BILLION-YEAR RECORDS AND MODEL PREDICTIONS OF ARIDITY CHANGE ON MARS.

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Summary: We still do not know why Mars' climate stopped supporting lakes, arguably the biggest known environmental catastrophe. One option is that warm events ceased (temperature control) [1], another is that it got dry while staying warm (water-loss control) [2]. We sum up new geologic constraints on aridity over time, then put them in the context of big-picture questions, data synthesis, and models.

Latest results: As summarized in [3], we built a globally-distributed database of constraints on Mars late-stage paleolake size relative to catchment area (aridity index), and found evidence for climate zonation as Mars was drying out. Aridity increased over time in southern midlatitude highlands, where lakes became proportionally as small as in modern Nevada. Meanwhile, intermittently wetter climates persisted in equatorial and northern-midlatitude lowlands (Fig. 1). This is consistent with a change in Mars' greenhouse effect that left highlands too cold for liquid water except during a brief melt season, or alternatively with a fall in Mars' groundwater table. When we compare our new data to previously collected data from earlier time slices [4,5], the combined data are consistent with a switch of unknown cause in the dependence of aridity index on elevation, from high-and-wet early on, to high-and-dry later (Fig. 1). The evidence for the early high-and-wet pattern is not as clear as the evidence for the late-stage high-and-dry pattern. We do not understand this apparent shift: it might be linked to changes in global temperature, with snow/ice availability being limiting early on, as suggested by [6]. More modeling by multiple groups is needed, taking account of water movement (cycling?) between the deep subsurface and the atmosphere.

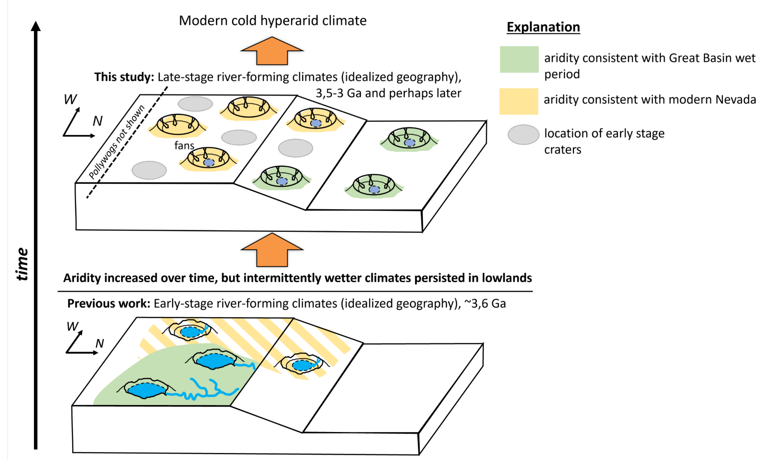

Fig. 1. Graphic summary [3].

The big picture: A synthesis of work by the community suggests that Mars did not undergo a single wet-to-dry transition, but rather seven major climate transitions (Fig. 2). On Mars, climate intermittently allowed surface liquid water even after 3.0 Gya, including at Gale and perhaps also Jezero. However, there is evidence for long dry spells, with some locations fully dry after 3.6 Gya. Possible triggers for these major habitability changes include volcanic eruptions and changes in mean obliquity. Alternations between very wet climates and very arid climates hint at strong positive feedbacks in the climate system. Rivers retreated from the highest, coldest elevations over time, suggesting a waning greenhouse effect [6]. As CO_2 escape-to-space is irreversible, it cannot explain all of Mars' climate transitions. However, CO_2 escape-to-space might contribute to the overall drying trend. The data have biases and gaps. Testing the proposed sequence of events will require more radiometric dates.

Looking ahead - linking aridity records and model predictions: Multiple modeling groups run climate models that are arid in the sense of "patchy lakes covering a small fraction of the simulated surface" (e.g. [7,8]). This aridity corresponds to a small ratio of precipitation to potential evaporation (small Aridity Index). These models are motivated in part by orbiter data constraints on paleolake size (e.g. [4]). Indeed, recent work suggests the water ice cloud greenhouse effect only works when planet-averaged near-surface Relative Humidity is much smaller than for present-day Earth [7,9]. By contrast, H_2-CO_2 CIA greenhouse warming can work for all Relative Humidities (e.g. [10,11]). Thus, orbiter data analyses documenting the size of lakes over time (reconstructing Aridity Index) help to constrain simulations of Early Mars climate and climate change. Together, data and models can constrain whether Early Mars was intermittently an Earth-like planet (perhaps with an ocean), or alternatively had an exotic climate regime unlike any recorded during Earth's history.

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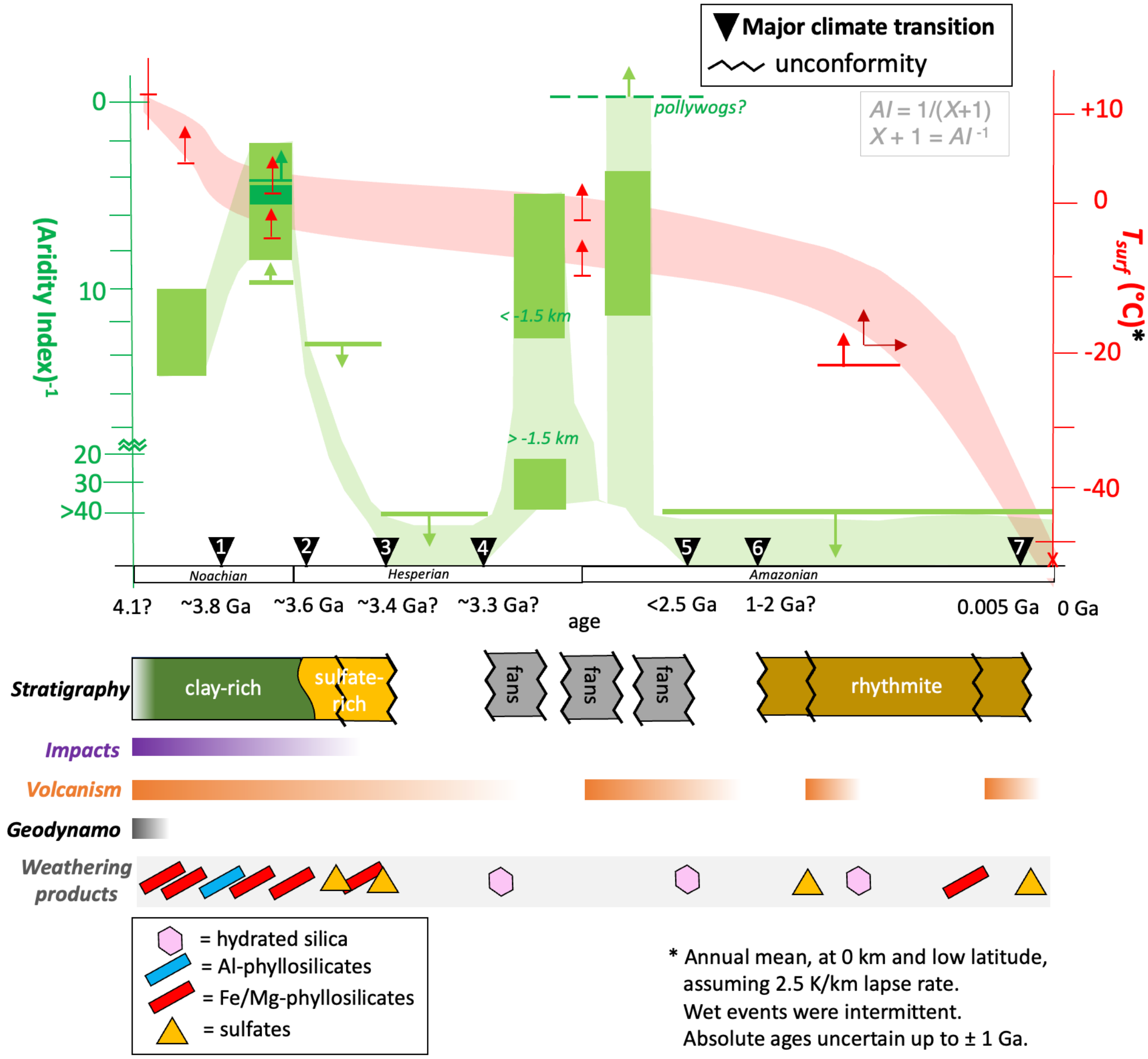

Fig. 2. Interpretative synthesis of community efforts concerning major environmental transitions of Early Mars, emphasizing aridity changes (green). Pastel bands connecting constraints are one possibility among many. This figure shows only long-term changes, and is biased toward the warmest and wettest events because these leave geologically obvious traces. Shorter-timescale climate fluctuations also occurred. Some constraints depend on parameters. Aridity references: Early/Mid-Noachian: [12]. Late-Noachian/Early-Hesperian: X = 1-4 based on valley incision [13], 3.1–7.7 [14] and $\lesssim$ 2.84 [4] from paleolakes. Late-stage lakes X-ratio: 4-12 below -1500m and 20-35 above -1500 m [3]. Gale late-stage lakes: ref. [15]. Gale lakes and mudcracks: climate transition scenario of refs. [16-17]. Temperature curve uses elevation of water-associated landforms and the assumption that rivers do not form for annual-average temperature <-18°C (no latitude adjustment), which is the annual average temperature for stream-fed lakes in McMurdo Dry Valleys: LN/EH: Warrego Valles, +7 km. Alluvial fans, +4 km. Lyot, - 3.5 km. Middle Noachian constraint is from [18]. Temperature symbol for rhythmite (dark red) assumes the seasonal meltwater hypothesis [19]. Lower strips are modified after refs. [20-22].