CADENCE AND CAUSE OF LAKE-FORMING CLIMATES ON MARS.

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The problem: Many models give an account of how Early Mars' *mean state* approached the melting point, but all have trouble matching the constraints on the *time-variability* of climates that permitted precipitation-fed lakes - their number, duration, and spacing.

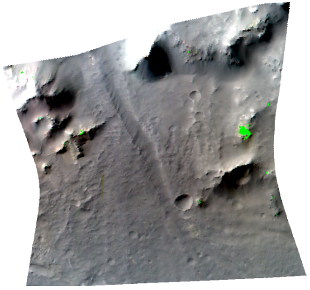

Fig. 1. The olivine constraint. An olivine outcrop in an alluvial fan source region (fan drains to bottom of image). Olivine detections highlighted in green. CRISM FRT00016E79, Saheki crater.

Some deltas (e.g. Eberswalde), and all large alluvial fans, had a top-down water source (rain or snowmelt). Hydrologic constraints suggest Lake Eberswalde lasted 10^4-10^6 yr [1]. Alluvial-fan volume and facies suggest >3 km column runoff [2], requiring $>10^4$ yr runoff in a snowmelt climate. Olivine dissolves in $<10^7$ yr for Mars-relevant conditions [3], but olivine is found in both the source regions (plus adjacent plateaus) and the deposits of post-Noachian Mars rivers (e.g. Fig. 1). After sediment transport ceased, subsequent soil-wetting events were insufficient to dissolve all the olivine. Many sites show two generations of river valleys [e.g. 4]. Crisp banks are seen on young valleys, but older valleys have subdued banks. This suggests a long interval of diffusive bank-softening between valley-forming events. The rarity of late-stage incision into delta deposits and the rarity of embedded craters within alluvial fans suggest fan deposition was completed in $<10^8$ yr, with little or no reactivation. These data suggest that post-Noachian lake-forming climates were (a) widely separated in time, (b) lasted $>10^4$ yr individually, (c) were few in number but (d) cumulatively lasted $<10^7$ yr (to allow olivine to survive globally). What model can match these constraints?

How well do proposed triggers of lake-forming climates match cadence constraints?: Wetting the soil (dissolving olivine) requires much less rain/melt than sediment transport by runoff (because of refreezing and infiltration). If the atmosphere was thin, and wetting was due to snowmelt, then runoff requires ~50 W/m^2 more energy than does soil wetting. This large energy gap, plus the olivine constraint and the lake-lifetime constraint, together imply that the post-Noachian climate system was below the melt threshold in most times and places, *but when it was above the melt threshold it was also above the sediment-transport threshold for a surprisingly large fraction of that time.* A baseline of warming can be provided by long-lived greenhouse gases such as CO_2(+/-H_2), supplemented by cloud and $H_2O_{(v)}$ feedbacks [5-7]. However, long-lived forcings cannot be solely responsible for lake-forming climates, because this would violate the olivine constraint. Possible triggers for lake-forming events are impacts, volcanic SO_2, solar brightening, tidal breakup of a low-albedo moon, and orbital variability. SO_2 warming struggles to match the minimum-duration constraint [8]. Post-Noachian impacts usually had subdued local hydrologic response, so why would they have a global response [9]? Cirrus-warming can be a positive feedback on orbital forcing, or indeed on any trigger [6]. It is not clear what would halt metastable H_2O-supported climates (whose existence is model-dependent); if the duration of metastable climates is set by H_2 escape at current (slow) rates [10], then metastable wet climates would last too long to match the olivine constraint. Groundwater-outburst floods have the right cadence to match cadence constraints on the triggers of lake-forming climates, but $H_2O_{(v)}$ released by outbursts is cold-trapped close to source and does not affect global climate [11,12]. CO_2 release during outburst floods is probably unimportant [13]. Is there an alternative scenario that better matches the data?

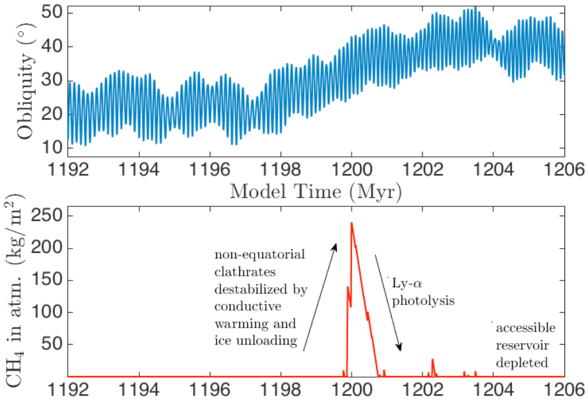

Fig. 2. (Preliminary) CH_4-release scenario, driven by orbital forcing from one of our 912 possible histories. Ice-load removal drives the main release pulse, with heating dominant for later minor pulses.

Can variable lake-forming climates be triggered by orbital variability?: The main driver of climate variability on 10^2-10^7 year timescales on Amazonian Mars is thought to be orbital forcing, so perhaps the main driver of climate variability on these lake-hydrology-relevant timescales on Early Mars was also orbital forcing.

To test this, we calculated ~4 trillion years of Mars obliquity/eccentricity/longitude-of-perihelion (912 randomly-initialized runs each >3.5 Gyr long), using `mercury6` and J.C. Armstrong's obliquity code. Including solar brightening, the annual-maximum insolation that is exceeded (somewhere) for 10^7 yr tends to be <50 W/m^2 below the overall-maximum insolation. Therefore, the hypothesis that direct forcing by orbitally-driven insolation is solely responsible for the variability of lake-forming climates is in tension with the olivine constraint.

The *transitions* in mean (10^6-yr averaged) obliquity, ϕ, are more attractive as a candidate trigger for lake-forming climates. ϕ transitions last a few Myr, and are remarkably rare (it is a coincidence that a ϕ transition occurred only ~5 Mya) [14,15]. To illustrate this, set the boundary between high ϕ and low ϕ at 40° (about the threshold for equatorial vs. non-equatorial surface ice). Then, time-travelling to a random point in Mars' history, one would expect to find oneself in an interval of continuously high (or low) ϕ of 800 Myr duration. If Early Mars lasted ~1 Ga, then the median number of ϕ transitions is 1. Two or fewer ϕ transitions occur for 72% of "Early Mars" instantiations. The brevity and large time interval of ϕ transitions make them an attractive trigger for rare lake-forming climates. But what mechanism could link ϕ transitions to lake-forming climates?

Mechanism #1: Methane bursts: CH_4 stored in clathrates is quickly released by warming [26] and decompression when ice cover migrates subsequent to obliquity shift. Although CH_4 is irreversibly destroyed by photolysis, this is photon-limited at high CH_4 concentration. This might permit a CH_4 boost to the greenhouse effect lasting $>10^5$ yr, provided >1 mbar of CH_4 (≡ 20 cm global-equivalent layer of clathrate) destabilized in $<10^5$ yr. A low-to-high shift in ϕ warms and depressurizes (via ice-overburden removal) shallow-subsurface clathrates poleward of ~30°. A preliminary calculation is shown in Fig. 2. (CH_4 can also be quickly released by a groundwater outburst [19].) Assuming that snow/ice is just below the melting point in the absence of CH_4, long-wave radiative forcing from CH_4 in CO_2-dominated atmospheres can exceed 25 W/m^2 [16]. This gives 300 m^3 km^{-2} hr^{-1} meltwater, well within the range of runoff estimates for river-forming climates [17]. With $H_2O_{(v)}$ and cirrus feedback, discharge increases. Therefore, CH_4 release could in principle trigger a lake-forming climate. In this scenario, the cold shallow subsurface acts as a capacitor for CH_4 (ultimately sourced from water-rock reactions). The greenhouse-warming potential is released in one-to-a-few bursts in Mars' past, and the clathrate reservoir is almost all depleted today. Mechanism #1 can be tested by photochemical modeling of CH_4 oxidation in a water-rich atmosphere, as well as by geologic assay of the number of lake-forming events (which cannot exceed a few in this scenario).

Mechanism #2: $H_2O_{(v)}$ feedbacks on a planet with more H_2O: Mars had ~3× more H_2O ~3 Gya [27]. Adding H_2O does not directly cause a wet Mars surface: the "extra" ice piles up at cold traps, still frozen [22,23]. However, adding H_2O can indirectly cause a wet Mars surface. For example, a thicker ice cap requires more time to completely shift from the pole to the equator. This increased time delay implies that, during rare shifts from low φ to high ϕ, ice at the pole can persist to higher obliquity. Therefore, the peak water vapor pressures above the pole are higher [9]. Direct $H_2O_{(v)}$ radiative forcing, plus cloud feedbacks, then warm the planet. Once all the ice has shifted to the equator (10^5 yr?), or retreated beneath $\gg 1$ m sublimation/debris lag, the lakes dry out. #1 and #2 predict geologically-simultaneous discharge from destabilized groundwater reservoirs [20].

Mechanism #3: Late-stage carbonate formation: A climate evolution model for Mars with only CO_2, surface snow/ice, and solar brightening, can produce late bursts of habitable climate on Mars – the trigger is late low-to-high ϕ shifts. Rapid CO_2 removal could end the wet burst, by increasing evaporitic cooling [24]. CO_2 removal by (post-Noachian) escape-to-space processes cannot remove climatically significant CO_2 in 10^7 yr. CO_2 removal by carbonate formation can end the wet episode more quickly. The amount of CO_2 that must be sequestered is >20 mbar. The only sufficiently voluminous and sufficiently young reservoir for carbonate is the dust-covered "rhythmite" rocks [25]. If late-stage carbonate formation is responsible for the end of lake-forming climates on Mars, then "rhythmite" must contain several wt% carbonate. "Rhythmite" is exemplified by the upper mound in Gale. Therefore, nondetection of carbonate in the upper mound would disprove mechanism #3. This test requires that MSL is driven at least as high as the major unconformity marking the boundary between the Lower and Upper formations at Mt. Sharp.

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