Persistent or repeated surface habitability on Mars during the Late Hesperian - Amazonian

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Abstract.
Large alluvial fan deposits on Mars record the most recent undisputed habitable window of surface conditions (≤3.5 Ga, Late Hesperian – Amazonian). We find net sedimentation rate <(4-8) μm/yr in the alluvial-fan deposits, using the frequency of craters that are interbedded with alluvial-fan deposits. Considering only the observed interbedded craters sets a lower bound of >20 Myr on the total time interval spanned by alluvial-fan aggradation, >103-fold longer than previous lower limits. A more realistic approach that corrects for craters fully entombed in the fan deposits raises the lower bound to >(100-300) Myr. Several factors not included in our calculations would further increase the lower bound. The lower bound rules out fan-formation by a brief climate anomaly. Therefore, during the Late Hesperian – Amazonian on Mars, persistent or repeated processes permitted habitable surface conditions.

1. Introduction.

Large alluvial fans on Mars record one or more river-supporting climates on ≤3.5 Ga Mars (e.g. Moore & Howard 2005, Grant & Wilson 2012, Kite et al. 2015, Williams et al. 2013) (Fig. 1). This climate permitted precipitation-sourced runoff production of >0.1 mm/hr that fed rivers with discharge up to 10² m³/s (Palucis et al. 2014, Morgan et al. 2014). The large alluvial fans correspond to the youngest (Grant & Wilson 2011) unambiguous evidence for Mars surface habitability. Although small (<10 km²) alluvial fans with >10° slopes formed <5 Mya on Mars, these need not record a habitable environment (e.g. Williams & Malin 2008), and might not be the result of liquid water (Pilorget & Forget 2016). By contrast, large (>10 km²) alluvial fans with ≤2° slopes formed from aqueous flows (Williams et al. 2013), and these fans are more deeply eroded and more cratered, so they are older. In this paper we focus on the large alluvial fans. Did they result from a single anomalous burst of wet conditions, such as might result from an impact (Williams & Malin 2008) or volcanic eruption? Or, do the fans record persistent or repeated wet conditions, for example as the result of a sustained warmer climate regime? Better constraints on the time span of alluvial fan formation would constrain models of Late Hesperian – Amazonian climate.

Previous work on the duration of the interval of fan build-up used sedimentology to estimate the time over which sediment transport occurred (e.g., Armitage 2011, Williams et al. 2011, Palucis et al. 2014). These sedimentologic methods require assumptions about flow intermittency or sediment:water ratio, which (for almost all Mars alluvial fans) are poorly constrained. Therefore, the lower limits obtained from sedimentological methods are short –
for example, ~3600 years (Morgan et al. 2014). Moreover, brief (1-100 yr) aggradation intervals have been proposed for deltas on Mars that are similar to the alluvial fans in age and volume (Kleinhans et al. 2010, Hauber et al. 2013). Another approach to estimating the interval of alluvial-fan build-up is to measure the density of craters superimposed on different fans, and use the spread of crater-retention ages for the fan surfaces as a proxy for the range of fan-formation ages. This method is not reliable, because crater-retention ages for areas <10^3 km^2 are not reliable (Warner et al. 2015). Therefore, the time span of habitable climates in the Late Hesperian - Amazonian remains an open question.

**Figure 1.** Large alluvial fans on Mars (28°S 333°E). The ≤3.5 Ga age of the fans is shown by their low crater density. Aeolian erosion exposes layers and channels within the deposit.
Figure 2. Idealized cross-section through an alluvial fan deposit. Crater density within alluvial fans may be estimated using the frequency of visible interbedded craters at the exposed surface. Case A: If postfluvial erosion was modest, some craters that formed late in the history of alluvial-fan aggradation (filled semicircles) are only partially buried and are visible today (though outnumbered by postfluvial craters; outlines). Case B: If postfluvial erosion was severe, the areal density of exposed embedded craters of a given diameter is still proportional to the volumetric density of those craters. In either case, assuming steady aggradation, a count of interbedded craters constrains the fan aggradation rate.

To get a more accurate estimate of the interval over which alluvial fans formed, we used the embedded-crater method (Hartmann 1974, Kite et al. 2013a). This method works as follows. Crater density on a quiescent planetary surface is proportional to exposure duration. This method may be extended to three dimensions: the total number of craters interbedded within a sedimentary deposit is proportional to the time spanned by active sedimentation (including any hiatuses) (Fig. 2). The greater the volumetric density of craters, the longer the time span of deposition. Of course, many or most of the interbedded craters may be
completely buried (Fig. 2); therefore a complete count of interbedded craters is usually impossible. However, if an impact occurs near the end of active sedimentation, then the corresponding crater may be only partially buried. Smaller craters are more readily buried, and larger craters require more sediment to be completely obscured. The time needed to accumulate the population of visibly embedded (synfluvial) craters is

\[ \tau_{\text{raw},D} = \frac{N_D}{(f_D \ a)} \]  

where \( D \) is the minimum crater diameter of interest to be considered, \( \tau_{\text{raw},D} \) is the minimum time required to build up the observed embedded-crater population, \( N_D \) is the number of observed embedded craters, \( f_D \) is the past crater flux (\#/km²/yr), and \( a \) is the count area (km²). Prefluvial craters (which are overlain by alluvial fan deposits, but that formed before the start of fluvial deposition; Irwin et al. 2015) are excluded. This procedure gives a strict lower limit on the interval of fan formation; it does not account for craters that are fully entombed within the deposit. To correct for fully entombed craters, we can assume steady aggradation and divide fan thickness \( Z \) by best-fit aggradation rate \( W \) to get duration of fan formation \( \tau_{\text{steady}} \):

\[ W_D \approx 1.33 \ D \varphi / \tau_D \]  

\[ \tau_{\text{steady},D} = Z / W_D \]

The numerator in [2] corresponds to the required burial depth for obliteration. The amount of burial that is required is constrained by the geometry of small impact craters (Melosh 1989, Watters et al. 2015). \( \varphi \) is the obliteration depth fraction for a given crater, expressed relative to crater diameter. (In this paper, we define a crater as “obliterated” if it can no longer be identified in a high-resolution optical image; Kite & Mayer 2016). The factor of 1.33 corrects for the fact that, for any minimum-diameter \( D \), the median diameter in a count will exceed \( D \) – thus, \( D \varphi \) is an underestimate of the required burial depth. This correction depends on the crater production function used. The correction is relatively small (1.3×-1.5×) in our size range of interest, because crater frequency falls off steeply with increasing diameter, and we represent it by a fixed factor. Post-depositional erosion of alluvial fan deposits does not affect this procedure. A randomly oriented cut through the crater-containing volume intersects each crater with a probability proportional to that crater’s size; the sample of craters partially exhumed at an erosional surface is biased towards larger impacts. Just as with partial burial, the number of craters that are exposed is proportional to the volumetric crater density (and inversely proportional to aggradation rate). Thus, the volumetric density of interbedded craters may be estimated from surface counts both on pristine fan surfaces and for fans that are deeply eroded (Kite et al. 2013a). Therefore, embedded-crater counts can be used as a Mars fluvial process speedometer.

2. Methods and results.

In order to set a lower bound on the time span of alluvial-fan formation, we searched \( 1.7 \times 10^4 \) km² of previously-catalogued fans (corresponding to most of the surface area of large alluvial fans on Mars; Wilson et al. 2012) using 6m-per-pixel CTX images to scout for candidate embedded craters. Candidate craters show possible evidence of interbedding with
paleochannels or other fan deposits. Each candidate feature was reviewed by three of the authors (E.S.K, D.P.M., and J.S.) for final classification. Where available, 25cm-per-pixel HiRISE images and anaglyphs, plus CTX Digital Terrain Models (DTMs) were used to inspect candidates flagged in the initial CTX survey. HiRISE anaglyphs proved particularly valuable for detecting crater rims. Each candidate feature was categorized as quality level 1, 2, 3 (representing decreasing confidence that the crater was embedded), or it was discarded. A total of 25 embedded craters were found at <30° latitude ($D = 0.08 - 5.0$ km; Fig. 3, Supplementary Information). These embedded craters were then classified (usually with the aid of 24-m-per-pixel CTX DTMs) as “synfluvial,” “uncertain”, or “prefluvial.” These craters constitute a tiny fraction of the total number of craters on the surfaces of the fans (Grant & Wilson 2012).

**Figure 3.** Embedded craters within alluvial fans on Mars from our catalog (Supplementary Information).

A supplementary HiRISE-only survey (570 km$^2$) was carried out to check for resolution effects. 13 embedded craters were found ($D = 0.05 - 0.22$ km; Supplementary Information). HiRISE embedded-crater densities $N_D/a$ for $D<0.2$ km are the same (within Poisson error) as CTX embedded-crater densities for $D>0.2$ km. Therefore, the HiRISE check provides no evidence that our conclusions would be changed by a HiRISE re-survey of the $1.7 \times 10^4$ km$^2$ area covered by our CTX survey.

Diameter measurement error was estimated by blindly remeasuring craters and found to be negligible compared to other errors. Possible crater shrinkage or expansion during degradation is ignored.

The contribution of false positives to our catalog is likely small. Although polygonal faulting in Earth marine sediments can produce crater-like concentric layering (Tewksebury et al. 2014), this is unlikely for Mars alluvial-fan deposits. For example, the embedded craters are isolated (not space-filling), and frequently show preserved rims. On the other hand, there are certainly false negatives in our survey area: re-survey of a crater of interest found several additional candidates with scores $\leq 3$ on panel inspection. Therefore, our crater densities are lower limits.

We estimated alluvial fan thicknesses by differencing CTX DTM profiles across fans and analogous profiles across parts of the same fan-hosting craters ($n = 13$) that lacked fans. We found maximum fan thickness of 1.1 km, with thicknesses $\sim 1$ km common.
3. Analysis.

The usual procedure for estimating crater-counting error is to use Poisson statistics (Michael et al. 2016). The results of this procedure are shown by the blue lines and blue error bars in Fig. 4. To generate these results, we assumed a fixed crater flux (Michael et al. 2013), no change in atmospheric screening from today’s Mars, a strong-rock target strength, and a fixed obliteration depth fraction \( \varphi = 0.1 \).

The true error is larger than this because of uncertainty in (1) true crater flux (Johnson et al. 2016), (2) target strength, (3) filtering by a potentially thicker past atmosphere, (4) the time of formation of the alluvial fans, and (5) the amount of burial or erosion – expressed as a fraction of the crater’s diameter – that is needed to prevent the crater from being detected at CTX resolution. Therefore, we adopted conservative prior probabilities on parameters (1) - (5) in a Monte Carlo simulation of our lower bound that also includes Poisson error (details are given in the Supplementary Information). Specifically, we assumed (1) a factor-of-4 uncertainty in crater flux (log-uniform uncertainty between 0.5× and 2× the Michael et al. 2013 fluxes); (2) log-uniform uncertainty in target strength between limits of 65 kPa and 10 MPa (Dundas et al. 2010); (3) log-uniform uncertainty in paleo-atmospheric pressure between limits of 6 mbar and 1000 mbar for a simple model of atmospheric filtering; (4) a uniform uncertainty between fan formation 2.0 Ga (low-end fan crater retention age) and 3.6 Ga (age of the large craters which host alluvial fans); and (5) a log-uniform prior for obliteration depth fraction (expressed as a fraction of crater diameter) from 0.05 (rim burial; Melosh 1989) and 0.2 (original crater depth; Watters et al. 2015). For each of \( 10^3 \) Monte Carlo trials, the effect of Poisson error is calculated analytically. Given the observations and the randomly-sampled parameters, each Monte Carlo trial yields an analytic probability for each candidate age (or each candidate aggradation rate) in each size bin. These probabilities are summed over \( 10^3 \) Monte Carlo trials and normalized. Results are shown by the gray error bands and black stars in Fig. 4.

We report only lower limits because we do not know our false negative rate, and it is possible that many embedded craters are easily identifiable as impact craters in CTX imagery, but have an expression that is indistinguishable from postfluvial craters at CTX scale.

The best-fit lower limit (Fig. 4a) increases with increasing diameter, as expected. Bins \( \geq 1.4 \) km contain only 1 crater, and the Poisson uncertainty constitutes most of the total uncertainty in the lower limit. For the smaller diameters, the counting-statistics error is small compared to the total uncertainty in the lower limit, but systematic undercounting of embedded craters is most likely for craters that are smaller and thus more easily buried and modified. The largest \( > 1 \) km-diameter bin contains 2 embedded craters and yields a 2-sigma lower limit of \( > 17 \) Myr, which we round to \( > 20 \) Myr. Using the single \( \sim 5 \) km crater found in our survey gives a \( > 54 \) Myr lower bound.
Figure 4. (a) Minimum time-span of sedimentation based on observed synfluvial craters. Blue error bars bracket the 90% confidence intervals on lower limit (by Poisson estimation). Full Monte Carlo fit corresponds to the gray band. Black zone is excluded with >95% confidence. White zone is excluded in <5% of trials. Black asterisks correspond to the median outcome of the Monte Carlo procedure. Red dashed lines assume a constant aggradation rate and that burial by 10% of a crater’s diameter is sufficient to obscure the crater from orbiter-image surveys. (b) Corresponding aggradation rate estimates for alluvial fans, binned by diameter. Error bars are the same as in (a).
Turning to the rate plot (Fig. 4b), constant aggradation rates of <(4-8) μm/year match our data. For sediment-water ratio of $10^{-4}$, this corresponds to runoff of <(4-8) cm/yr. Different crater diameters probe different depth ranges and thus aggradation rate over different timescales, but our data do not provide strong evidence for a change in aggradation rate with timescale (Jerolmack & Sadler 2007). Dividing typical fan thicknesses by this rate gives 125-250 Myr, which we round to 100-300 Myr. For both plots, the Monte Carlo procedure gives limits that are more uncertain (gray band versus blue error bars in Fig. 4) and slightly more permissive (black asterisks versus blue lines in Fig. 4).

The >(100-300) Myr age estimate from steady aggradation (Fig. 4b) is a more realistic estimate of the true fan-forming interval than the >20 Myr time span from observed synfluvial craters (Fig. 4a). That is because, if the observed embedded craters represent the total embedded-crater population, then fan aggradation must have started very fast and decreased sharply near the end of fan build-up. Such an accumulation history would favor small-crater preservation relative to large-crater preservation – the opposite of what is observed. Furthermore, after fluvial deposition stopped, many of the alluvial fan deposits were eroded by aeolian processes (e.g. Fig. 1). Because postfluvial erosion would destroy some embedded craters, the observed embedded craters are very unlikely to represent the total population of craters that formed embedded within the alluvial fans.

Results are plotted excluding craters for which synfluvial versus prefluvial status could not be determined, but including craters of quality score 3. These choices have little effect on our conclusions. That is because the quality-3 embedded craters, and the craters whose synfluvial status is uncertain, correspond to small diameter bins for which our counts are probably incomplete.

4. Discussion.

4.1. Factors not taken into account would increase our lower limit.

By fitting a single time-span (and separately fitting a single erosion rate) to the fan deposits, we implicitly assume that the probability of finding an embedded crater is spatially uniform. However, the observed spatial distribution of embedded craters is too clumpy to be consistent with a spatially uniform probability. For example, one site (Crater "W"; Kraal et al. 2008) has 20% of the embedded craters (5 out of 25) even though the fan area at that site is only 500 km², 3% of the total. This cluster is unlikely to be due to chance (assuming cratering is a Poisson process): if the fan area is divided into $17000 \text{ km}^2/(500 \text{ km}^2) = 34$ equal-area sites, then the expected number of craters per site is $\lambda = 25/34 = 0.73$. The probability of finding 5 or more embedded craters in at least one site is then only $1 - \left(1 - \sum_{x=5}^{\infty} f(x | 0.73) \right)^{34} = 3\%$, where $f$ is the Poisson probability distribution function. To be consistent with data at the 50% level, we must increase $\lambda$ (equivalently, fan age) by 200%. This might correspond to uniform fan age with spatially non-uniform detectability of embedded craters. Alternatively Crater "W" might record anomalously slow aggradation. In either case, our best estimate of the time span of fan-forming climates is 200% longer than in our lower limit.
Spatial staggering of fan aggradation would increase our lower limit. Time-varying orbital forcing would favor snowmelt (e.g. Kite et al. 2013b) in different places at different times. Localized precipitation would not be globally correlated (Williams & Malin 2008, Kite et al. 2011).

If the alluvial fan deposits underwent erosion during the period of net aggradation, then this would destroy some embedded craters. Therefore, if erosion occurred during fan aggradation, our upper limit would increase further.

Mars crater fluxes are extrapolated from Lunar radiogenic ages and corresponding crater densities. Those crater densities have been argued to be incorrect (Robbins 2014). We compared Robbins’ chronology function to the Neukum (2001) chronology function at $D_{min} = 1$ km. An age range of 2.0 – 3.6 Gyr (Neukum) maps to 1.4 – 3.0 Ga (Robbins). The flux uncertainty is reduced from (1-12)$\times$ modern (Neukum) to (1.5 – 2.2)$\times$ modern (Robbins). Because high aggradation rates in our Monte Carlo runs always correspond to high crater fluxes, including Robbins’ chronology would cause our error bars to shrink and thus raise our lower limit.

4.2. Implications for paleohydrology and climate.

$D < 100$ m embedded craters place an upper limit on paleoatmospheric pressure (Kite et al. 2014). Since $D < 50$ m impact craters are extremely rare on Earth (atmospheric column density $10^4$ kg/m$^3$), the existence of $D < 100$ m embedded craters in the alluvial fans on Mars suggests atmospheric column density $<2\times10^4$ kg/m$^3$, i.e. $P < 1$ bar around the time of alluvial fan aggradation.

Previous analyses of the interval over which alluvial fans formed have divided fan volume by the inferred fluvial sediment transport flux (e.g. Jerolmack et al. 2004). This duration is a lower bound on the interval over which alluvial fans formed, because not all years need produce runoff. Our lower bound exceeds sedimentological lower bounds by >1000$\times$. Many alluvial fans are ~1 km thick. Suppose a fan:alcove area ratio of 0.5. Typical water:sediment ratios on Earth are $10^3$:$1$. 2000 km of water at 0.5 m snowmelt/year gives 4 Myr. However these calculations are highly uncertain. For example, if the amount of snowmelt is limited by a snow supply rate of 10 cm/yr, then the time required rises to 20 Myr, equal to our strict lower limit on the total time span of alluvial fan formation. Therefore our data do not require intermittency. However, given quasi-periodic orbital variability, fine-tuning of Mars’ hydrological cycle is required to produce small amounts of runoff every year, especially for our preferred lower limit of >(100-300) Myr. Broadly, the very slow net aggradation rates in areas of steep relief (Fig. 1) suggest intermittency.

Intermittency in alluvial-fan-forming climate is further suggested by combining our data with other constraints. The paucity of mineralogic evidence for in-situ alteration of fan deposits (McKeown et al. 2013), the presence of hydrated silica (possibly opal; Carter et al. 2012), and the persistence of olivine which dissolves at 0°C and pH = 5.5 in <5 Myr (Stopar et al. 2006), when combined with the >20 Myr span of surface liquid water required by our
data, suggest that climate conditions were cold and that intermittency further reduced liquid water interaction with soil. Cold conditions are also suggested by sedimentary-deposit mineralogy at Gale (McLennan et al. 2014, Siebach et al. 2017). Intermittency is also suggested by multiple pulses of fan formation at Holden (Irwin et al. 2008), Gale (Palucis et al. 2016), and Melas Chasma (Williams & Weitz 2014).

In summary, the data exclude any explanation that produces a single burst of habitability of <20 Myr duration. For example, the data exclude triggering by the thermal pulse caused by the impacts that formed the large craters which host the alluvial fans. The data disfavor fluvial sediment transport every year for >20 Myr. Among other possibilities, the data permit a long-lived habitable environment (snowmelt or rainfall); a chaos trigger (Baker et al. 1991); or obliquity-paced fluvial intermittency (Kite et al. 2013b).

**Figure 5.** Geomorphic history of Mars (Howard 2007, Fassett & Head 2011). FSV = Fresh Shallow Valleys (Wilson et al. 2016). RSL = Recurring Slope Lineae, FSV = Fresh Shallow Valleys. “*” symbol denotes questionable status of gullies, which are modified by CO₂ ice. Pre-valley network fluvial sediment transport is from Irwin et al. (2013).

### 4.3. Implications for habitability.

The time span of aggradation of the alluvial fan deposits that we have calculated is a proxy for the time span of spatially associated paleolakes. Those paleolakes include candidate playa deposits at the toes of alluvial fans (e.g. Morgan et al. 2014), a >100m deep paleolake in Crater “P” (Kraal et al. 2008) suggested by a common fan-frontal-scarp elevation of -2700 m (in our CTX DTMs), and the Eberswalde paleolake (which shares a drainage divide with alluvial fans at Holden; Irwin et al. 2015). In addition, rivers and lakes occurred during the Late Hesperian - Amazonian in Valles Marineris (e.g. Mangold et al. 2004, Williams & Weitz 2014) and Arabia Terra (Wilson et al. 2016). Lake deposits have good biosignature recovery potential (Summons et al. 2011), and biosignature recovery from Proterozoic lake deposits
is routine (Peters et al. 2005). On the other hand, biosignatures would have been destroyed if lake waters were oxidizing.

5. Conclusions.

Explaining young alluvial fans on Mars is a challenge to climate models. To determine the time span of alluvial fan forming conditions, we counted embedded craters. We found a high density of embedded craters, which requires that the river-permitting climate(s) spanned >20 Myr. If aggradation was steady at \(<(4-8) \mu m/yr\), which is consistent with our data, then fan build-up required \((100-300)\) Myr (Table 1). The data make the challenge of explaining the alluvial fans more severe, because they exclude a single short-lived anomaly as the cause of the alluvial fans.

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