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# Geological evidence for multiple climate transitions on Early Mars

Edwin S. Kite<sup>1</sup> & Susan Conway<sup>2</sup>

1. University of Chicago, Chicago, IL, 60637, USA.

2. Nantes Université, Université d'Angers, Le Mans Université, CNRS, UMR 6112 Laboratoire de Planétologie et Géosciences, France.

**Landforms and deposits observed on the Martian surface suggest that Mars' early climate supported rivers and lakes over a time span of more than a billion years. But like Earth, which has over the past billion years experienced periods of global glaciations and hyperthermals, the climate history of Early Mars may have been intermittent. Here we synthesize sedimentary and erosional evidence for multiple climate transitions on Early Mars. We suggest that Mars did not undergo a single wet-to-dry transition, but rather experienced seven major climate transitions, with the planet intermittently under climates warm enough to support surface liquid water even after 3.0 Ga. However, there is evidence for long dry spells, with some locations fully dry after 3.6 Ga. We evaluate hypotheses for the cause of the climate transitions, such as volcanic eruptions and changes in mean obliquity. Testing the sequence of events and understanding the underlying drivers of environmental change will require future missions to Mars.**

Early Mars' climate was intermittently wet (1-4), but Mars is dry today, suggesting varying levels of habitable conditions (in this paper, we focus on surface liquid water as a necessary component of surface habitability). Hence, a better understanding of Mars' history may allow independent tests of Earth-derived theories for planetary habitability (5). For example, Mars was warmest when it received only  $\frac{1}{3}$  as much energy from the Sun as Earth does today. These warmest paleo-Mars climates cannot be explained by CO<sub>2</sub> (+H<sub>2</sub>O vapor) greenhouse warming alone (6). A strong non-CO<sub>2</sub> warming mechanism is needed, not included in standard theory for the circumstellar habitable zone (7). Another example is the hypothesis that escape of volatiles to space determines which worlds have atmospheres and oceans, versus which are dry and airless (8). This can be tested using Mars' transition from a world with a thicker atmosphere and seas, to today's tenuous 6 mbar atmosphere, 210 K surface temperature, desert world. Tests are timely: with the launch of James Webb Space Telescope, the era of rocky-exoplanet characterization is beginning. Mars' geologic record of long-term climate change complements short-timescale "snapshots" of exoplanet climates that can be obtained from monitoring exoplanets on years-to-decades timescales (9). Early Mars and early Earth both saw big changes in their habitable climates on the long timescales that are relevant to life's evolution, and studying processes that occurred on both worlds helps to identify the necessary conditions for those processes.

As the major climate transitions of Mars have come into focus, better constraints have emerged on candidate drivers of change. For example, water loss from Mars, a process that plausibly drove the planet's desertification, is now closely monitored (10). We discuss new interpretations regarding climate change on ancient Mars in the context of emerging hypotheses for the potential driving mechanisms. A central question is how to interpret the fact that climate-sensitive geologic features in the low (<30°) latitudes record a consistent sequence of facies and mineralogic shifts (1,11-12) and unconformities (Fig. 1). In this Perspective we adopt a "lumping" view: that allostratigraphy corresponds to climate history, with wet climates permitting river sediment transport and/or aqueous cementation to form sedimentary rock, alternating with dry climates that permitted wind erosion that sculpted unconformities (12-14) (Fig. 2). Mars lacks plate tectonics and has undergone

63 relatively little true polar wander, so the latitudes, elevations, and relative positions of climate-  
64 sensitive landforms change little over time, permitting reconstruction from orbit. On the other hand,  
65 a "splitting" view in which different watersheds record asynchronous and local events is not ruled  
66 out by existing data (15) (Fig. 2). Testing these hypotheses will ultimately require more radiogenic  
67 dates (16), and is important because it affects the continuity of habitability on Mars' surface (Fig. 2).  
68 Mars' geology (1-2,15,17) (Fig. 1) provides evidence for a sequence of events that is consistent with  
69 the following low-latitude (<30°) environmental history (Fig. 3):  
70

## 71 **The Seven Major Climate Transitions of Mars.**

### 72 ① **The Earliest Record.**

73 Among the oldest sedimentary units seen on Mars are river deposits (e.g., 18) (Early-to-Middle  
74 Noachian, >3.95 Ga according to 19). The shapes of the oldest craters suggest reworking by liquid  
75 water. These craters are flat-floored and shallow, with subdued rims, yet retain relatively steep inner  
76 walls (20). These indirect data, and the bimodal distribution of crater infilling states, are hard to  
77 explain without reworking by streams or debris flows (20). Alternatively, perhaps the early crust  
78 was icy, and slurry-like impact ejecta filled topographic lows (21). ~1 km of surface denudation,  
79 presumably by water- or ice- erosion during events of unknown timescale, is suggested by the  
80 relative rarity of ancient craters that are small (<16 km diameter) (22-23, but see also 24). Crater  
81 lakes did not overspill, suggesting climate aridity similar to modern Nevada (23).  
82

83 Unexpectedly few minerals seen from orbit were formed by aqueous weathering, though clays are  
84 widespread (25). Some clays formed ~4.25 Ga based on meteorite data (26). Intense alteration is  
85 seen in some layers and veins, with modest or isochemical alteration in other, nearby materials (27-  
86 28). Rain (or snowmelt) and hydrothermal fluids altered layers of ash and ejecta (27-28,30). Ancient  
87 clasts within Mars meteorites are mostly igneous, and rarely sedimentary in origin (29). Water close  
88 to the surface was at ~10 °C at 3.95±0.02 Ga, based on meteorite isotopologue data (26). Atmospheric  
89 pressure at this time is poorly constrained (<2 bar; 32), although isotopic evidence shows escape-to-  
90 space was most intense pre-4 Ga (33).  
91

92 Together, the data suggest wet, habitable climates spanning a time interval of >100 Myr (22-23),  
93 >3.9 Ga ago on Mars. At this time Mars would have received less insolation than the outer edge of the  
94 calculated circumstellar habitable zone for worlds with a CO<sub>2</sub>-H<sub>2</sub>O-N<sub>2</sub> atmosphere (7). Therefore, the  
95 standard model for exoplanet habitability does not explain Mars at this time. A continuously warm  
96 and wet climate overpredicts both weathering and (slow) erosion on Mars (22). One possibility is  
97 that early Mars was intermittently warm and wet. Another possible resolution is ultra-low rainfall  
98 rates (31).  
99

### 100 ① **The Great Wetting.**

101 Next (>3.75 Ga, perhaps <1-Myr duration), aqueous fluids leached the soil, dissolved primary  
102 minerals, and formed Al-clays overlying Fe/Mg-clays (e.g. 34): a global anomaly. Hypotheses for the  
103 fluid range from ~0.3 km-column of volcano-sourced acid (35), to ~30 km-column of rainfall (34).  
104

105 The weathering sequence is crosscut by valley networks including 10<sup>3</sup> km-long rivers, large seas (36),  
106 and overflowing lakes – together, these define a global climate optimum. The valley networks, which  
107 are spatially pervasive, formed over >10<sup>4</sup> yr (37), probably longer (Fig. 4). These data are consistent  
108 with a climate warm enough for runoff everywhere on the planet, which is not the case for  
109 subsequent wet events discussed later in this paper. Eventually, global Al-clay layers no longer  
110 formed, and erosion became spatially patchy: for example, lakes overspilled into Holden crater,  
111 eroding the rim, but shallow secondary craters from the Holden impact are still visible. As another  
112 example, consistent with the evidence for post-3.9 Ga patchiness in erosion, the ALH84001 meteorite

113 shows “absolutely no evidence” (26) for post-3.9 Ga habitability. The Spirit rover at Gusev crater  
114 found little evidence for post-Great-Wetting rivers or lakes. Fe/Mg-clay formation continued through  
115 the valley-network era (38), but the elemental composition of sedimentary rocks at most locations  
116 lacks the changes expected for climate-driven weathering. Instead, elemental composition matches  
117 expectations for acid-sulfate alteration (39-40). Mineralogy suggests that warm/wet events were  
118 intercalated with long periods that were drier, colder, or both (28,40,41).  
119

120 Valley-network-era surface temperature is poorly constrained. At annual average surface  
121 temperature  $T_{surf} = -18$  °C in Antarctica, rivers carve into bedrock and feed perennial ice-covered  
122 lakes (42, 43), providing a reasonable lower estimate for the surface temperature at which fluvial  
123 valley networks can be formed. Supposing valleys do not form below  $T_{surf} = -18$  °C, then for a lapse  
124 rate of  $\partial T_{surf} / \partial z = -2.5$  K/km (appropriate for Early Mars; 6), the observation of valley networks at  
125 +6 km elevation implies  $T_{surf} > 5$  °C at equatorial low spots (-5 km) (e.g., *Curiosity*’s field site at Gale  
126 crater’s floor). A large polar ice sheet existed at a time that is indistinguishable, given large age-dating  
127 uncertainties, from that of the valley networks (44). Such high temperatures, and the stability of  
128 liquid water, suggest a thicker atmosphere at this time than Mars has today.  
129

130 A possible explanation for these data is if Mars’ atmospheric column mass peaked at this time. Theory  
131 predicts that air may escape from planetary atmospheres that are heated by the high X-ray and  
132 Extreme Ultraviolet (XUV) flux that emanates from young host stars. This process may define the  
133 “cosmic shoreline” between uninhabitably gassy and uninhabitably airless exoplanets (8).  
134 Atmospheric erosion from low-gravity Mars may have been extreme >4.1 Gya due to the young Sun’s  
135 high XUV flux (45). As the Sun calmed down, volcanic outgassing continued, perhaps permitting  
136 atmosphere build-up (45) even though Mars’ geodynamo ceased before this time (46). Atmospheric  
137 pressure  $\sim 1$  bar during the Great Wetting is consistent with proxy data (32). In this hypothesis,  
138 climate optima on Mars-like exoplanets depend on gravity, host-star activity, and intensity of volcanic  
139 activity.  
140

## 141 ② The Shift to Salts.

142 Clay-rich rocks are succeeded by rocks that are rich in sulfate salts (11), with sedimentary textures  
143 recording aeolian transport (e.g. 47). This transition, suggesting a more arid climate, was gradual  
144 (48). Minerals indicating pH = 2-4 are present (e.g., 49). Mudcracks found in one location suggest  
145 sustained wet-dry cycling on seasonal or even shorter timescales (50), which is favorable for  
146 prebiotic synthesis in some models (51). Sulfate formation continued until recently (52), though  
147 sulfate-rich rocks mostly predate 2.5 Gya.  
148

149 Sulfate-era  $T_{surf}$  is a key unknown. Sulfates can form in ultra-cold climates (53). In cold-climate  
150 models of Mars, there is only seasonal liquid water in the sulfate era (e.g., 54). One warm-versus-cold  
151 test is the extent of groundwater flow: ice is impermeable, so above-freezing temperatures make the  
152 flow of deep groundwater to the surface easier. Meter-scale near-surface groundwater flow did occur  
153 (47,55), but because a warm season can unfreeze ground to several meters depth, this is consistent  
154 with both cold and warm models. Flow of groundwater to the surface along  $10^3$ -km long flowpaths,  
155 predicted by warm models (13), should fractionate cations by solubility, in tension with the near-  
156 uniform S-free bulk compositions of water-altered rocks, which suggest immobility of Na, Si, and K,  
157 among other elements (55). However, a deep-groundwater role in the origin of the sulfates may still  
158 be possible if sulfates were remobilized from more-ancient salts (35), or if groundwater is the water  
159 source for the sulfates but not the source of the salts (56). A lukewarm climate solution for the sulfate  
160 era (Fig. 3) would involve open water at low-lying locations, and below-freezing highlands (e.g., 57).  
161

162 A possible cause of aridification is H<sub>2</sub>O escape-to-space (10,58). Mars has lost >½ (perhaps ¾) of its  
163 surface-exchangeable water since clay-rich rocks stopped forming (58). Observations of Mars from  
164 orbit indicate great sensitivity of water escape rate to details such as dust cover that will be hard to  
165 resolve on exoplanets (10).  
166

### 167 ③ The Great Drying.

168 Next, wind erosion cut troughs >1 km deep (59-61). This strongly suggests ultra-arid conditions. For  
169 example, in order for wind to sandblast rock, sand is required, but sand is trapped by even small  
170 amounts of liquid water. If this Great Drying was a global event, as we suggest, then it may have been  
171 triggered by a change in mean obliquity. Simulations predict Mars experiences only a few mean-  
172 obliquity shifts per Gyr (62). Climate is sensitive to obliquity (63). For example, water ice (a possible  
173 source of liquid water) is most stable at low latitudes when obliquity is high (63), so desiccation of  
174 the low latitudes is favored if obliquity decreases.  
175

176 Moreover, when obliquity is low and the CO<sub>2</sub> atmosphere is not thick, theory predicts runaway  
177 atmosphere collapse, consuming >90% of the planet's atmosphere in  $\lesssim 10^3$  yr, leaving behind CO<sub>2</sub> ice  
178 and a very thin, cold atmosphere (64).  
179

### 180 ④ Patchy, Regional Return of Lakes.

181 Later, deep lakes formed, some more voluminous than Earth's Caspian Sea (e.g., 65-69). Individual  
182 lakes lasted centuries or more, based on estimates for delta formation timescales (66-69). Orbiter  
183 data suggest high peak paleodischarge, suggesting rainfall (70). However, measurements of grain size  
184 are needed to confirm this. Alluvial fans ~1 km thick also formed, over a time span of >100-300 Myr  
185 (4). Some sites record multiple lakestands (66). Rivers formed until <3.0 Ga (best estimate  
186 ~1.8 Gya) (3). Aridity varied spatially, with proportionally larger lakes in lower-elevation  
187 catchments (67), inconsistent with the elevation trend in aridity during the Great Wetting (68). Valles  
188 Marineris apparently hosted seas later in Mars history than elsewhere in Mars' low latitudes (64).  
189 The midlatitudes hosted small internally-overspilling craters ("tadpoles") (71); overspill timing is  
190 uncertain. Together, these landforms suggest globally distributed, although patchy, late-stage  
191 habitable conditions with surface temperatures above freezing.  
192

193 These late-stage warm climates challenge climate models because most of Mars' atmosphere was lost  
194 early on, and very thin atmospheres cannot support liquid water (17,72-73). Climate models need to  
195 accommodate the conditions that allow for patchy post-Noachian fluvial erosion. Most late-stage  
196 water-worn landforms formed at low elevations (e.g., 57) and most lakes did not overflow. Erosion  
197 was minimal on the highlands (74), where highly-soluble salts accumulated (75). The data suggest  
198 snowmelt, though some models predict an open-water late-stage ocean, with rain (76). Snowmelt  
199 versus rain might be tested by improving constraints for paleo-runoff production (rain enables  
200 higher peak runoff production). Even for thin atmospheres, the greenhouse effect of high altitude  
201 water ice clouds (HAWIC) can be strong (77, see also 31). HAWIC might explain these late, habitable,  
202 climates. However, predicting the amplitude of cloud warming depends on details (such as ice-nuclei  
203 abundance), which might not be available for exoplanetary systems and thus limit our predictive  
204 power for the habitable-zone edge in these systems.  
205

### 206 ⑤ The Final Dry-Out of Low-Latitude Rivers.

207 Large alluvial fans apparently stopped forming  $\gg 10^8$  yr ago (the youngest large craters lack >10 km<sup>2</sup>  
208 fans, 78). The cause of this dry-out could have been loss of radiative forcing from CO<sub>2</sub>, loss of non-CO<sub>2</sub>  
209 greenhouse forcing, or loss of H<sub>2</sub>O. Loss of H<sub>2</sub>O might lower the water table, helping to drain lakes,  
210 but it is not clear if this would stop river flow. It is perhaps surprising that the effect of a lower water  
211 table on planetary surface/atmosphere hydrology (water vapor, rain, etc.) has not been

212 quantitatively investigated, given its importance for interpreting soon-to-be-acquired exoplanet  
213 water vapor data. The direct effect of loss of radiative forcing from CO<sub>2</sub> matters less than loss of non-  
214 CO<sub>2</sub> greenhouse forcing, according to climate models (57). In summary, we lack a good explanation  
215 for arguably the key environmental shift in terms of the planet's transition to uninhabitable surface  
216 conditions.

### 217 218 ⑥ **Liquid Water Without Rivers.**

219 After rivers dried up at Aeolis Dorsa (~5°S), wind erosion into the alluvial fans cut deep hollows,  
220 suggesting Myr of dry conditions at least locally (14) before deposition resumed.

221  
222 Later, wind-blown silt or ash became indurated, strongly suggesting aqueous cementation (1,79).  
223 This formed >1 km thickness of rhythmic layers (“rhythmite”) recording ≥10 Myr of deposition (79).  
224 The time span of deposition was longer than this: rhythmite has internal unconformities, and  
225 reworking is plausible (e.g., 79). Where rhythmite overlies older wet-era rocks, the density of craters  
226 at the contact marks a ≥1 Gyr hiatus (14), comparable to Earth’s Great Unconformity. Rhythmite is  
227 never crosscut by stream channels. Induration of sediments has continued until recently (e.g., 80-  
228 81). Snowmelt can provide enough water to explain these data (54,43). Dusty snowpack can melt  
229 under a ~50 mbar CO<sub>2</sub> atmosphere for some orbital conditions (54).

230  
231 Minor surface wetting and anhydrous oxidation is recorded by veneers, rinds, and crusts (e.g., 82).  
232 Local magmatism or impacts likely caused the transient <1 Ga water recorded by Mars meteorites  
233 (83), and local impact effects are likely responsible for small alluvial fans near some young impact  
234 craters (84), although the triggering mechanism is uncertain. In the midlatitudes, some channels  
235 formed atop debris-covered glaciers as late as 0.1 Gya (85). Extensive midlatitude debris covered  
236 glaciers have been present since <0.5 Ga (86) and limited amounts of meltwater may have been  
237 released from them via subglacial melting in local areas with positive geothermal anomalies (87). In  
238 addition, there is evidence for widespread subglacial melt ~5 Ma, in the form of porewater, which  
239 was not sufficient to outflow to the surface.

### 240 241 ⑦ **The Most Recent Drying.**

242 Mars’ surface is too cold and dry for liquid water today. Channels formed on steep slopes <5 Mya,  
243 at least partly due to CO<sub>2</sub>-driven processes (88). Under pre-modern orbital conditions, a contribution  
244 by H<sub>2</sub>O snowmelt is possible (89). If brines flow on the surface today, which has been questioned  
245 (90), then their water activity is less than that of honey, uninhabitable for life as we know it (91). The  
246 only potential reservoirs for liquid water today are in the subsurface: sandwiched beneath Mars’  
247 putative cryosphere (e.g. 92) or conceivably as brine under the south polar ice cap (93).

### 248 249 **Open questions.**

250  
251 In summary, our interpretation of the data suggests that Mars did not undergo a single wet-to-dry  
252 transition. Instead, in our perspective, Early Mars saw many environmental transitions. The wettest  
253 climates were apparently intermittent. Alternations between very wet climates and very arid  
254 climates hint at strong positive feedbacks or bistability in the climate system. Rivers retreated from  
255 the highest, coldest elevations over time, suggesting a waning greenhouse effect (57). Because CO<sub>2</sub>  
256 escape-to-space is irreversible, it cannot explain all of the climate transitions discussed here.  
257 However, CO<sub>2</sub> escape-to-space, alongside carbonate formation (95), might contribute to the overall  
258 drying trend.

259  
260 The data have biases and gaps. Testing the sequence of events proposed here will require more  
261 radiometric dates (16). Moreover, the stratigraphically intact record reviewed here – impeccably-

262 preserved at the decameter scale inspected by orbiters – is predated by the earliest, now-fragmented,  
263 geologic record. Water-altered crust was present by 4.43 Ga (94). To get access to the earlier, now-  
264 fragmented record, ancient megabreccia samples should be included among those returned to Earth.  
265 It is possible that megabreccia record the most habitable times in Mars history (e.g., 17).  
266

267 Abundant surface liquid water recorded by geomorphology and surface-formed phyllosilicates, yet a  
268 relative paucity of evidence for open-system aqueous weathering, is a fundamental paradox. One  
269 possible explanation for limited open-system weathering is cold ( $\leq 10^\circ\text{C}$ ) temperature (e.g., 41).  
270 Alternatively, perhaps fluvial erosion was fast. For fast-eroding terrain, minerals are flushed to the  
271 sediment sink without much time for weathering. If  $\sim 1$  mm-thick layers observed at Gale are  
272 interpreted as annual/seasonal layers, then sedimentation was fast, suggesting correspondingly fast  
273 erosion.  
274

275 Would the dry periods between river-forming climates have allowed life? A climate like that of  
276 modern Mars would be extremely hostile to life. Alternatives include a climate similar to the  
277 hyperarid Atacama (which sustains life), or seasonal soil wetting similar to terrestrial active-layer  
278 environments. This knowledge gap has potentially deep astrobiological implications. If Mars' surface  
279 was sterilized during dry spells, then the most-continuous habitat was the deep subsurface (96).  
280

## 281 **Drivers of environmental change.**

282

283 What caused wet episodes? What caused the dryings? One hypothesis is volcanic outgassing of  $\text{H}_2$   
284 into a thick  $\text{CO}_2$  atmosphere ( $>1$  bar) (97-98). The resulting  $\text{H}_2$ - $\text{CO}_2$  Collision-induced Absorption  
285 (CIA) greenhouse effect allows rivers to flow for  $10^5$ - $10^6$  yr before  $\text{H}_2$  leaks to space (98). A challenge  
286 for this idea is outgassing  $10^7$ - $10^8$   $\text{km}^3$  magma in  $\sim 10^5$  yr, 100-1000 times faster than the most  
287 intense known volcanic events on Earth (99), perhaps unrealistic for a smaller planet. Perhaps  $\text{H}_2$   
288 was instead produced by serpentinization, or extremely large impacts (e.g. 100). Alternatively, High-  
289 Altitude Water Ice Clouds (HAWIC) (31,101) can produce warming. This mechanism, which requires  
290  $>10$   $\mu\text{m}$ -sized cloud particles, can generate strong warming for a wide range of  $p\text{CO}_2$  (31, 101). Tests  
291 of paleo- $p\text{CO}_2$ , wet-event duration, and  $\text{H}_2$  production mechanisms can discriminate between these  
292 ideas. Many previously proposed climate-warming hypotheses, for example impact energy, fail to  
293 match new data (e.g. 102). The Sun's rising luminosity may have contributed to the later re-wetting  
294 events.  
295

296 Volcanic release of  $\text{CO}_2$ ,  $\text{H}_2\text{O}$  and  $\text{SO}_2$  may have influenced Mars' environmental transitions, but there  
297 is surprisingly little evidence for this. Mars' atmospheric C reservoir ( $2.5 \times 10^{16}$  kg today, perhaps  
298  $10^{19}$  kg in the past) is vast compared to Earth's, and this buffers Mars climate against volcanic  $\text{CO}_2$   
299 release. Similarly, Mars's surface  $\text{H}_2\text{O}$  reservoir is  $5 \times 10^{18}$  kg today and was larger in the past. Relative  
300 to these reservoirs, peak (plume head arrival) volcanic degassing flux  $Q_{\text{volc}}$  appears insufficient for  
301 rapid climate warming. Let  $Q_{\text{volc}} \leq \pi X v r^2 f_{\text{erupt}} \rho$ , where  $v$  is mantle plume ascent velocity (0.1 m/yr),  
302  $X$  is melt fraction ( $\sim 0.1$ ),  $r$  is plume-head radius ( $10^6$  m), the extrusive (degassed) fraction  $f_{\text{erupt}}$  is 0.2,  
303 and  $\rho$  is kg/(magma  $\text{m}^3$ ) for the volatile of interest. This gives  $< 2 \times 10^{10}$  kg/yr even if the volatile of  
304 interest has concentration 1,000 ppmw, which is unlikely (e.g., 104).  $\text{SO}_2$  release forms aerosols that  
305 cool Mars (105). One plume head would not warm climate much. (On the other hand, *total*  $\text{CO}_2$   
306 outgassing from Tharsis could be as much as 100 mbar for  $\sim 10^8$   $\text{km}^3$  volume and 1000 ppmw  
307 magmatic  $\text{CO}_2$  content.)  
308

309 A plausible cause of major climate transitions is mean-obliquity change. High obliquity destabilizes  
310 polar water ice, so that ice accumulates at low latitude, where it is more likely to melt (54). Mars'  
311 obliquity is chaotic (62) and has varied  $>20$ -fold more than Earth's. Obliquity change can drive

312 hundred-fold shifts in atmospheric pCO<sub>2</sub> (64). Theory indicates that Mars has undergone ~10 rapid  
313 shifts in *mean* obliquity (in addition to ~100 Kyr-period obliquity cycles). In the most recent such  
314 shift, mean obliquity fell by 20° in just 1 Myr (62). This happened ~5 Mya. Geologic constraints on  
315 obliquity (e.g., 106) are necessary >0.1 Ga because deterministic reverse integration of the solar  
316 system fails in deep time due to solar system chaos (62). Mechanisms linking mean-obliquity change  
317 to habitable-era climate transitions remain to be explored and tested.

318  
319 Mars has lost water over time (from >100 m Global-Equivalent Layer of surface H<sub>2</sub>O >3.5 Ga, to 30m  
320 today) (58). Whether or not H<sub>2</sub>O loss to space is coupled or decoupled from Mars' geologic record of  
321 rivers and lakes depends on Mars' poorly constrained paleo-temperature. Specifically, if Early Mars  
322 was warm, a falling water table might dry the surface (13). If Early Mars was cold enough for an ice  
323 cap, low total water content would destabilize any ocean, because water would move via the  
324 atmosphere to the cap, draining the ocean. However, if Early Mars was cold enough to form an  
325 impermeable cryosphere, then seasonal melt could feed perennial lakes (as in the Antarctic Dry  
326 Valleys; 42), even for the modern 30m GEL. Indeed, if Mars warms in the future, lakes could re-form.  
327 This uncertainty has implications for astrobiology: theory predicts that Mars today could support  
328 habitable subsurface aquifers (107). However, if Mars lacked an impermeable cryosphere to protect  
329 the deep aquifer, then water loss to space could desiccate the crust (107).

330  
331 The thinness of Mars' CO<sub>2</sub> atmosphere causes warm H<sub>2</sub>O-ice to undergo extreme evaporitic cooling.  
332 This can explain the lack of snow/ice melt today (72). Mars is currently losing CO<sub>2</sub> to space (slowly;  
333 ~1 mbar/Gyr, 108). However, it does not follow that loss of CO<sub>2</sub> to space is the cause of Mars' surface  
334 being uninhabitably cold. To the contrary, raising  $T_{surf}$  raises pCO<sub>2</sub>: a warmer planet would unbind  
335 CO<sub>2</sub> from icy deposits and regolith (up to ×8 atmospheric thickness; 109). It is possible that snowpack  
336 melted under different orbital forcing recently (1-5 Mya).

### 337 338 **Implications for Early Mars habitability.**

339  
340 A possible synthesis is as follows. Early on, H<sub>2</sub> outgassing causes a handful of river-forming climates  
341 of 10<sup>5</sup>-10<sup>6</sup> year duration (98), boosted by High-Altitude Water Ice Cloud warming (HAWIC) (31,101).  
342 Volcanic acids, which stay liquid at low temperatures, alter soil (35). Later, carbonate formation  
343 lowers pCO<sub>2</sub> (95) until H<sub>2</sub>-CO<sub>2</sub> CIA warming becomes ineffective. Intermittent HAWIC continues,  
344 enabling late lakes (31). Once pCO<sub>2</sub> falls below ~50 mbar, low-latitude rivers cease but minor  
345 snowmelt continues (54), allowing rhythmite to form. Relative to Earth's continuous surface  
346 habitability, this scenario would challenge (preclude?) the continuous persistence of surface life.

347  
348 We do not know whether Early Mars was warm and wet, or cold and icy (30) (Fig. 5). Possible tests  
349 include analyzing paleosols, testing for open-system weathering, and river paleodischarge estimates  
350 (70). Another major unknown is "does Mars retain subsurface habitable aquifers at multi-km depth?"  
351 (107). Electromagnetic sounding may answer this question.

352  
353 Mars and Earth both saw big changes in their habitable climates on the long timescales that are  
354 relevant to life's evolution. To determine what enabled Mars' habitable climates requires asking "how  
355 warm were Mars' wet climates?", and "how dry were Mars' cold climates?" The answer to the first  
356 question tests greenhouse models, with major implications for exoplanet habitability models. The  
357 answer to the second will constrain whether if the early surface was habitable continuously, or only  
358 intermittently. Both questions will be greatly advanced by returning samples from Mars, and other  
359 missions. As the era of rocky-exoplanet characterization begins, the seven major climate transitions  
360 of early Mars comprise an accessible natural laboratory for understanding the habitability of planets  
361 in general.



362 **Corresponding author**

363 Correspondence to Edwin Kite (kite@uchicago.edu).

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366

367 **References.**

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**Fig. 1. Examples of major Early Mars climate transitions recorded by geology.** (a) Valley networks near 60°E/12.5°S record Late Noachian/Early Hesperian great wetting. (HRSC\_h0532\_0000). (b) River delta from Jezero crater (18°N/77°E) (CaSSIS synthetic RGB MY36\_014886\_164\_0, ref. 70). (c) Delta close-up: steep-dipping planar beds mark past boundary between river and lake. View is ~100m across. (NASA/JPL-Caltech/ASU; <https://mastcamz.asu.edu/galleries/kodiak-dawn/>). (d) Sulfate-rich aeolian dunes from Victoria crater (2°S/6°W) (NASA/JPL-Caltech/Cornell, [http://pancam.sese.asu.edu/1121B\\_CStVincent.html](http://pancam.sese.asu.edu/1121B_CStVincent.html)). (e) Dark-toned lithified aeolian dunes superpose an erosional unconformity from the Great Drying (dashed line) that is itself incised into light-toned clay-rich deposits from Mars' lake era. Distant light-toned background rocks (at left) likely postdate all low-latitude rivers on Mars (NASA/JPL/MSSS, 5°S/138°E).

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**Fig. 2. Options for correlating Mars' sedimentary record.** Climate-sensitive geologic features in Mars' low (<30°) latitudes record a consistent sequence of facies and mineralogic shifts (1,11-12) and unconformities (Fig. 1). We interpret this as (left column) a record of major climate transitions (12-14). Alternatively (right column), perhaps different watersheds record asynchronous and local events (15). This matters because surface life cannot persist indefinitely, even as spores, on a planet whose surface is globally uninhabitable. On the other hand, wind dispersal would allow the persistence of surface life on a planetary surface that was continuously habitable, even if only patchily.

629

**Fig. 3. Major environmental transitions of Early Mars.** This figure is biased toward warmer/wetter events because these leave geologically obvious traces. Shorter-timescale climate fluctuations also occurred (e.g., 50). Some constraints depend on parameters. Temperature curve uses elevation of water-associated landforms and the assumption that rivers do not form for annual-average temperature <-18°C (with no latitude adjustment). For details of how parameters were obtained from the data sources (23, 66-68, 110-113), please see the Supplementary Data Table.

630

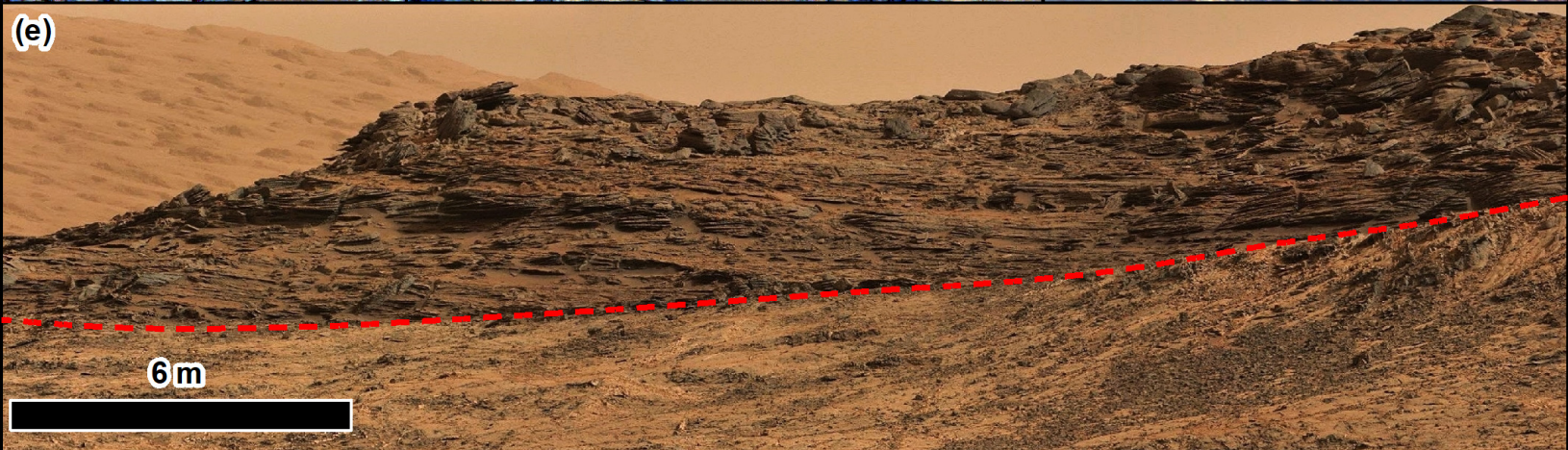
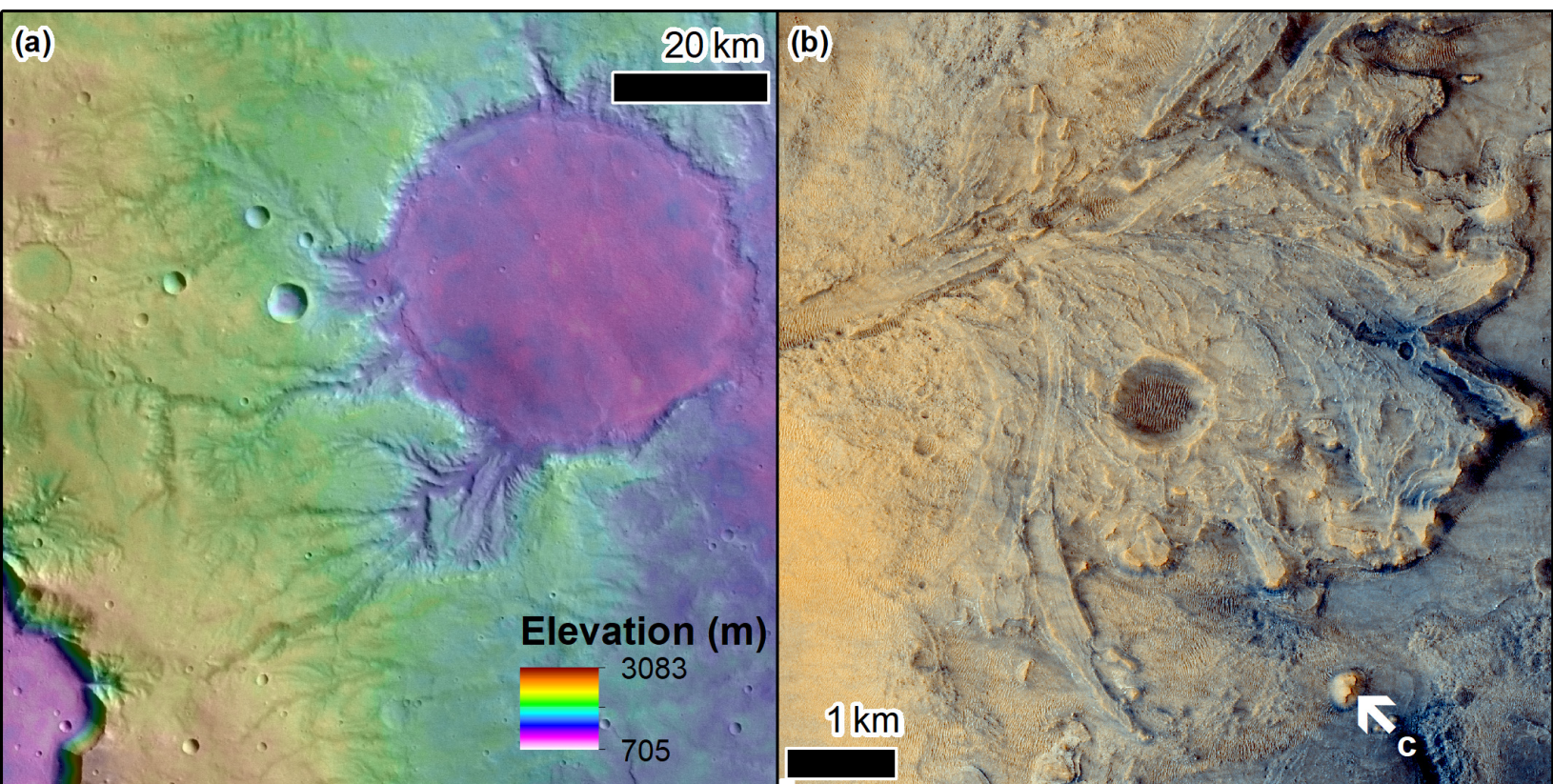
**Fig. 4. Timescales ( $\tau$ ) for the wettest climates.** Cumulative durations and individual durations for Early Mars river-forming climates could be much shorter than the time span of Early Mars river-forming climates (17). Sources of data: Early stage, estimate from landscape evolution (23), with factor-of-ten uncertainty added. Great wetting, lower blue limit from valley formation timescale (37). Dashed line: with 5% intermittency. Patchy, regional return of lakes: Lower limits based on delta build-out times, with and without intermittency (e.g., 69). Upper limit based on olivine's persistence (114). For details of how the parameters were obtained from the data sources, please see the Supplementary Data Table.

631


**Fig. 5. Graphical summary of possible environmental evolution trajectories.** Possible trajectories (including reversals) are shown. Top-left: "warm-wet" climate end-member, with rain, rivers, lakes and subsurface aquifer. Sediment accumulates in/near lakes, and diffusive hillslope transport modifies hillslopes. Top-right: "warm-dry" climate, dominated by aeolian erosion of layered rocks and migrating dunefields. Slopes are modified by dry processes (rockfall). Bottom-left: "cold-wet" climate end-member, permitting periodic surface melting of snow and ice-covered lakes. A supra-glacial melt-water channel dissects a debris-covered glacier. Layered lake sediments, a talik, and a cryosphere overlying a possible sub-surface aquifer are present. Bottom-right: "cold-dry" climate end-member, with limited snowfall, debris covered glaciers, a cryosphere, and rhythmite rock.

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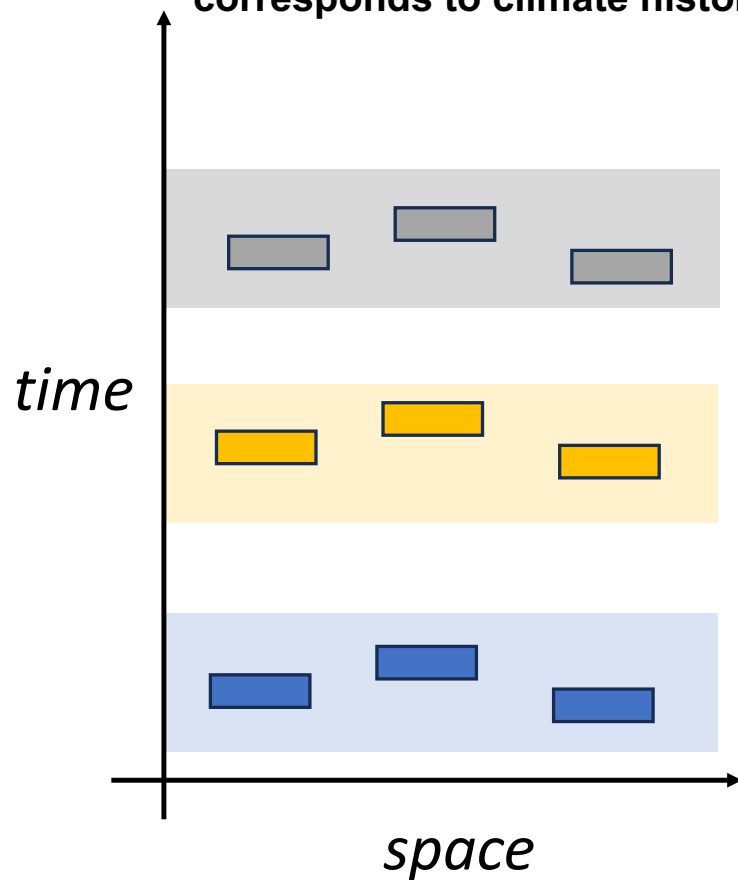




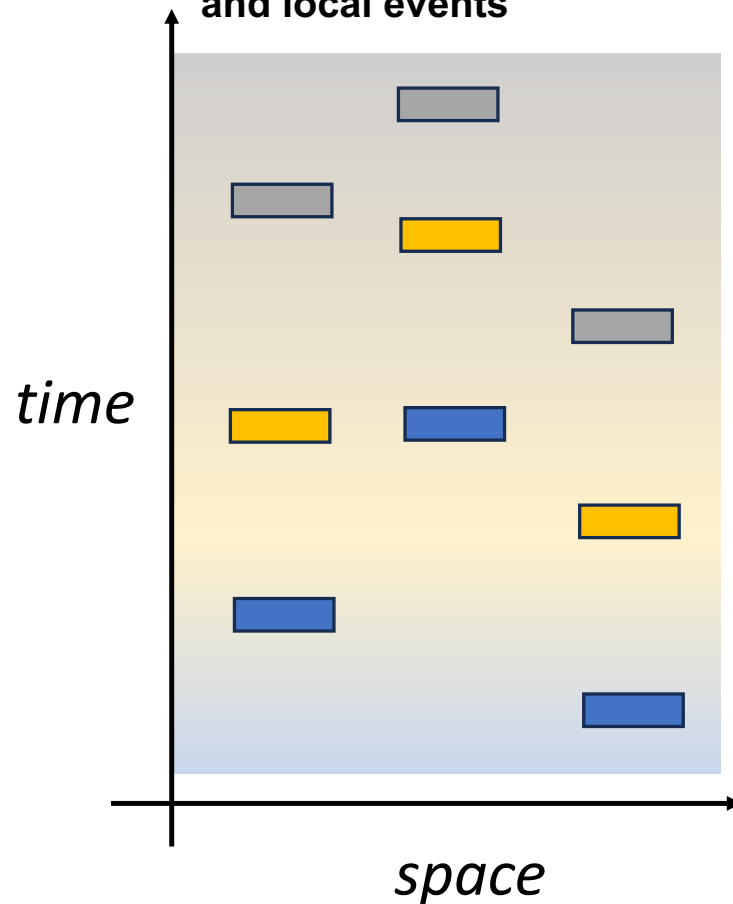


 = Observation: climate-sensitive geologic feature in the low (<math><30^\circ</math>) latitudes

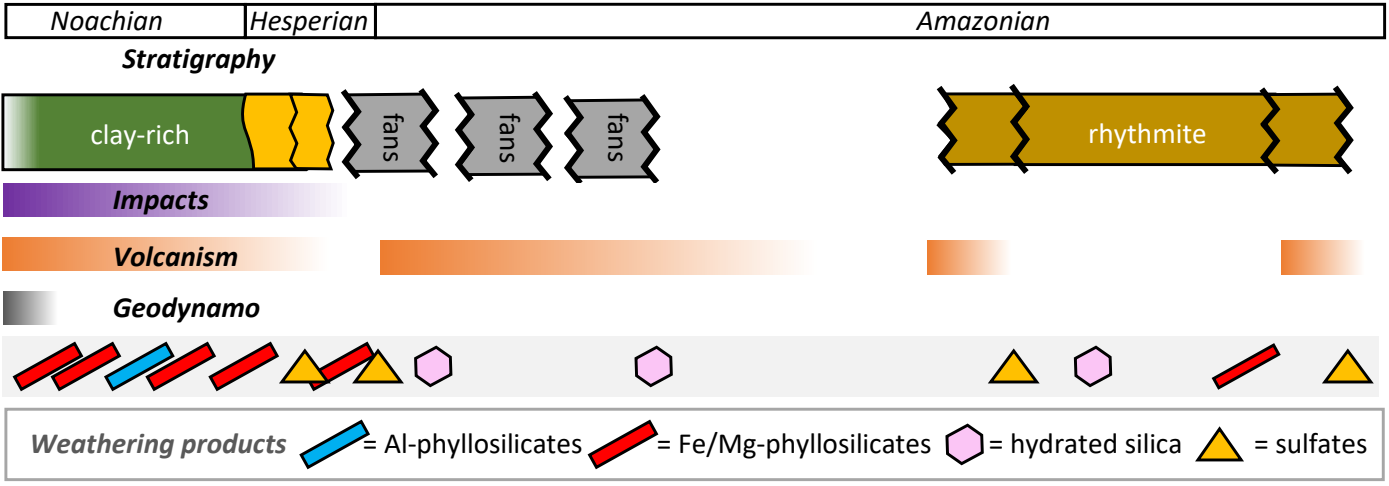
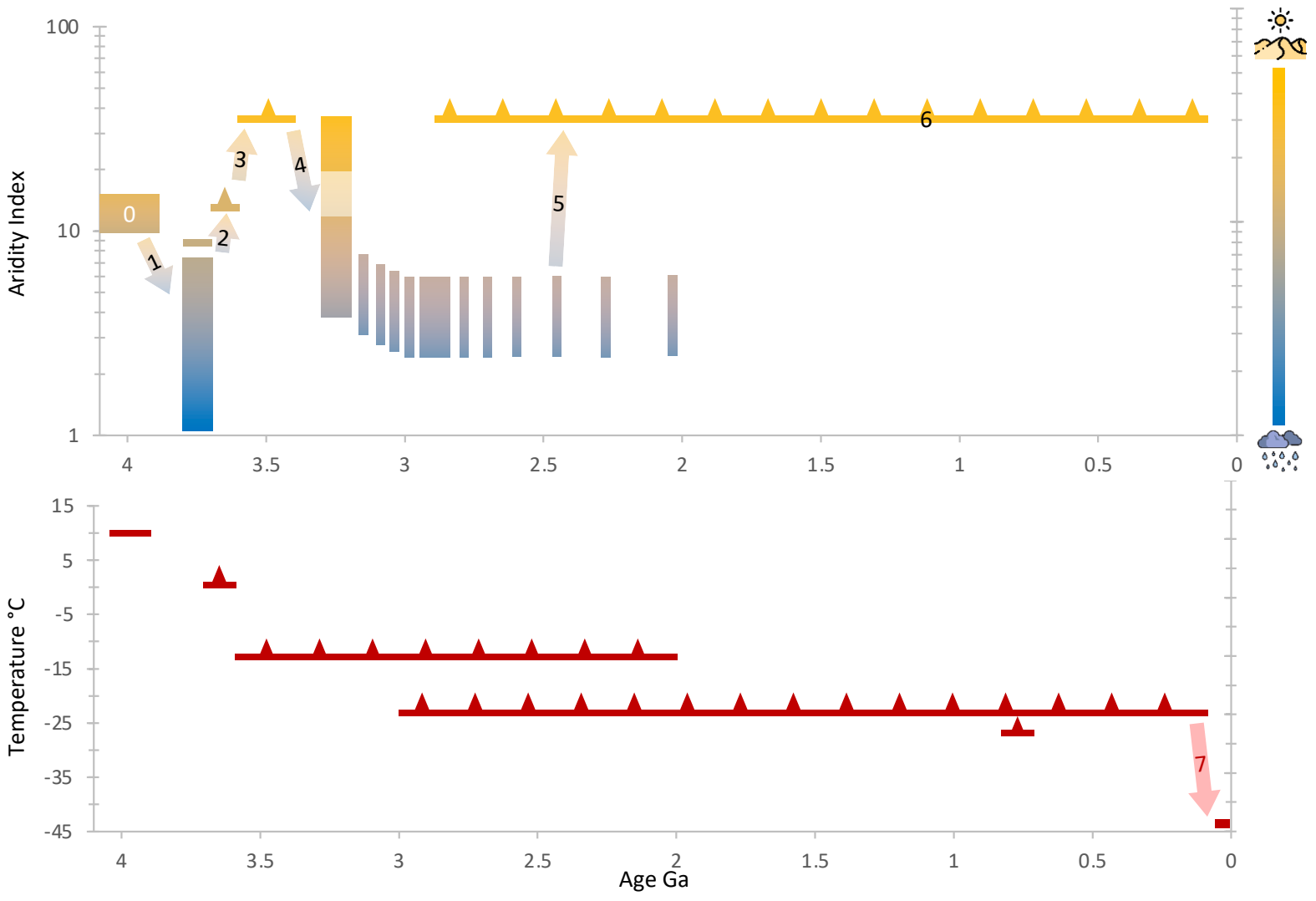
**Climate transitions perspective, adopted here: allostratigraphy corresponds to climate history**



**Alternate view: Different watersheds record asynchronous and local events**

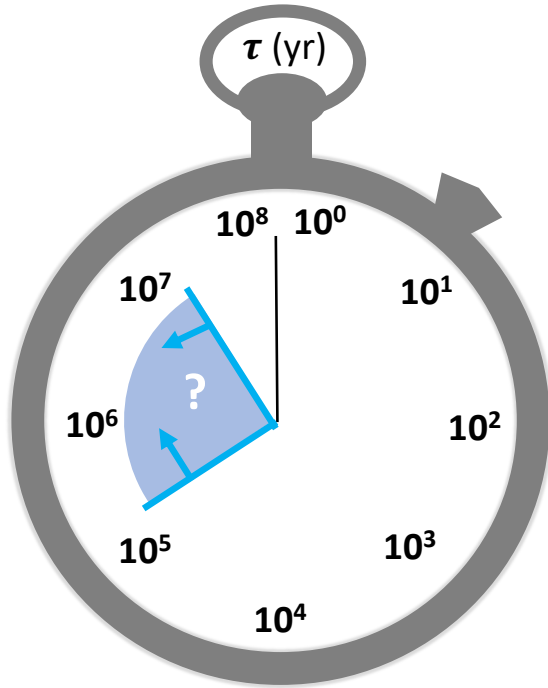






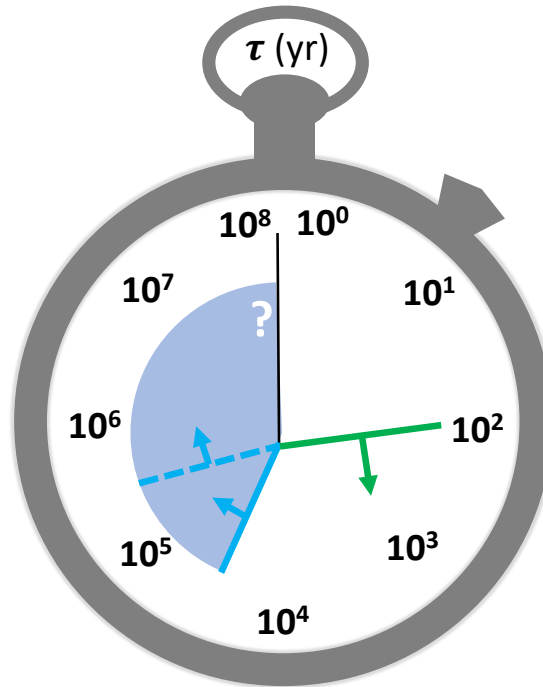
## EARLY RIVERS

(Early/Middle Noachian)



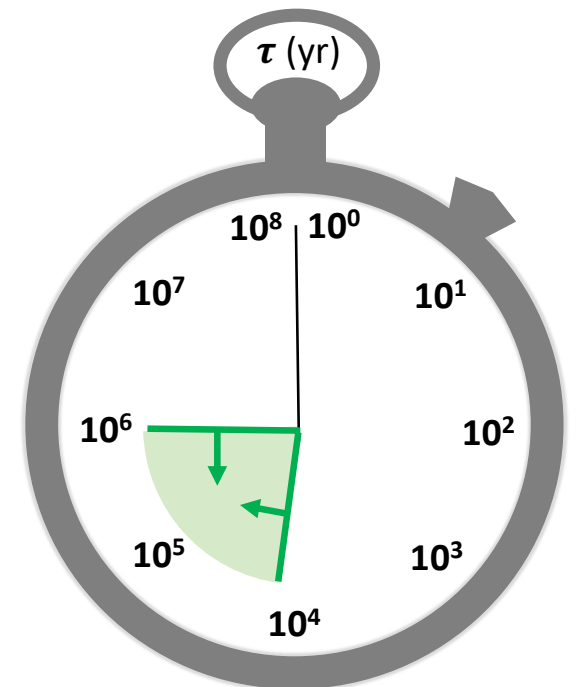
## THE GREAT WETTING



(Late Noachian/Early Hesperian)



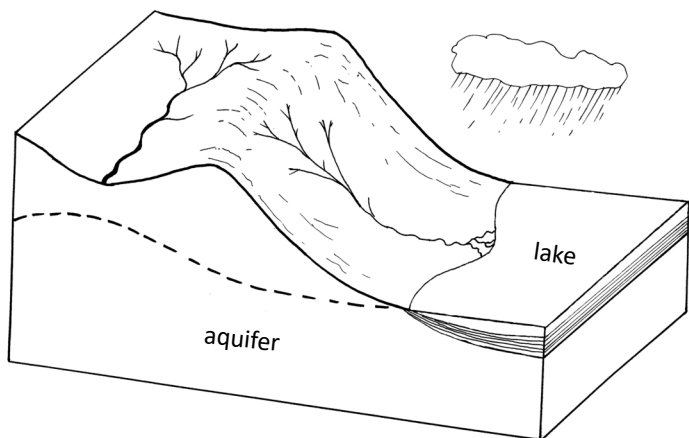
## PATCHY, REGIONAL RETURN OF LAKES

(Late Hesperian/Early Amazonian)

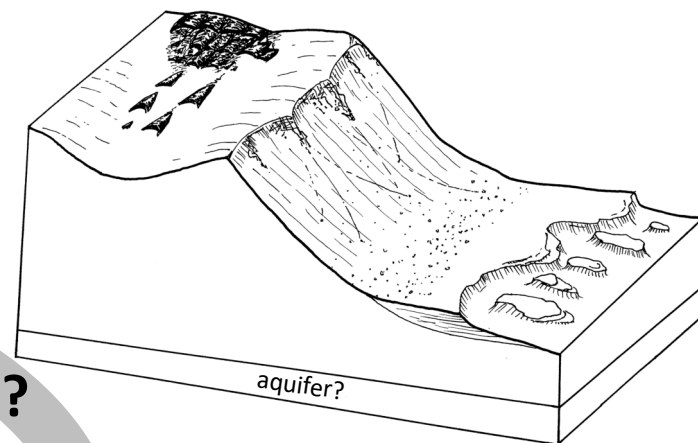


-  Duration of individual river-forming climate
-  Cumulative duration of river-forming climates

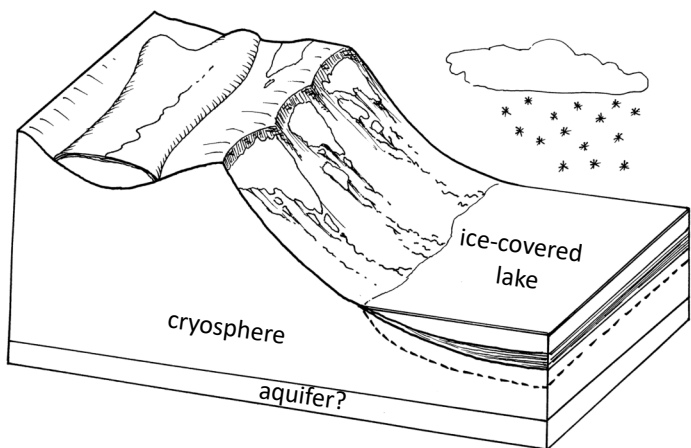
warm & wet



warm & dry

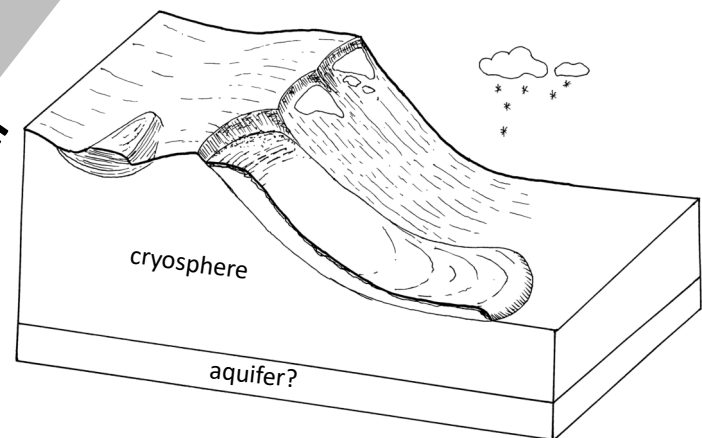


$T_{surf} = 0^{\circ}\text{C}$



cold & wet

TODAY



cold & dry

$(\text{Aridity Index})^{-1} = 40$

