands, Texas. LPI Contribution, vol. 2083 (2018), p. 2375
- L. Kerber, J.W. Head, The age of the Medusae Fossae formation: evidence of Hesperian emplacement from crater morphology, stratigraphy, and ancient lava contacts. *Icarus* **206**(2), 669–684 (2010)
- L. Kerber, F. Forget, R. Wordsworth, Sulfur in the early Martian atmosphere revisited: experiments with a 3-D global climate model. *Icarus* **261**, 133–148 (2015)
- E.S. Kite, An ice-and-snow hypothesis for early Mars, and the runoff-production test, in *Fourth International Conference on Early Mars: Geologic, Hydrologic, and Climatic Evolution and the Implications for Life, Proceedings of the Conference*. 2–6 October, 2017, Flagstaff, Arizona. LPI Contribution, vol. 2014 (2017), p. 3044
- E.S. Kite, R.C.A. Hindmarsh, Did ice streams shape the largest channels on Mars? *Geophys. Res. Lett.* **34**, L19202 (2007). <https://doi.org/10.1029/2007GL030530>
- E.S. Kite, I. Matsuyama, M. Manga, J.T. Perron, J.X. Mitrovica, True Polar Wander driven by late-stage volcanism and the distribution of paleopolar deposits on Mars. *Earth Planet. Sci. Lett.* **280**, 254–267 (2009)
- E.S. Kite, T.I. Michaels, S.C.R. Rafkin, M. Manga, W.E. Dietrich, Localized precipitation and runoff on Mars. *J. Geophys. Res., Planets* **116**, E07002, 20 (2011a). <https://doi.org/10.1029/2010JE003783>
- E.S. Kite, S. Rafkin, T.I. Michaels, W.E. Dietrich, M. Manga, Chaos terrain, storms, and past climate on Mars. *J. Geophys. Res.* **116**(E10), E10002 (2011b)
- E.S. Kite, I. Halevy, M.A. Kahre, M.J. Wolff, M. Manga, Seasonal melting and the formation of sedimentary rocks on Mars, with predictions for the Gale Crater mound. *Icarus* **223**(1), 181–210 (2013a)
- E.S. Kite, A. Lucas, C.I. Fassett, Pacing Early Mars river activity: embedded craters in the Aeolis Dorsa region imply river activity spanned \gtrsim (1–20) Myr. *Icarus* **225**, 850–855 (2013b)
- E.S. Kite, J.-P. Williams, A. Lucas, O. Aharonson, Low palaeopressure of the Martian atmosphere estimated from the size distribution of ancient craters. *Nat. Geosci.* **7**(5), 335–339 (2014)
- E.S. Kite, A.D. Howard, A.S. Lucas, J.C. Armstrong, O. Aharonson, M.P. Lamb, Stratigraphy of Aeolis Dorsa, Mars: stratigraphic context of the great river deposits. *Icarus* **253**, 223–242 (2015)
- E.S. Kite, P. Gao, C. Goldblatt, M.A. Mischna, D.P. Mayer, Y.L. Yung, Methane bursts as a trigger for intermittent lake-forming climates on post-Noachian Mars. *Nat. Geosci.* **10**, 737–740 (2017a)
- E.S. Kite, J. Sneed, D.P. Mayer, S.A. Wilson, Persistent or repeated surface habitability on Mars during the late Hesperian–Amazonian. *Geophys. Res. Lett.* **44**(9), 3991–3999 (2017b)
- E.S. Kite, L.J. Steele, M.A. Mischna, The cirrus cloud greenhouse on Early Mars: an explanation, the explanation, or no explanation for rivers and lakes? in *AGU Fall Meeting* (2018), P51F-2942
- E.S. Kite, D.P. Mayer, S.A. Wilson, J.M. Davis, A.S. Lucas, G. Stucky de Quay, Persistence of intense, climate-driven runoff late in Mars history. *Sci. Adv.* (2019, in press)

- M.G. Kleinhans, Flow discharge and sediment transport models for estimating a minimum timescale of hydrological activity and channel and delta formation on Mars. *J. Geophys. Res.* **110**(E12), E12003 (2005)
- M.G. Kleinhans, H.E. van de Kastelee, E. Hauber, Palaeoflow reconstruction from fan delta morphology on Mars. *Earth Planet. Sci. Lett.* **294**(3–4), 378–392 (2010)
- A.H. Knoll, M. Carr, B. Clark, D.J. Des Marais, J.D. Farmer, W.W. Fischer, J.P. Grotzinger, S.M. McLennan, M. Malin, C. Schröder, S. Squyres, N.J. Tosca, T. Wdowiak, An astrobiological perspective on Meridiani Planum. *Earth Planet. Sci. Lett.* **240**(1), 179–189 (2005)
- A.H. Knoll, B.L. Jolliff, W.H. Farrand, J.F. Bell III, B.C. Clark, R. Gellert, M.P. Golombek, J.P. Grotzinger, K.E. Herkenhoff, J.R. Johnson, S.M. McLennan, R. Morris, S.W. Squyres, R. Sullivan, N.J. Tosca, A. Yen, Z. Lerner, Veneers, rinds, and fracture fills: relatively late alteration of sedimentary rocks at Meridiani Planum, Mars. *J. Geophys. Res.* **113**(E6), E06S16 (2008)
- W.C. Koeppen, V.E. Hamilton, Global distribution, composition, and abundance of olivine on the surface of Mars from thermal infrared data. *J. Geophys. Res.* **113**, E05001 (2008)
- R.K. Kopparapu, R. Ramirez, J.F. Kasting, V. Eymet, T.D. Robinson, S. Mahadevan, R.C. Terrien, S. Domagal-Goldman, V. Meadows, R. Deshpande, Habitable zones around main-sequence stars: new estimates. *Astrophys. J.* **765**(2), 131 (2013)
- E.R. Kraal, E. Asphaug, J.M. Moore, A. Howard, A. Brecht, Catalogue of large alluvial fans in Martian impact craters. *Icarus* **194**(1), 101–110 (2008a)
- E.R. Kraal, M. van Dijk, G. Postma, M.G. Kleinhans, Martian stepped-delta formation by rapid water release. *Nature* **451**(7181), 973–976 (2008b)
- T. Kurahashi-Nakamura, E. Tajika, Atmospheric collapse and transport of carbon dioxide into the subsurface on early Mars. *Geophys. Res. Lett.* **33**(18), L18205 (2006)
- H. Kurokawa, K. Kurosawa, T. Usui, A lower limit of atmospheric pressure on early Mars inferred from nitrogen and argon isotopic compositions. *Icarus* **299**, 443–459 (2018)
- M.P. Lamb, W.E. Dietrich, S.M. Aciego, D.J. DePaolo, M. Manga, Formation of Box Canyon, Idaho, by megaflood: implications for Seepage Erosion on Earth and Mars. *Science* **320**(5879), 1067 (2008)
- M.P. Lamb, N.J. Finnegan, J.S. Scheingross, L.S. Sklar, New insights into the mechanics of fluvial bedrock erosion through flume experiments and theory. *Geomorphology* **244**, 33–55 (2015)
- H. Lammer, E. Chassefière, Ö. Karatekin, A. Morschhauser, P.B. Niles, O. Mousis, P. Odert, U.V. Möstl, D. Breuer, V. Dehant, M. Grott, H. Gröllner, E. Hauber, L.B.S. Pham, Outgassing history and escape of the Martian atmosphere and water inventory. *Space Sci. Rev.* **174**(1–4), 113–154 (2013)
- M.G.A. Lapôtre, M.P. Lamb, Substrate controls on valley formation by groundwater on Earth and Mars. *Geology* **46**(6), 531–534 (2018)
- M.G.A. Lapôtre, R.C. Ewing, M.P. Lamb et al., Large wind ripples on Mars: a record of atmospheric evolution. *Science* **353**(6294), 55–58 (2016)
- L. Le Deit, J. Flahaut, C. Quantin, E. Hauber, D. Mège, O. Bourgeois, J. Gurgurewicz, M. Massé, R. Jaumann, Extensive surface pedogenic alteration of the Martian Noachian crust suggested by plateau phyllosilicates around Valles Marineris. *J. Geophys. Res.* **117**, E00J05 (2012)
- H.J. Leask, L. Wilson, K.L. Mitchell, Formation of Mangala Valles outflow channel, Mars: morphological development and water discharge and duration estimates. *J. Geophys. Res.* **112**(E8), E08003 (2007)
- E.K. Leask, B.L. Ehlmann, M.M. Dundar, S.L. Murchie, F.P. Seelos, Challenges in the search for perchlorate and other hydrated minerals with 2.1- μm absorptions on Mars. *Geophys. Res. Lett.* **45**, 12180–12189 (2018)
- C.O. Lee, B.M. Jakosky, J.G. Luhmann, D.A. Brain, M.L. Mays, D.M. Hassler, M. Holmström, D.E. Larson, D.L. Mitchell, C. Mazelle, J.S. Halekas, Observations and impacts of the 10 September 2017 solar events at Mars: an overview and synthesis of the initial results. *Geophys. Res. Lett.* **45**, 8871–8885 (2018)
- A. Lefort, D.M. Burr, R.A. Beyer, A.D. Howard, Inverted fluvial features in the Aeolis-Zephyria plana, western Medusae Fossae formation, Mars: evidence for post-formation modification. *J. Geophys. Res.* **117**(E3), E03007 (2012)
- K.W. Lewis, O. Aharonson, Stratigraphic analysis of the distributary fan in Eberswalde Crater using stereo imagery. *J. Geophys. Res.* **111**(E6), E06001 (2006)
- K.W. Lewis, O. Aharonson, Occurrence and origin of rhythmic sedimentary rocks on Mars. *J. Geophys. Res., Planets* **119**(6), 1432–1457 (2014)
- K.W. Lewis, O. Aharonson, J.P. Grotzinger et al., Quasi-periodic bedding in the sedimentary rock record of Mars. *Science* **322**(5907), 1532–1535 (2008)
- C. Li, M.J. Czapiga, E.C. Eke, E. Viparelli, G. Parker, Variable shields number model for river bankfull geometry: bankfull shear velocity is viscosity-dependent but grain size-independent. *J. Hydraul. Res.* **53**, 36–48 (2015)
- R.J. Lillis, S. Robbins, M. Manga, J.S. Halekas, H.V. Frey, Time history of the Martian dynamo from crater magnetic field analysis. *J. Geophys. Res., Planets* **118**(7), 1488–1511 (2013)

- R.J. Lillis, D.A. Brain, S.W. Bougher, F. Leblanc, J.G. Luhmann, B.M. Jakosky, R. Modolo, J. Fox, J. Deighan, X. Fang, Y.C. Wang, Y. Lee, C. Dong, Y. Ma, T. Cravens, L. Andersson, S.M. Curry, N. Schneider, M. Combi, I. Stewart, J. Clarke, J. Grebowsky, D.L. Mitchell, R. Yelle, A.F. Nagy, D. Baker, R.P. Lin, Characterizing atmospheric escape from Mars today and through time, with MAVEN. *Space Sci. Rev.* **195**(1–4), 357–422 (2015)
- R.J. Lillis, J. Deighan, J.L. Fox, S.W. Bougher, Y. Lee, M.R. Combi, T.E. Cravens, A. Rahmati, P.R. Mahaffy, M. Benna, M.K. Elrod, J.P. McFadden, R.E. Ergun, L. Andersson, C.M. Fowler, B.M. Jakosky, E. Thiemann, F. Eparvier, J.S. Halekas, F. Leblanc, J.-Y. Chaufray, Photochemical escape of oxygen from Mars: first results from MAVEN in situ data. *J. Geophys. Res. Space Phys.* **122**, 3815–3836 (2017)
- D. Loizeau, S.C. Werner, N. Mangold, J.-P. Bibring, J.L. Vago, Chronology of deposition and alteration in the Mawrth Vallis region, Mars. *Planet. Space Sci.* **72**(1), 31–43 (2012)
- D. Loizeau, C. Quantin-Nataf, J. Carter, J. Flahaut, P. Thollot, L. Lozac'h, C. Millot, Quantifying widespread aqueous surface weathering on Mars: the plateaus south of Coprates Chasma. *Icarus* **302**, 451–469 (2018)
- J. Longhi, Phase equilibrium in the system CO₂-H₂O: application to Mars. *J. Geophys. Res.* **111**(E6), E06011 (2006)
- R. Lundin, S. Barabash, M. Holmström, H. Nilsson, Y. Futaana, R. Ramstad, M. Yamauchi, E. Dubinin, M. Fraenz, Solar cycle effects on the ion escape from Mars. *Geophys. Res. Lett.* **40**, 6028–6032r (2013)
- W. Luo, X. Cang, A.D. Howard, New Martian valley network estimate consistent with ancient ocean and warm and wet climate. *Nat. Commun.* **8**, 15766 (2017)
- R. Mahaffy, C.R. Webster, J.C. Stern et al., The imprint of atmospheric evolution in the D/H of Hesperian clay minerals on Mars. *Science* **347**(6220), 412–414 (2015)
- M.C. Malin, 1. Comparison of volcanic features of Elysium (Mars) and Tibesti (Earth). 2. Age of Martian channels. 3. Nature and origin of intercrater plains on Mars. Ph.D. Thesis, Caltech (1976)
- M.C. Malin, K.S. Edgett, Oceans or seas in the Martian northern lowlands: high resolution imaging tests of proposed coastlines. *Geophys. Res. Lett.* **26**(19), 3049–3052 (1999)
- M.C. Malin, K.S. Edgett, Sedimentary rocks of early Mars. *Science* **290**(5498), 1927–1937 (2000)
- M.C. Malin, K.S. Edgett, Evidence for persistent flow and aqueous sedimentation on early Mars. *Science* **302**(5652), 1931–1934 (2003)
- M.C. Malin, J.F. Bell, B.A. Cantor, M.A. Caplinger, W.M. Calvin, R.T. Clancy, K.S. Edgett, L. Edwards, R.M. Haberle, P.B. James, S.W. Lee, M.A. Ravine, P.C. Thomas, M.J. Wolff, Context camera investigation on board the Mars reconnaissance orbiter. *J. Geophys. Res.* **112**, E5, E05S04 (2007)
- M.C. Malin, K.S. Edgett, B.A. Cantor, M.A. Caplinger, G.E. Danielson, E.H. Jensen, M.A. Ravine, J.L. Sandoval, K.D. Sulpulver, An overview of the 1985–2006 Mars orbiter camera science investigation. *Mars Int. J. Mars Sci. Explor.* **4**, 1–60 (2010)
- M. Manga, A. Patel, J. Dufek, E.S. Kite, Wet surface and dense atmosphere on early Mars suggested by the bomb sag at Home Plate, Mars. *Geophys. Res. Lett.* **39**(1), L01202 (2012)
- N. Mangold, Fluvial landforms on fresh impact ejecta on Mars. *Planet. Space Sci.* **62**(1), 69–85 (2012)
- N. Mangold, C. Quantin, V. Ansan, C. Delacourt, P. Allemand, Evidence for precipitation on Mars from dendritic valleys in the Valles Marineris Area. *Science* **305**(5680), 78–81 (2004)
- N. Mangold, V. Ansan, Ph. Masson, C. Quantin, G. Neukum, Geomorphic study of fluvial landforms on the northern Valles Marineris plateau, Mars. *J. Geophys. Res.* **113**(E8), E08009 (2008)
- N. Mangold, S. Adeli, S. Conway, V. Ansan, B. Langlais, A chronology of early Mars climatic evolution from impact crater degradation. *J. Geophys. Res.* **117**(E4), E04003 (2012)
- N. Mangold et al., Chemical alteration of fine-grained sedimentary rocks at Gale crater. *Icarus* **321**, 619–631 (2019)
- C.V. Manning, C.P. McKay, K.J. Zahnle, Thick and thin models of the evolution of carbon dioxide on Mars. *Icarus* **180**(1), 38–59 (2006)
- C.V. Manning, C. Bierson, N.E. Putzig, C.P. McKay, The formation and stability of buried polar CO₂ deposits on Mars. *Icarus* **317**, 509–517 (2019)
- M. Mansfield, E.S. Kite, M.A. Mischna, Effect of Mars atmospheric loss on snow melt potential in a 3.5 Gyr Mars climate evolution model. *J. Geophys. Res., Planets* **123**(4), 794–806 (2018)
- P.E. Marcelo Garcia, *Sedimentation Engineering: Processes, Measurements, Modeling, and Practice*. MOP, vol. 110 (American Society of Civil Engineers, Reston, 2008). ISBN 978-0-7844-0814-8
- E. Martin, K.A. Farley, M.B. Baker, C.A. Malespin, S. Schwenzer, B.A. Cohen, R. Mahaffy, A.C. McAdam, D.W. Ming, M. Vasconcelos, R. Navarro-González, A two-step K-Ar experiment on Mars: dating the diagenetic formation of jarosite from Amazonian groundwaters. *J. Geophys. Res., Planets* (2017). <https://doi.org/10.1002/2017JE005445>
- H. Masursky, An overview of geological results from Mariner 9. *J. Geophys. Res.* **78**, 4009–4030 (1973)
- Y. Matsubara, A.D. Howard, S.A. Drummond, Hydrology of early Mars: lake basins. *J. Geophys. Res.* **116**(E4), E04001 (2011)

- Y. Matsubara, A.D. Howard, R.P. Irwin, Constraints on the Noachian paleoclimate of the Martian highlands from landscape evolution modeling. *J. Geophys. Res.* **123**(11) (2018). <https://doi.org/10.1029/2018JE005572>
- T.J. McCoy, M. Sims, M.E. Schmidt, L. Edwards, L.L. Tornabene, L.S. Crumpler, B.A. Cohen, L.A. Soderblom, D.L. Blaney, S.W. Squyres, R.E. Arvidson, J.W. Rice, E. Tréguier, C. d'Uston, J.A. Grant, H.Y. McSween, M.P. Golombek, A.F.C. Haldemann, P.A. de Souza, Structure, stratigraphy, and origin of Husband Hill, Columbia Hills, Gusev Crater, Mars. *J. Geophys. Res.* **113**, E6, E06S03 (2008)
- F.M. McCubbin, J.W. Boyce, T. Novák-Szabó, A.R. Santos, R. Tartèse, N. Muttik, G. Domokos, J. Vazquez, L.P. Keller, D.E. Moser, D.J. Jerolmack, C.K. Shearer, A. Steele, S.M. Elardo, Z. Rahman, M. Anand, T. Delhaye, C.B. Agee, Geologic history of Martian regolith breccia northwest Africa 7034: evidence for hydrothermal activity and lithologic diversity in the Martian crust. *J. Geophys. Res., Planets* **121**(10), 2120–2149 (2016)
- A.S. McEwen, E.M. Eliason, J.W. Bergstrom, N.T. Bridges, C.J. Hansen, W.A. Delamere, J.A. Grant, V.C. Gulick, K.E. Herkenhoff, L. Keszthelyi, R.L. Kirk, M.T. Mellon, S.W. Squyres, N. Thomas, C.M. Weitz, Mars Reconnaissance Orbiter's High Resolution Imaging Science Experiment (HiRISE). *J. Geophys. Res.* **112**, E5, E05S02 (2007)
- A. McEwen, J. Grant, J. Mustard, J. Wray, L. Tornabene, Early Noachian rocks in megabreccia deposits on Mars, in *European Planetary Science Congress*, 14–18 September, 2009, Potsdam, Germany (2009), p. 504. <http://meetings.copernicus.org/epsc2009>
- I.O. McGlynn, C.M. Fedo, H.Y. McSween Jr., Soil mineralogy at the Mars Exploration Rover landing sites: an assessment of the competing roles of physical sorting and chemical weathering. *J. Geophys. Res.* **117**(E1), E01006 (2012)
- C.P. McKay, R.A. Wharton Jr., S.W. Squyres, G.D. Clow, Thickness of ice on perennially frozen lakes. *Nature* **313**, 561–562 (1985)
- C.P. McKay, D.T. Andersen, W.H. Pollard, J.L. Heldmann, P.T. Doran, C.H. Fritsen, J.C. Prisco, Polar lakes, streams, and springs as analogs for the hydrological cycle on Mars, in *Water on Mars and Life* (Springer, Berlin, 2005), pp. 219–233
- S.M. McLennan, Geochemistry of sedimentary processes on Mars, in *Sedimentary Geology of Mars*, ed. by Grotzinger, Milliken. SEPM Special Publication, vol. 102 (SEPM, McLean, 2012), pp. 119–138. ISBN 978-1-56576-312-8
- S.M. McLennan, J.P. Grotzinger, The sedimentary rock cycle of Mars, in *The Martian Surface—Composition, Mineralogy, and Physical Properties*, ed. by J Bell III (Cambridge University Press, Cambridge, 2008), p. 541. ISBN 9780521866989
- S.M. McLennan, J.F. Bell, W.M. Calvin, P.R. Christensen, B.C. Clark, P.A. de Souza, J. Farmer, W.H. Farrand, D.A. Fike, R. Gellert, A. Ghosh, T.D. Glotch, J.P. Grotzinger, B. Hahn, K.E. Herkenhoff, J.A. Hurowitz, J.R. Johnson, S.S. Johnson, B. Jolliff, G. Klingelhöfer, A.H. Knoll, Z. Learner, M.C. Malin, H.Y. McSween, J. Pockock, S.W. Ruff, L.A. Soderblom, S.W. Squyres, N.J. Tosca, W.A. Watters, M.B. Wyatt, A. Yen, Provenance and diagenesis of the evaporite-bearing Burns formation, Meridiani Planum, Mars. *Earth Planet. Sci. Lett.* **240**, 95–121 (2005)
- S.M. McLennan, R.B. Anderson, J.F. Bell III et al., Elemental geochemistry of sedimentary rocks at Yellowknife bay, Gale Crater, Mars. *Science* **343**(6169), 1244734 (2014)
- S.M. McLennan, J.P. Grotzinger, J.A. Hurowitz, N.J. Tosca, The sedimentary cycle on Early Mars. *Annu. Rev. Earth Planet. Sci.* **47** (2019). <https://doi.org/10.1146/annurev-earth-053018-060332>
- S. McMahon, T. Bosak, J.P. Grotzinger, R.E. Milliken, R.E. Summons, M. Daye, S.A. Newman, A. Fraeman, K.H. Williford, D.E.G. Briggs, A field guide to finding fossils on Mars. *J. Geophys. Res., Planets* (2018). <https://doi.org/10.1029/2017JE005478>
- M.T. Mellon, R.J. Phillips, Recent gullies on Mars and the source of liquid water. *J. Geophys. Res.* **106**(E10), 23165–23180 (2001)
- J. Melosh, *Planetary Surface Processes* (Cambridge University Press, Cambridge, 2009)
- M. Melwani Daswani, E.S. Kite, Paleohydrology on Mars constrained by mass balance and mineralogy of pre-Amazonian sodium chloride lakes: deep groundwater not required. *J. Geophys. Res., Planets* **122**, 1802–1823 (2017). <https://doi.org/10.1002/2017JE005319>
- MEPAG, Mars Scientific Goals, Objectives, Investigations, and Priorities: 2018. D. Banfield, ed., 81 p. white paper posted October, 2018 by the Mars Exploration Program Analysis Group (MEPAG) at <https://mepag.jpl.nasa.gov/reports.cfm> (2018)
- J.M. Metz, J.P. Grotzinger, D.M. Rubin, K.W. Lewis, S.W. Squyres, J.F. Bell, Sulfate-rich Eolian and wet interdune deposits, Erebus Crater, Mars. *J. Sediment. Res.* **79**, 247–264 (2009a)
- J. Metz, J. Grotzinger, D. Mohrig, R. Milliken, B. Prather, C. Pirmez, A.S. McEwen, C. Weitz, Sublacustrine depositional fans in southwest Melas Chasma. *J. Geophys. Res.* **114**(E10), E10002 (2009b)
- G.G. Michael, Planetary surface dating from crater size-frequency distribution measurements: multiple resurfacing episodes and differential isochron fitting. *Icarus* **226**(1), 885–890 (2013)

- J.R. Michalski, J. Cuadros, J.L. Bishop, M. Darby Dyar, V. Dekov, S. Fiore, Constraints on the crystal-chemistry of Fe/Mg-rich smectitic clays on Mars and links to global alteration trends. *Earth Planet. Sci. Lett.* **427**, 215–225 (2015)
- J.A. Mikucki, E. Auken, S. Tulaczyk, R.A. Virginia, C. Schamper, K.I. Sørensen, P.T. Doran, H. Dugan, N. Foley, Deep groundwater and potential subsurface habitats beneath an Antarctic dry valley. *Nat. Commun.* **6**, 6831 (2015)
- R.E. Milliken, D.L. Bish, Sources and sinks of clay minerals on Mars. *Philos. Mag.* **90**(17), 2293–2308 (2010)
- R.E. Milliken, R.C. Ewing, W.W. Fischer, J. Hurowitz, Wind-blown sandstones cemented by sulfate and clay minerals in Gale Crater, Mars. *Geophys. Res. Lett.* **41**(4), 1149–1154 (2014)
- J.D. Milliman, J.P.M. Syvitski, Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. *J. Geol.* **100**, 525–544 (1992)
- D.W. Ming, D.W. Mittlefehldt, R.V. Morris, D.C. Golden, R. Gellert, A. Yen, B.C. Clark, S.W. Squyres, W.H. Farrand, S.W. Ruff, R.E. Arvidson, G. Klingelhöfer, H.Y. McSween, D.S. Rodionov, C. Schröder, P.A. de Souza, A. Wang, Geochemical and mineralogical indicators for aqueous processes in the Columbia Hills of Gusev Crater, Mars. *J. Geophys. Res.* **111**, E2, E02S12 (2006)
- M.A. Mischna, M.I. Richardson, A reanalysis of water abundances in the Martian atmosphere at high obliquity. *Geophys. Res. Lett.* **32**(3), L03201 (2005)
- M.A. Mischna, V. Baker, R. Milliken, M. Richardson, C. Lee, Effects of obliquity and water vapor/trace gas greenhouses in the early Martian climate. *J. Geophys. Res., Planets* **118**(3), 560–576 (2013)
- Z.M. Moratto, M.J. Broxton, R.A. Beyer, M. Lundy, K. Husmann, Ames stereo pipeline, NASA's open source automated stereogrammetry software, in *41st Lunar and Planetary Science Conference*, March 1–5, 2010, The Woodlands, Texas. LPI Contribution, vol. 1533 (2010), p. 2364
- A.M. Morgan, A.D. Howard, D.E.J. Hobbey, J.M. Moore, W.E. Dietrich, R.M.E. Williams, D.M. Burr, J.A. Grant, S.A. Wilson, Y. Matsubara, Sedimentology and climatic environment of alluvial fans in the Martian Saheki Crater and a comparison with terrestrial fans in the Atacama Desert. *Icarus* **229**, 131–156 (2014)
- A.M. Morgan, S.A. Wilson, A.D. Howard, R.A. Craddock, J.A. Grant, Global distribution of alluvial fans and deltas on Mars, in *49th Lunar and Planetary Science Conference*, 19–23 March, 2018, The Woodlands, Texas. LPI Contribution, vol. 2083 (2018), p. 2219
- S. Murchie, L. Roach, F. Seelos, R. Milliken, J. Mustard, R. Arvidson, S. Wiseman, K. Lichtenberg, J. Andrews-Hanna, J. Bishop, J.-P. Bibring, M. Parente, R. Morris, Evidence for the origin of layered deposits in Candor Chasma, Mars, from mineral composition and hydrologic modeling. *J. Geophys. Res.* **114**(E12), E00D05 (2009)
- J.F. Mustard, M. Adler, A. Allwood, D.S. Bass, D.W. Beaty, J.F. Bell III, W.B. Brinckerhoff, M. Carr, D.J. Des Marais, B. Drake, K.S. Edgett, J. Eigenbrode, L.T. Elkins-Tanton, J.A. Grant, S.M. Milkovich, D. Ming, C. Moore, S. Murchie, T.C. Onstott, S.W. Ruff, M.A. Sephton, A. Steele, A. Treiman, Report of the Mars 2020 Science Definition Team, 154, posted July, 2013, by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/MEP/Mars_2020_SDT_Report_Final.pdf
- M. Nachon, N. Mangold, O. Forni, L.C. Kah, A. Cousin, R.C. Wiens, R. Anderson, D. Blaney, J.G. Blank, F. Calef, S.M. Clegg, C. Fabre, M.R. Fisk, O. Gasnault, J.P. Grotzinger, R. Kronyak, N.L. Lanza, J. Lasue, L. Le Deit, S. Le Mouélic, S. Maurice, P.-Y. Meslin, D.Z. Oehler, V. Payré, W. Rapin, S. Schröder, K. Stack, D. Sumner, Chemistry of diagenetic features analyzed by ChemCam at Pahrump Hills, Gale Crater, Mars. *Icarus* **281**, 121–136 (2017). <https://doi.org/10.1016/j.icarus.2016.08.026>
- A.A. Nemchin, M. Humayun, M.J. Whitehouse et al., Record of the ancient Martian hydrosphere and atmosphere preserved in zircon from a Martian meteorite. *Nat. Geosci.* **7**(9), 638–642 (2014)
- B. Niles, J. Michalski, Meridiani Planum sediments on Mars formed through weathering in massive ice deposits. *Nat. Geosci.* **2**(3), 215–220 (2009)
- P.B. Niles, M.Y. Zolotov, L.A. Leshin, Insights into the formation of Fe- and Mg-rich aqueous solutions on early Mars provided by the ALH 84001 carbonates. *Earth Planet. Sci. Lett.* **286**(1–2), 122–130 (2009)
- P.B. Niles, D.C. Catling, G. Berger, E. Chassefière, B.L. Ehlmann, J.R. Michalski, R. Morris, S.W. Ruff, B. Sutter, Geochemistry of carbonates on Mars: implications for climate history and nature of aqueous environments. *Space Sci. Rev.* **174**(1–4), 301–328 (2013)
- B. Niles, J. Michalski, D.W. Ming, D.C. Golden, Elevated olivine weathering rates and sulfate formation at cryogenic temperatures on Mars. *Nat. Commun.* **8**, 998 (2017)
- A. Ody et al., Global investigation of olivine on Mars. *J. Geophys. Res.* **118**, 234–262 (2013)
- C.H. Okubo, A.S. McEwen, Fracture-controlled paleo-fluid flow in Candor Chasma, Mars. *Science* **315**(5814), 983 (2007)
- A.A. Olsen, J.D. Rimstidt, Using a mineral lifetime diagram to evaluate the persistence of olivine on Mars. *Am. Mineral.* **92**(4), 598–602 (2007)

- T.C. Onstott, B.L. Ehlmann, H. Sapers, M. Coleman, M. Ivarsson, J.J. Marlow, A. Neubeck, P. Niles, Paleo-rock-hosted life on Earth and the search on Mars: a review and strategy for exploration (2018). [arXiv:1809.08266](https://arxiv.org/abs/1809.08266)
- V. Orofino, G. Alemanno, G. Di Achille, F. Mancarella, Estimate of the water flow duration in large Martian fluvial systems. *Planet. Space Sci.* (2018). <https://doi.org/10.1016/j.pss.2018.06.001>
- M.M. Osterloo, F.S. Anderson, V.E. Hamilton, B.M. Hynek, Geologic context of proposed chloride-bearing materials on Mars. *J. Geophys. Res.* **115**(E10), E10012 (2010)
- M.C. Palucis, W.E. Dietrich, A.G. Hayes, R.M.E. Williams, S. Gupta, N. Mangold, H. Newsom, C. Hardgrove, F. Calef, D.Y. Sumner, The origin and evolution of the Peace Vallis fan system that drains to the Curiosity landing area, Gale Crater, Mars. *J. Geophys. Res.*, *Planets* **119**(4), 705–728 (2014)
- M.C. Palucis, W.E. Dietrich, R.M.E. Williams, A.G. Hayes, T. Parker, D.Y. Sumner, N. Mangold, K. Lewis, H. Newsom, Sequence and relative timing of large lakes in Gale Crater (Mars) after the formation of Mount Sharp. *J. Geophys. Res.*, *Planets* **121**(3), 472–496 (2016)
- A.M. Palumbo, J.W. Head, Early Mars climate history: characterizing a “warm and wet” martian climate with a 3-D global climate model and testing geological predictions. *Geophys. Res. Lett.* **45**, 10,249–10,258 (2018). <https://doi.org/10.1029/2018GL079767>
- T.J. Parker, D.S. Gorsline, R.S. Saunders, D.C. Pieri, D.M. Schneeberger, Coastal geomorphology of the Martian northern plains. *J. Geophys. Res.* **98**(E6), 11,061–11,078 (1993)
- G. Parker, P. Wilcock, C. Paola, W.E. Dietrich, J. Pitlick, Physical basis for quasi-universal relations describing bankfull hydraulic geometry of single-thread gravel bed rivers. *J. Geophys. Res.*, *Earth Surf.* **112**(F4), F04005 (2007)
- J.C. Penido, C.I. Fassett, S.M. Som, Scaling relationships and concavity of small valley networks on Mars. *Planet. Space Sci.* **75**, 105–116 (2013)
- T.S. Peretyazhko, B. Niles, B. Sutter, R.V. Morris, D.G. Agresti, L. Le, D.W. Ming, Smectite formation in the presence of sulfuric acid: implications for acidic smectite formation on early Mars. *Geochim. Cosmochim. Acta* **220**, 248–260 (2018)
- J.T. Perron, J.X. Mitrovica, M. Manga, I. Matsuyama, M.A. Richards, Evidence for an ancient Martian ocean in the topography of deformed shorelines. *Nature* **447**(7146), 840–843 (2007)
- G.H. Peters, E.M. Carey, R.C. Anderson, W.J. Abbey, R. Kinnett, J.A. Watkins, M. Schemel, M.O. Lashore, M.D. Chasek, W. Green, L.W. Beegle, A.R. Vasavada, Uniaxial compressive strengths of rocks drilled at Gale Crater, Mars. *Geophys. Res. Lett.* **45**(1), 108–116 (2018)
- R.C. Peterson, W. Nelson, B. Madu, H.F. Shurvell, Meridianiite: a new mineral species observed on Earth and predicted to exist on Mars. *Am. Mineral.* **92**, 1756–1759 (2007)
- A.M. Pfeiffer, N.J. Finnegan, J.K. Willenbring, Sediment supply controls equilibrium channel geometry in gravel rivers. *Proc. Natl. Acad. Sci.* **114**(13), 3346–3351 (2017)
- L.B.S. Pham, Ö. Karatekin, Scenarios of atmospheric mass evolution on Mars influenced by asteroid and comet impacts since the late Noachian. *Planet. Space Sci.* **125**, 1–11 (2016)
- R.J. Phillips, B.J. Davis, K.L. Tanaka et al., Massive CO₂ ice deposits sequestered in the South polar layered deposits of Mars. *Science* **332**, 838–841 (2011)
- W.T. Pike, U. Staufer, M.H. Hecht, W. Goetz, D. Parrat, H. Sykulka-Lawrence, S. Vijendran, M.B. Madsen, Quantification of the dry history of the Martian soil inferred from in situ microscopy. *Geophys. Res. Lett.* **38**(24), L24201 (2011)
- J.T. Pitman et al., Remote sensing space science enabled by the multiple instrument distributed aperture sensor (MIDAS) concept, in *Proceedings 5555, Instruments, Methods, and Missions for Astrobiology VIII, Optical Science and Technology, the SPIE 49th Annual Meeting 2004*, Denver, Colorado, United States (2004). <https://doi.org/10.1117/12.560290>
- J.B. Pollack, J.F. Kasting, S.M. Richardson, K. Poliakoff, The case for a wet, warm climate on early Mars. *Icarus* **71**, 203–224 (1987)
- C. Quantin-Nataf, R.A. Craddock, F. Dubuffet, L. Lozac’h, M. Martinot, Decline of crater obliteration rates during early Martian history. *Icarus* **317**, 427–433 (2019)
- R.M. Ramirez, A warmer and wetter solution for early Mars and the challenges with transient warming. *Icarus* **297**, 71–82 (2017)
- R.M. Ramirez, R.A. Craddock, The geological and climatological case for a warmer and wetter early Mars. *Nat. Geosci.* **11**(4), 230–237 (2018)
- R.M. Ramirez, J.F. Kasting, Could cirrus clouds have warmed early Mars? *Icarus* **281**, 248–261 (2017)
- R.M. Ramirez, R. Koppaapu, M.E. Zegger, T.D. Robinson, R. Freedman, J.F. Kasting, Warming early Mars with CO₂ and H₂. *Nat. Geosci.* **7**(1), 59–63 (2014)
- E.B. Rampe, D.W. Ming, D.F. Blake, T.F. Bristow, S.J. Chipera, J.P. Grotzinger, R.V. Morris, S.M. Morrison, D.T. Vaniman, A.S. Yen, C.N. Achilles, P.I. Craig, D.J. Des Marais, R.T. Downs, J.D. Farmer, K.V. Fendrich, R. Gellert, R.M. Hazen, L.C. Kah, J.M. Morookian, T.S. Peretyazhko, P. Sarrazin, A.H. Treiman, J.A. Berger, J. Eigenbrode, A.G. Fairén, O. Forni, S. Gupta, J.A. Hurowitz, N.L. Lanza, M.E.

- Schmidt, K. Siebach, B. Sutter, L.M. Thompson, Mineralogy of an ancient lacustrine mudstone succession from the Murray formation, Gale Crater, Mars. *Earth Planet. Sci. Lett.* **471**, 172–185 (2017)
- R. Ramstad, S. Barabash, Y. Futaana, H. Nilsson, M. Holmström, Ion escape from Mars through time: an extrapolation of atmospheric loss based on 10 years of Mars Express measurements. *J. Geophys. Res., Planets* **123**, 3051–3060 (2018)
- M.H. Reed, Hydrothermal alteration and its relationship to ore fluid composition, in *Geochemistry of Hydrothermal Ore Deposits*, vol. 3 (1997), pp. 303–365
- F. Rivera-Hernandez, D.Y. Sumner, T.J. Mackey, I. Hawes, D.T. Andersen, In a PICL: the sedimentary deposits and facies of perennially ice-covered lakes. *Sedimentology* (2018). <https://doi.org/10.1111/sed.12522>
- S.J. Robbins, New crater calibrations for the lunar crater-age chronology. *Earth Planet. Sci. Lett.* **403**, 188–198 (2014)
- S.J. Robbins, B.M. Hynek, R.J. Lillis, W.F. Bottke, Large impact crater histories of Mars: the effect of different model crater age techniques. *Icarus* **225**(1), 173–184 (2013)
- S.J. Robbins et al., Revised recommended methods for analyzing crater size-frequency distributions. *Meteorit. Planet. Sci.* **53**, 891–931 (2018)
- J.A.P. Rodriguez, A.G. Fairén, K.L. Tanaka, M. Zarroca, R. Linares, T. Platz, G. Komatsu, H. Miyamoto, J.S. Kargel, J. Yan, V. Gulick, K. Higuchi, V.R. Baker, N. Glines, Tsunami waves extensively resurfaced the shorelines of an early Martian ocean. *Sci. Rep.* **6**, 25106 (2016)
- E.N. Rosenberg, J.W. Head III, Late Noachian fluvial erosion on Mars: cumulative water s required to carve the valley networks and grain size of bed-sediment. *Planet. Space Sci.* **117**, 429–435 (2015)
- E.N. Rosenberg, A.M. Palumbo, J.P. Cassanelli, J.W. Head, D.K. Weiss, *Icarus* **317**, 379–387 (2019)
- S.W. Ruff, V.E. Hamilton, Wishstone to watchtower: amorphous alteration of plagioclase-rich rocks in Gusev Crater, Mars. *Am. Mineral.* **102**(2), 235–251 (2017)
- S.W. Ruff, P.B. Niles, F. Alfano, A.B. Clarke, Evidence for a Noachian-aged ephemeral lake in Gusev Crater, Mars. *Geology* **42**(4), 359–362 (2014)
- M.R. Salvatore, R. Christensen, On the origin of the Vastitas Borealis formation in Chryse and Acidalia Planitiae, Mars. *J. Geophys. Res.* **119**, 2437–2456 (2014). <https://doi.org/10.1029/2014JE004682>
- M.R. Salvatore, J.F. Mustard, J.W. Head, A.D. Rogers, R.F. Cooper, The dominance of cold and dry alteration processes on recent Mars, as revealed through pan-spectral orbital analyses. *Earth Planet. Sci. Lett.* **404**, 261–272 (2014)
- K.E. Scanlon, J.W. Head III, J.L. Fastook, R.D. Wordsworth, The Dorsa Argentea formation and the Noachian-Hesperian climate transition. *Icarus* **299**, 339–363 (2018)
- J.M. Scheidegger, V.F. Bense, Impacts of glacially recharged groundwater flow systems on talik evolution. *J. Geophys. Res., Earth Surf.* **119**(4), 758–778 (2014)
- J. Schieber, D. Bish, M. Coleman, M. Reed, E.M. Hausrath, J. Cosgrove, S. Gupta, M.E. Minitti, K.S. Edgett, M. Malin, Encounters with an unearthy mudstone: understanding the first mudstone found on Mars. *Sedimentology* **64**(2), 311–358 (2017)
- T.L. Segura, O.B. Toon, A. Colaprete, Modeling the environmental effects of moderate-sized impacts on Mars. *J. Geophys. Res.* **113**(E11), E11007 (2008)
- T.L. Segura, K. Zahnle, O.B. Toon, C.P. McKay, The effects of impacts on the climates of terrestrial planets, in *Comparative Climatology of Terrestrial Planets*, vol. 610, ed. by S.J. Mackwell, A.A. Simon-Miller, J.W. Harder, M.A. Bullock (University of Arizona Press, Tucson, 2013), pp. 417–437
- R. Shaheen, B. Niles, K. Chong et al., Carbonate formation events in ALH 84001 trace the evolution of the Martian atmosphere. *Proc. Natl. Acad. Sci.* **112**, 336–341 (2015)
- K.L. Siebach, J.P. Grotzinger, L.C. Kah, K.M. Stack, M. Malin, R. Léveillé, D.Y. Sumner, Subaqueous shrinkage cracks in the Sheepbed mudstone: implications for early fluid diagenesis, Gale Crater, Mars. *J. Geophys. Res., Planets* **119**(7), 1597–1613 (2014)
- K.L. Siebach, M.B. Baker, J.P. Grotzinger, S.M. McLennan, R. Gellert, L.M. Thompson, J.A. Hurowitz, Sorting out compositional trends in sedimentary rocks of the Bradbury group (Aeolis Palus), Gale Crater, Mars. *J. Geophys. Res., Planets* **122**(2), 295–328 (2017)
- M.D. Smith, The annual cycle of water vapor as observed by the thermal emission spectrometer. *J. Geophys. Res.* **107**, 1–19 (2002). <https://doi.org/10.1029/2001JE001522>
- D.E. Smith, M.T. Zuber, S.C. Solomon, R.J. Phillips, J.W. Head, J.B. Garvin, W.B. Banerdt, D.O. Muhleman, G.H. Pettengill, G.A. Neumann et al., The global topography of Mars and implications for surface evolution. *Science* **284**, Iss. 5419, 1495 (1999)
- D.E. Smith, M.T. Zuber, H.V. Frey, J.B. Garvin, J.W. Head, D.O. Muhleman, G.H. Pettengill, R.J. Phillips, S.C. Solomon, H.J. Zwally, W.B. Banerdt, T.C. Duxbury, M.P. Golombek, F.G. Lemoine, G.A. Neumann, D.D. Rowlands, O. Aharonson, P.G. Ford, A.B. Ivanov, C.L. Johnson, P.J. McGovern, J.B. Abshire, R.S. Afzal, X. Sun, Mars orbiter laser altimeter: experiment summary during the first year of global mapping of Mars. *J. Geophys. Res.* **106**(E10), 23689–23722 (2001)

- S.M. Som, D.R. Montgomery, H.M. Greenberg, Scaling relations for large Martian valleys. *J. Geophys. Res.* **114**(E2), E02005 (2009)
- A. Soto, M. Mischna, T. Schneider, C. Lee, M.I. Richardson, Martian atmospheric collapse: idealized GCM studies. *Icarus* **250**, 553–569 (2015)
- S.W. Squyres, Urey prize lecture—water on Mars. *Icarus* **79**, 229–288 (1989)
- S.W. Squyres, R.E. Arvidson, D.L. Blaney, B.C. Clark, L. Crumpler, W.H. Farrand, S. Gorevan, K.E. Herkenhoff, J. Hurowitz, A. Kusack, H.Y. McSween, D.W. Ming, R.V. Morris, S.W. Ruff, A. Wang, A. Yen, Rocks of the Columbia Hills. *J. Geophys. Res.* **111**, E2, E02S11 (2006)
- S.W. Squyres, R.E. Arvidson, S. Ruff, R. Gellert, R.V. Morris, D.W. Ming, L. Crumpler, J.D. Farmer, D.J. Des Marais, A. Yen, S.M. McLennan, W. Calvin, J.F. Bell, B.C. Clark, A. Wang, T.J. McCoy, M.E. Schmidt, P.A. de Souza, Detection of silica-rich deposits on Mars. *Science* **320**(5879), 1063 (2008)
- S.W. Squyres, A.H. Knoll, R.E. Arvidson, J.W. Ashley, J.F. Bell, W.M. Calvin, P.R. Christensen, B.C. Clark, B.A. Cohen, P.A. de Souza, L. Edgar, W.H. Farrand, I. Fleischer, R. Gellert, M.P. Golombek, J. Grant, J. Grotzinger, A. Hayes, K.E. Herkenhoff, J.R. Johnson, B. Jolliff, G. Klingelhöfer, A. Knudson, R. Li, T.J. McCoy, S.M. McLennan, D.W. Ming, D.W. Mittlefehldt, R.V. Morris, J.W. Rice, C. Schröder, R.J. Sullivan, A. Yen, R.A. Yingst, Exploration of Victoria Crater by the Mars Rover Opportunity. *Science* **324**(5930), 1058 (2009)
- K.M. Stack, C.S. Edwards, J.P. Grotzinger, S. Gupta, D.Y. Sumner, F.J. Calef, L.A. Edgar, K.S. Edgett, A.A. Fraeman, S.R. Jacob, L. Le Deit, K.W. Lewis, M.S. Rice, D. Rubin, R.M.E. Williams, K.H. Williford, Comparing orbiter and rover image-based mapping of an ancient sedimentary environment, Aeolis Palus, Gale crater, Mars. *Icarus* **280**, 3–21 (2016)
- K.E. Steakley, M.A. Kahre, J.R. Murphy, R.M. Haberle, A. Kling, Revisiting the impact heating hypothesis for early Mars with a 3D GCM, in *Fourth International Conference on Early Mars, Proceedings of the Conference*, 2–6 October, 2017, Flagstaff, Arizona. LPI Contribution, vol. 2014 (2017), p. 3074
- L. Steele, E.S. Kite, T.I. Michaels, Crater mound formation by wind erosion on Mars. *J. Geophys. Res., Planets* **123**, 113–130 (2018)
- N. Stein, J.P. Grotzinger, J. Schieber, N. Mangold, B. Hallet, H. Newsom, K.M. Stack, J.A. Berger, L. Thompson, K.L. Siebach, A. Cousin, S. Le Mouélic, M. Minitti, D.Y. Sumner, C. Fedo, C.H. House, S. Gupta, A.R. Vasavada, R. Gellert, R.C. Wiens, J. Frydenvang, O. Forni, P.Y.M.V. Payré, E. Dehouck, Desiccation cracks provide evidence of lake drying on Mars, Sutton Island member, Murray formation, Gale Crater. *Geology* **46**(6), 515–518 (2018)
- J.D. Stopar, G.J. Taylor, V.E. Hamilton, L. Browning, Kinetic model of olivine dissolution and extent of aqueous alteration on Mars. *Geochim. Cosmochim. Acta* **70**(24), 6136–6152 (2006)
- T. Swindle, A. Treiman, D. Lindstrom, M. Burckland, B. Cohen, J. Grier, B. Li, E. Olson, Noble gases in iddingsite from the lafayette meteorite: evidence for liquid water on Mars in the last few hundred million years. *Meteorit. Planet. Sci.* **35**(1), 107–115 (2000)
- K.L. Tanaka, S.J. Robbins, C.M. Fortezzo, J.A. Skinner, T.M. Hare, The digital global geologic map of Mars. *Planet. Space Sci.* **95**, 11–24 (2014)
- S.R. Taylor, S. McLennan, *Planetary Crusts: Their Composition, Origin and Evolution* (Cambridge University Press, Cambridge, 2009)
- G.J. Taylor et al., Causes of variations in K/Th on Mars. *J. Geophys. Res.* **111**, E03S06 (2006). <https://doi.org/10.1029/2006JE002676>
- L.M. Thompson, M.E. Schmidt, J.G. Spray, J.A. Berger, A.G. Fairén, J.L. Campbell, G.M. Perrett, N. Boyd, R. Gellert, I. Pradler, S.J. VanBommel, Potassium-rich sandstones within the Gale impact crater, Mars: the APXS perspective. *J. Geophys. Res., Planets* **121**(10), 1981–2003 (2016)
- B.J. Thomson, N.T. Bridges, J. Cohen, J.A. Hurowitz, A. Lennon, G. Paulsen, K. Zaczyny, Estimating rock compressive strength from Rock Abrasion Tool (RAT) grinds. *J. Geophys. Res., Planets* **118**(6), 1233–1244 (2013)
- F. Tian, M.W. Claire, J.D. Haqq-Misra, M. Smith, D.C. Crisp, D. Catling, K. Zahnle, J.F. Kasting, Photochemical and climate consequences of sulfur outgassing on early Mars. *Earth Planet. Sci. Lett.* **295**, 412–418 (2010)
- J.D. Toner, D.C. Catling, R.S. Sletten, The geochemistry of Don Juan Pond: evidence for a deep groundwater flow system in Wright Valley, Antarctica. *Earth Planet. Sci. Lett.* **474**, 190–197 (2017)
- O.B. Toon, J.B. Pollack, W. Ward, J.A. Burns, K. Bilski, The astronomical theory of climatic change on Mars. *Icarus* **44**(3), 552–607 (1980). [https://doi.org/10.1016/0019-1035\(80\)90130-X](https://doi.org/10.1016/0019-1035(80)90130-X)
- O.B. Toon, T. Segura, K. Zahnle, The formation of Martian river valleys by impacts. *Annu. Rev. Earth Planet. Sci.* **38**, 303–322 (2010)
- N.J. Tosca, A.H. Knoll, Juvenile chemical sediments and the long term persistence of water at the surface of Mars. *Earth Planet. Sci. Lett.* **286**(3–4), 379–386 (2009)
- N.J. Tosca, A.H. Knoll, S.M. McLennan, Water activity and the challenge for life on early Mars. *Science* **320**(5880), 1204 (2008)

- N.J. Tosca, I.A.M. Ahmed, B.M. Tutolo, A. Ashpitel, J.A. Hurowitz, Magnetite authigenesis and the warming of early Mars. *Nat. Geosci.* **11**, 635–639 (2018)
- N.J. Tosca, I.A.M. Ahmed, B.M. Tutolo, A. Ashpitel, J.A. Hurowitz, Magnetite authigenesis and the warming of early Mars. *Nat. Geosci.* **11**, 635–639 (2018)
- M. Turbet, H. Tran, Comment on “Radiative transfer in CO₂-rich atmospheres: 1. Collisional line mixing implies a colder early Mars”. *J. Geophys. Res., Planets* **122**(11), 2362–2365 (2017)
- M. Turbet, J. Leconte, F. Selsis, E. Bolmont, F. Forget, I. Ribas, S.N. Raymond, G. Anglada-Escudé, The habitability of Proxima Centauri b. II. Possible climates and observability. *Astron. Astrophys.* **596**, A112 (2016)
- M. Turbet, F. Forget, V. Svetsov, H. Tran, J.-M. Hartmann, O. Karatekin, C. Gillmann, O. Popova, J. Head, The environmental effect of meteoritic impacts on early Mars with a versatile 3-D global climate model, in *Fourth International Conference on Early Mars, Proceedings of the Conference*, 2–6 October, 2017, Flagstaff, Arizona. LPI Contribution, vol. 2014, (2017a), p. 3062
- M. Turbet, F. Forget, J.W. Head, R. Wordsworth, 3D modelling of the climatic impact of outflow channel formation events on early Mars. *Icarus* **288**, 10–36 (2017b)
- R.A. Urata, O.B. Toon, Simulations of the Martian hydrologic cycle with a general circulation model: implications for the ancient Martian climate. *Icarus* **226**(1), 229–250 (2013)
- W. Van Berk, Y. Fu, J.-M. Ilger, Reproducing early Martian atmospheric carbon dioxide partial pressure by modeling the formation of Mg–Fe–Ca carbonate identified in the Comanche rock outcrops on Mars. *J. Geophys. Res.* **117**, E10008 (2012)
- D.T. Vaniman, G.M. Mart^Á-nez, E.B. Rampe, T.F. Bristow, D.F. Blake, A.S. Yen, D.W. Ming, W. Rapin, P.-Y. Meslin, J.M. Morookian, R.T. Downs, S.J. Chipera, R.V. Morris, S.M. Morrison, A.H. Treiman, C.H. Achilles, K. Robertson, J.P. Grotzinger, R.M. Hazen, R.C. Wiens, D.Y. Sumner, Gypsum, basanite, and anhydrite at Gale Crater, Mars. *Am. Mineral.* **103**(7), 1011–1020 (2018). <https://doi.org/10.2138/am-2018-6346>
- A.R. Vasavada, Our changing view of Mars. *Phys. Today* **70**(3), 34–41 (2017)
- A.R. Vasavada, T.J. Milavec, D.A. Paige, Microcraters on Mars—evidence for past climate variations. *J. Geophys. Res.* **98**(E2), 3469–3476 (1993)
- P. von Paris, A. Petau, J.L. Grenfell, E. Hauber, D. Breuer, R. Jaumann, H. Rauer, D. Tirsch, Estimating precipitation on early Mars using a radiative-convective model of the atmosphere and comparison with inferred runoff from geomorphology. *Planet. Space Sci.* **105**, 133–147 (2015)
- A. Wang, L.A. Haskin, S.W. Squyres, B.L. Jolliff, L. Crumpler, R. Gellert, C. Schröder, K. Herkenhoff, J. Hurowitz, N.J. Tosca, W.H. Farrand, R. Anderson, A.T. Knudson, Sulfate deposition in subsurface regolith in Gusev Crater, Mars. *J. Geophys. Res.* **111**, E2, E02S17 (2006)
- A. Wang, B.L. Jolliff, Y. Liu, K. Connor, Setting constraints on the nature and origin of the two major hydrous sulfates on Mars: monohydrated and polyhydrated sulfates. *J. Geophys. Res., Planets* **121**, 678–694 (2016)
- M.K. Ward, W.H. Pollard, A hydrohalite spring deposit in the Canadian high Arctic: a potential Mars analogue. *Earth Planet. Sci. Lett.* **504**, 126–138 (2018)
- N.H. Warner, M. Sowe, S. Gupta et al., Fill and spill of giant lakes in the eastern Valles Marineris region of Mars. *Geology* **41**, 675–678 (2013)
- N.H. Warner, S. Gupta, F. Calef, P. Grindrod, N. Boll, K. Goddard, Minimum effective area for high resolution crater counting of Martian terrains. *Icarus* **245**, 198–240 (2015)
- C.R. Webster, R. Mahaffy, G.J. Flesch et al., Isotope ratios of H, C, and O in CO₂ and H₂O of the Martian atmosphere. *Science* **341**(6143), 260–263 (2013)
- B.P. Weiss, J.L. Kirschvink, F.J. Baudenbacher, H. Vali, N.T. Peters, F.A. Macdonald, J.P. Wikswo, A low temperature transfer of ALH84001 from Mars to Earth. *Science* **290**(5492), 791–795 (2000)
- B.P. Weiss, E. Scheller, Z. Gallegos, B.L. Ehlmann, N. Lanza, H. Newsom, Megabreccia at Northeast Syrtis major and its importance for Mars science, in *49th Lunar and Planetary Science Conference*, 19–23 March, 2018, The Woodlands, Texas. LPI Contribution, vol. 2083 (2018), p. 1385
- C.M. Weitz, R.E. Milliken, J.A. Grant, A.S. McEwen, R.M.E. Williams, J.L. Bishop, B.J. Thomson, Mars Reconnaissance Orbiter observations of light-toned layered deposits and associated fluvial landforms on the plateaus adjacent to Valles Marineris. *Icarus* **205**, 73–102 (2010)
- F. Westall, F. Foucher, N. Bost, M. Bertrand, D. Loizeau, J.L. Vago, G. Kminek, G. Frédéric, K.A. Campbell, J.-G. Bréhéret, P. Gautret, C.S. Cockell, Biosignatures on Mars: what, where, and how? Implications for the search for Martian life. *Astrobiology* **15**(11), 998–1029 (2015)
- K.X. Whipple, N.P. Snyder, K. Dollenmayer, Rates and processes of bedrock incision by the Upper Ukak River since the 1912 Novarupta ash flow in the Valley of Ten Thousand Smokes, Alaska. *Geology* **28**(9), 835 (2000)
- R.M.E. Williams, M.C. Malin, Sub-kilometer fans in Mojave Crater, Mars. *Icarus* **198**(2), 365–383 (2008)

- R.M.E. Williams, R.J. Phillips, Morphometric measurements of Martian valley networks from Mars Orbiter Laser Altimeter (MOLA) data. *J. Geophys. Res.* **106**(E10), 23737–23752 (2001)
- R.M.E. Williams, C.M. Weitz, Reconstructing the aqueous history within the southwestern Melas basin, Mars: clues from stratigraphic and morphometric analyses of fans. *Icarus* **242**, 19–37 (2014)
- K.E. Williams, O.B. Toon, J.L. Heldmann, M.T. Mellon, Ancient melting of mid-latitude snowpacks on Mars as a water source for gullies. *Icarus* **200**(2), 418–425 (2009)
- R.M.E. Williams, D.A. Rogers, M. Chojnacki, J. Boyce, K.D. Seelos, C. Hardgrove, F. Chuang, Evidence for episodic alluvial fan formation in far western Terra Tyrrhena, Mars. *Icarus* **211**, 222–237 (2011)
- R.M.E. Williams, J.P. Grotzinger, W.E. Dietrich, S. Gupta, D.Y. Sumner, R.C. Wiens, N. Mangold, M.C. Malin, K.S. Edgett et al., Martian fluvial conglomerates at Gale Crater. *Science* **340**(6136), 1068–1072 (2013)
- J.-P. Williams, A.V. Pathare, O. Aharonson, The production of small primary craters on Mars and the Moon. *Icarus* **235**, 23–36 (2014)
- R.M.E. Williams, F.C. Chuang, D.C. Berman, Multiple surface wetting events in the greater Meridiani Planum region, Mars: evidence from valley networks within ancient cratered highlands. *Geophys. Res. Lett.* **44**(4), 1669–1678 (2017)
- R.M.E. Williams, M.C. Malin, K.M. Stack, D.M. Rubin, Assessment of Aeolis Palus stratigraphic relationships based on bench-forming strata in the Kylie and the Kimberley regions of Gale Crater, Mars. *Icarus* **309**, 84–104 (2018)
- S.A. Wilson, A.D. Howard, J.M. Moore, J.A. Grant, A cold-wet middle-latitude environment on Mars during the Hesperian–Amazonian transition: evidence from northern Arabia valleys and paleolakes. *J. Geophys. Res., Planets* **121**, 1667–1694 (2016)
- M.-K. Woo, *Permafrost Hydrology* (Springer, Berlin, 2012)
- R.D. Wordsworth, The climate of early Mars. *Annu. Rev. Earth Planet. Sci.* **44**, 381–408 (2016)
- R. Wordsworth, F. Forget, E. Millour, J.W. Head, J.-B. Madeleine, B. Charnay, Global modelling of the early Martian climate under a denser CO₂ atmosphere: water cycle and ice evolution. *Icarus* **222**, 1–19 (2013)
- R.D. Wordsworth, L. Kerber, R.T. Pierrehumbert, F. Forget, J.W. Head, Comparison of “warm and wet” and “cold and icy” scenarios for early Mars in a 3-D climate model. *J. Geophys. Res., Planets* **120**(6), 1201–1219 (2015)
- R. Wordsworth, Y. Kalugina, S. Lokshtanov, A. Vigasin, B. Ehlmann, J. Head, C. Sanders, H. Wang, Transient reducing greenhouse warming on early Mars. *Geophys. Res. Lett.* **44**(2), 665–671 (2017)
- J.J. Wray, S.L. Murchie, J.L. Bishop, B.L. Ehlmann, R.E. Milliken, M.B. Wilhelm, K.D. Seelos, M. Chojnacki, Orbital evidence for more widespread carbonate-bearing rocks on Mars. *J. Geophys. Res., Planets* **121**(4), 652–677 (2016)
- A.S. Yen, R. Gellert, C. Schröder, R.V. Morris, J.F. Bell, A.T. Knudson, B.C. Clark, D.W. Ming, J.A. Crisp, R.E. Arvidson et al., An integrated view of the chemistry and mineralogy of Martian soils. *Nature* **436**(7047), 49–54 (2005)
- A.S. Yen, D.W. Ming, D.T. Vaniman, R. Gellert, D.F. Blake, R.V. Morris, S.M. Morrison, T.F. Bristow, S.J. Chipera, K.S. Edgett, A.H. Treiman, B.C. Clark, R.T. Downs, J.D. Farmer, J.P. Grotzinger, E.B. Rampe, M.E. Schmidt, B. Sutter, L.M. Thompson (MSL Science Team), Multiple stages of aqueous alteration along fractures in mudstone and sandstone strata in Gale Crater, Mars. *Earth Planet. Sci. Lett.* **471**, 186–198 (2017)
- K. Zabrusky, J.C. Andrews-Hanna, S.M. Wiseman, Reconstructing the distribution and depositional history of the sedimentary deposits of Arabia Terra, Mars. *Icarus* **220**(2), 311–330 (2012)
- J.R. Zimbelman, S.P. Scheidt, Hesperian age for Western Medusae fossae formation, Mars. *Science* **336**(6089), 1683 (2012)
- M.Y. Zolotov, M.V. Mironenko, Timing of acid weathering on Mars: a kinetic-thermodynamic assessment. *J. Geophys. Res.* **112**(E7), E07006 (2007)
- M.Y. Zolotov, M.V. Mironenko, Chemical models for Martian weathering profiles: insights into formation of layered phyllosilicate and sulfate deposits. *Icarus* **275**, 203–220 (2016)