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Timescales of alluvial fan development by precipitation on Mars

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[1] Dozens of large, low-gradient alluvial fans are present within impact crater basins on the cratered highlands of Mars. The timescales and climate conditions that were required to generate such fans are unknown, but testable through our understanding of terrestrial hill slope erosion in the presence of precipitation. Previous estimates of fan formation time vary from years to millions of years. Here, we use an idealised physical model of 2-D catchment-fan evolution to present a framework within which the development of Martian alluvial fans should be considered. We simplify the erosional and depositional system so that there are only three variables: erodibility due to gravity, amount of water runoff due to precipitation, and catchment-fan boundary elevation. Within this framework, to generate large, low-gradient (<6°) alluvial fans on Mars requires significant periods of erosion due to runoff. We suggest two climate scenarios, either: (1) rates of precipitation that are similar to arid terrestrial climates over timescales of 10^7 to 10^8 yr or (2) a shorter duration of semiarid to temperate climate conditions over a period on the order of 10^6 yr. Hyper-arid conditions generate low-gradient alluvial fans under conditions of a topographically lowered fan-catchment boundary and only over timescales $>10^8$ yr if the substrate is extremely erodible relative to terrestrial examples. **Citation:** Armitage, J. J., N. H. Warner, K. Goddard, and S. Gupta (2011), Timescales of alluvial fan development by precipitation on Mars, *Geophys. Res. Lett.*, *38*, L17203, doi:10.1029/2011GL048907.

1. Introduction

[2] A key question for Mars exploration research is whether the planet experienced Earth-like climate conditions. Because of the astrobiological implications of a warm-wet Mars, this question has governed the course of all orbital and lander-based investigations for the last several decades. While some studies have suggested that early Mars was likely dry with relatively low erosion rates by Earth standards [*Craddock and Maxwell*, 1990; *Golombek et al.*, 2006], morphologic observations of Martian surfaces spanning the Noachian (4.1 Ga to 3.7 Ga), Hesperian (3.7 Ga to 2.9 Ga), and Amazonian (<2.9 Ga) Periods (chronology after *Hartmann and Neukum* [2001]) continue to indicate the likelihood that significant surface runoff occurred as a result of precipitation, with the most globally extensive evidence occurring in the form of dense valley networks and highly degraded impact craters on Late Noachian-age surfaces [*Craddock and Maxwell*, 1990; *Carr*, 1996; *Hynek and Phillips*, 2003; *Howard et al.*, 2005; *Irwin et al.*, 2005].

[3] It is unclear whether the observed valley networks, lakes, alluvial fans, and putative deltas on the ancient terrains of Mars [*Malin and Edgett*, 2003; *Howard et al.*, 2005; *Irwin et al.*, 2005; *Moore and Howard*, 2005; *Fassett and Head*, 2008a, 2008b; *Grant et al.*, 2011; *Warner et al.*, 2010] required Earth-like climate conditions to form. Furthermore, the duration, episodicity, and time-averaged rate of atmospherically-generated precipitation, leading to the development of fluvial-lacustrine features, is not well constrained. However, sedimentary fans formed within crater basins provide observations that are testable against physical models of surface erosion and fan deposition. Dozens of low-gradient alluvial fans have now been identified within ancient, Noachian to Hesperian-age impact crater basins along a consistent latitude band of the southern highland terrain [*Moore and Howard*, 2005]. With their highly dissected alcove catchments and channelized fan surfaces, these fans may be indicative of a relatively intense period (or periods) of Martian precipitation and fluvial activity, with age estimates for the fan surfaces (from impact crater statistics) ranging from the late Noachian to the Amazonian [*Moore and Howard*, 2005; *Grant and Wilson*, 2011; *Howard and Moore*, 2011]. Here, we investigate erosion and fan growth within an idealized Martian impact crater using a non-linear diffusion model that describes the gross characteristics of crater rim erosion and sediment delivery with different possible inputs of precipitation, hillslope diffusion and fan-catchment boundary height. The objective of this study is to constrain likely scenarios for the generation of sufficient sediment flux to produce large, low-gradient alluvial fans within impact craters under different conditions of precipitation and time. Our results provide estimates for the likely maximum and minimum duration of climate warming if fan development occurred by Earth-like precipitation-induced runoff.

2. Methods

[4] On a gross scale, catchment erosion can be treated as a non-linear diffusive process [*Smith and Bretherton*, 1972; *Simpson and Schlunegger*, 2003]. In our model, erosion is due to hillslope diffusion (gravity flow) on the interior of an impact crater and water runoff is provided by a time-averaged rate of atmospheric precipitation. This approach has been shown to reproduce expected catchment morphology for 3-D simulations [*Simpson and Schlunegger*, 2003] and captures the concentrative effect of erosion due to water runoff. The sediment flux is given by,

$$q_s = \kappa \frac{\partial h}{\partial x} + c(\alpha x)^n \frac{\partial h}{\partial x} \qquad (1)$$

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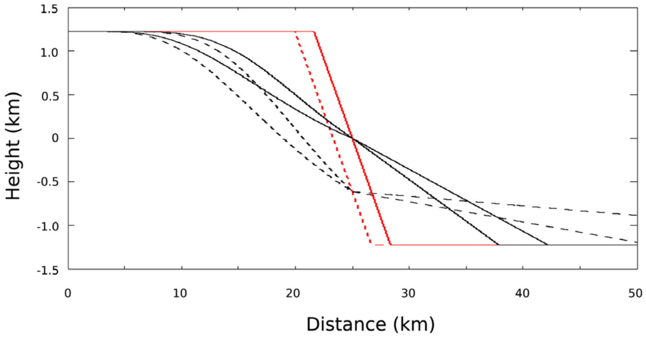

Figure 1. Idealised 2-D crater rim erosion and fan deposition model. Red lines show the initial condition and black lines the subsequent topography at 12.5 and 25 Myr. Solid lines are topography for a fan head elevation that is high (half rim height), dashed lines are topography for a fan head elevation that is low (quarter rim height).

The first term quantifies hillslope diffusion, the second erosion due to runoff. While the difference in the gravitational constant of Mars (3.72 ms^{-2}) relative to Earth is not directly modeled, gravity is inherent to the linear transport coefficient κ, which we vary by three orders of magnitude from 10^{-1} $\mathrm{m^2yr^{-1}}$ (easily eroded bedrock) to 10^{-3} $\mathrm{m^2\ yr^{-1}}$ (highly resistant bedrock), with 10^{-2} $\mathrm{m^2yr^{-1}}$ being the most commonly used value for κ in terrestrial and Martian systems [*Densmore et al.*, 2007; *Howard*, 2007; *Armitage et al.*, 2011]. In equation (1), $c = 10^{-6}$ $(\mathrm{m^2yr^{-1}})^{1-n}$ is the non-linear transport coefficient, α ($\mathrm{myr^{-1}}$) is the precipitation rate, and $n = 2$ is the exponent that describes the dependency of sediment transport on fluid discharge [*Simpson and Schlunegger*, 2003; *Densmore et al.*, 2007]. The idealized impact crater used in our model to construct the fans is 50 km in diameter, with a pristine interior crater wall height of 1.6 km [*Garvin et al.*, 2003]. The crater rim slope is initially 20°. Erosion is modeled up to a distance of 25 km from the rim (Figure 1). Change in elevation within the catchment is then given by,

$$\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left[\left(\kappa + c(\alpha x)^n\right)\frac{\partial h}{\partial x}\right] \tag{2}$$

With the diffusional approach to erosion we can define a response time to change in Martian climate, $T = L^2/\kappa_e$, where κ_e is the effective diffusivity as given in equation (2). Assuming an arid precipitation of 0.01 $\mathrm{myr^{-1}}$, a hillslope diffusivity of 10^{-2} $\mathrm{m^2yr^{-1}}$, and a catchment length of 25 km then $T \sim 10^9$ yr. Assuming temperate Earth-like rainfall of 1 $\mathrm{myr^{-1}}$, the response time reduces to $T \sim 1/(c\alpha^2) \sim 10^6$ yr. This would suggest that landscapes respond at least on the timescale of millions of years and that fan development to a steady state must follow on a similar scale.

[5] To understand the time evolution of a Martian fan we use the prediction of sediment flux out of the eroded crater rim to estimate fan development using two assumptions. First, we fix the elevation and position of the transition of catchment to fan, not allowing for erosion to continue into the fan and deposition in the catchment (Figure 1). On Earth, the elevation of the transition from catchment to fan has been shown to be controlled by a complex set of transport and depositional processes that likely lead to a continuity of slope [*Bull*, 1964; *Talling and Sowter*, 1998; *Densmore et al.*, 2007]. At long timescales erosion may push out into the fan thus reducing the fan head height. Or if the crater was to become filled and accommodation space is reduced, the fan head may retreat up into the catchment. Generally, the assumption of a fixed boundary is tenable for fans that have developed within impact craters on Mars, as base level for the fans may have been fixed in the absence of tectonics. However, some degree of fan head movement is to be expected. We therefore model two fan head elevations, high (half rim height; Figure 1, solid lines) and low (quarter rim height; Figure 1, dashed lines). This will capture to a degree the range of fan head movement throughout the system evolution.

[6] Second, we model deposition by a volume balance approach [*Densmore et al.*, 2007; *Armitage et al.*, 2011], rather than by a diffusional approach [*Paola et al.*, 1992]. We assume a constant fan gradient, as has been observed for steady-state fans in Death Valley [*Densmore et al.*, 2007], where individual depositional events are integrated over thousands of years. The geometry of the modeled Martian fan is calculated by finding the gradient of fan that has an area beneath a straight line, projected from the catchment-fan boundary, which matches the area eroded from the catchment. At each increment of time, the fan builds on top of the last fan surface so that the fan toe pushes out towards the center of the crater. By treating fan deposition as a simple balance of sediment budget, we time integrate the individual processes, such as changes in fan width within single channel flows [*Armitage et al.*, 2011]. Given the range of yet unknown parameters for complex models of erosion and deposition of alluvial fans on Earth [e.g., *Clevis et al.*, 2003], the model simplifications that we present here for the Martian scenario are designed to reduce the unknowns of the system, thus leaving the following three variables: precipitation (α), erodibility of the catchment (κ), and the position of catchment fan transition.

[7] Equation (2) is made dimensionless by the length of the catchment, x_c, and the time-scale x_c^2/κ, giving,

$$h = x_c\tilde{h} \qquad x = x_c\tilde{x} \qquad t = \frac{x_c^2}{\kappa}\tilde{t} \tag{3}$$

equation (2) becomes,

$$\frac{\partial\tilde{h}}{\partial\tilde{t}} = \frac{\partial}{\partial\tilde{x}}\left[\left(1 + D_e\tilde{x}^n\right)\frac{\partial\tilde{h}}{\partial\tilde{x}}\right] \tag{4}$$

where D_e expresses the relative importance of the concentrative processes of water run off versus the hillslope dispersive processes.

$$D_e = \frac{c(\alpha x)^n}{\kappa} \tag{5}$$

If D_e is greater than one, erosion of the catchment is dominated by fluvial processes. If it is less than one, then hillslope diffusion dominates. Equation (4) is solved using a standard finite element approach with linear weighting functions and linear time steps [*Zienkiewicz and Taylor*, 2000].

3. Results

[8] Figure 2 relates scenarios of precipitation, catchment erodibility (colored lines), and fan head elevation (dashed

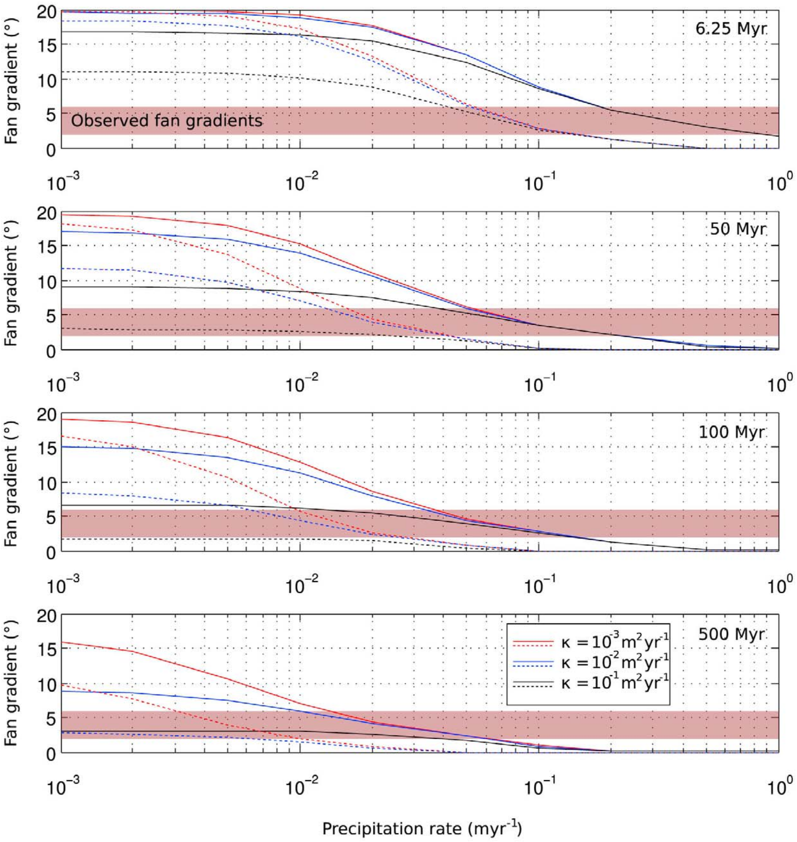

Figure 2. Fan slopes for differing rates of precipitation and hill slope diffusivity (κ). From top to bottom, fan slopes are plotted for increasing periods of model time, 6.25 to 500 Myr. Solid lines are topography for a fan head elevation that is high (half rim height), dashed lines are topography for a fan head elevation that is low (quarter rim height). The pink shaded area shows the range of crater fan slopes compiled by *Kraal et al.* [2008] and *Moore and Howard* [2005].

and solid lines), to the surface gradient of a Martian fan for different cumulative periods of precipitation. Gradients of large Martian sedimentary fans, calculated from Mars Orbiter Laser Altimeter (MOLA) topography data, are between 2° and 6° [*Moore and Howard*, 2005; *Kraal et al.*, 2008]. We highlight this slope band in Figure 2 and note the conditions required to generate this morphology.

[9] The fan development scenarios indicate that if precipitation is low ($<10^{-2}$ myr^{-1}) such that $D_e < 1$, then it will take a considerable duration of erosion due to water run off ($>10^8$ yr) to form fans of gradient <6°. However if precipitation is high such that $D_e > 1$ where fluvial erosion is large relative to hill slope diffusion, or the surface of Mars is formed of loose material with a large hill slope diffusivity ($\kappa \sim 10^{-1}$ m^{2}yr^{-1}), then with only a fraction of time averaged precipitation, low fan gradients can be generated (Figure 2). Finally, if fan head height is low (Figure 2, dashed lines) then the amount of precipitation required is reduced but not by more than an order of magnitude. This allows us to place bounds on fan formation timescales.

[10] More specifically, for all values of κ, if water in the atmosphere remained for a relatively short period of time (6.25 Myr), low-gradient fans are only formed under semi-arid to temperate Earth-like precipitation, with rates >0.2 myr^{-1} (Figure 2). As the duration of precipitation increases to between 50 Myr and 500 Myr, an order of magnitude less rainfall is required to reproduce the slopes observed. Given Earth-like values for κ (10^{-2} m^{2}yr^{-1}), and under the modeled 50 Myr timescale, the observed low-gradient Martian fan slopes are produced with precipitation rates between 0.01 and 0.05 myr^{-1}. At 100 Myr, between 0.005 and 0.03 myr^{-1} would be required, and for 500 Myr, <0.01 myr^{-1} is indicated. Complete burial of the impact crater (zero fan and catchment slope) by alluvial fans occurs (given all values of κ) under semiarid to temperate climate conditions (0.2 to 0.5 myr^{-1}) at >100 Myr. For erodible catchments ($\kappa = 10^{-1}$ m^{2}yr^{-1}) and under 500 Myr timescales, a time averaged rate of precipitation that is less than or equal to the driest localities on Earth (10^{-3} myr^{-1}) (e.g., Atacama Desert) [*Rech et al.*, 2002] can form fans with slopes approaching 2°. However, for other values of κ over this timescale, such limited rain can only provide low-gradient fans if the starting catchment-fan boundary elevation is low.

4. Discussion

[11] Within the model framework presented here we find that precipitation under conditions typical of arid to temperate climates ($>10^{-2}$ myr^{-1}) on Earth may have generated large, low-gradient alluvial fans on Mars over million-year timescales, assuming all scenarios of catchment erodibility. Furthermore, the model indicates that under hyperarid terrestrial rates of precipitation (10^{-3} myr^{-1}), low-gradient fans can only sensibly form under 10^8 yr timescales if the

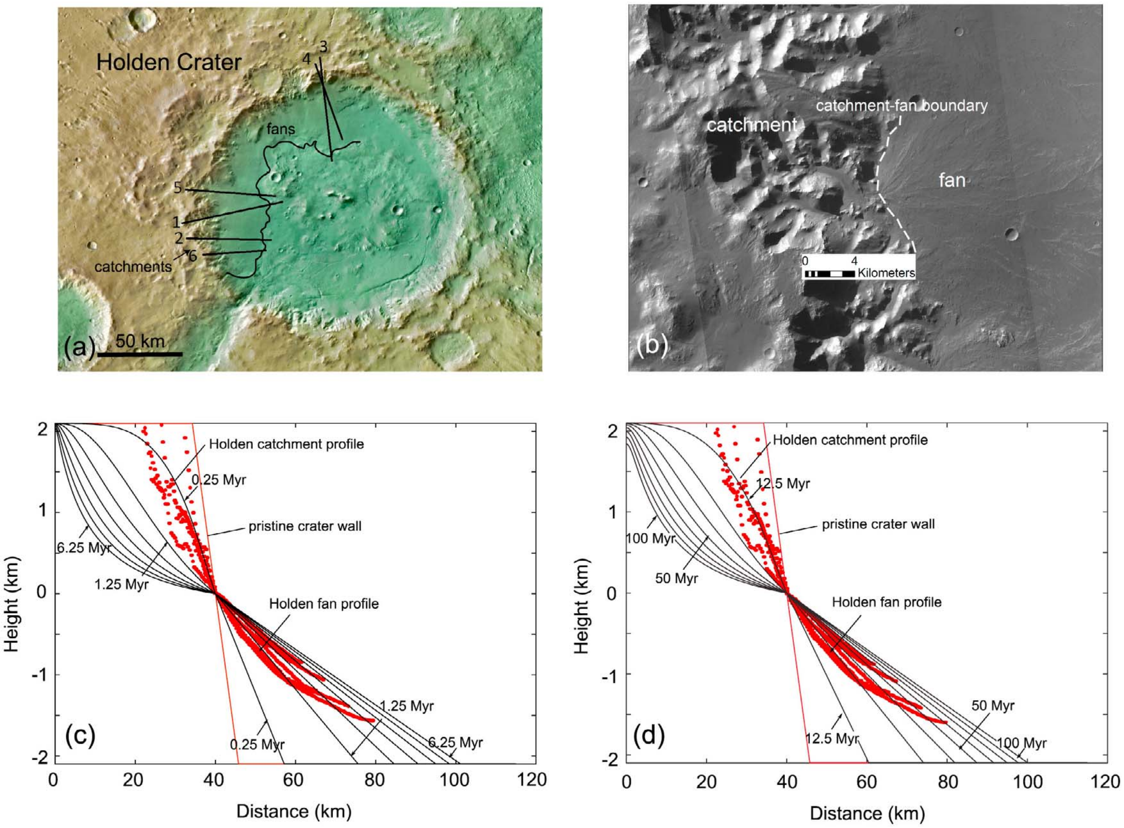

Figure 3. (a) MOLA color shaded relief overlying a THEMIS 100 m pixel^{-1} daytime IR mosaic of Holden crater. Topographic transects of select Holden fan-catchment systems, obtained from gridded MOLA topography data, are displayed. (b) Mars Reconnaissance Orbiter Context Camera (CTX) image of a single Holden sediment routing system showing catchment and fan. (c) Modeled and measured catchment fan profiles for the Holden crater for the semi-arid precipitation (0.2 myr^{-1}) scenario. Black lines show elevation for time steps of 1 Myr beginning at 0.25 Myr. Hill slope diffusivity is 10^{-2} m^{2}yr^{-1}. Red dots represent the MOLA topography points for the Holden fans and catchments. (d) Modeled and measured catchment fan profiles for Holden crater with precipitation rates of 0.05 myr^{-1}. Black lines show elevation for time steps of 12.5 Myr and red dots represent the MOLA topography data.

catchment is erodible and/or if the fan head is low relative to the crater rim height (Figure 2). To generate the low-gradient alluvial fans over a timescale on the order of 10^6 yr, a significant rate of precipitation, similar to temperate Earth-like conditions (>0.2 myr^{-1}) is required, which we term a "humid pulse". This duration of fan development is in closer agreement with the more complex geomorphic model of *Howard* [2007]. Yet, both our model results and those presented by *Howard* [2007] are in stark disagreement with the very short, <100 yr duration proposed by *Jerolmack et al.* [2004] for the development of the Eberswalde sedimentary fan, which occurs within the same southern latitude band as the discussed alluvial fans and was proposed by these authors to be an alluvial fan system opposed to a deltaic feature [*Wood*, 2006]. Finally, the 10^6 yr time scale is also longer than that suggested by *Moore and Howard* [2005] for the postulated formation of the fans by individual flash floods of an unknown recurrence time.

[12] For Earth-like semiarid to temperate rainfall, our model predicts a near-zero slope for the fan-catchment system over timescales of >10^8 yr (Figure 2). We suggest that similar, well-developed fan-catchment systems should be observable if these conditions were met on Mars. For the southern latitude impact crater basins that contain alluvial fans, *Moore and Howard* [2005] observed catchment alcoves, sloping fans, elevated crater rims, and sloping crater walls that indicate an intermediate state of crater degradation. Therefore, we reject the possibility of a long-duration (>10^8 yr), semiarid to temperate climate during the interval of fan formation for these features. However, the fans may have evolved over an extended time period (~10^8 yr) in a Martian climate that was more similar to arid regions on Earth (Figure 2). In this "Earth-like desert" scenario, large alluvial fans were generated by low rates of consistent precipitation or by periodic pulses of rain that, averaged over time, indicate an arid climate (~10^{-2} myr-1).

[13] As an example of well-preserved, low-gradient alluvial fans in the southern latitudes of Mars, the 150 km wide Holden crater contains a large bajada of integrated alluvial fans at the base of its western and northern interior walls [*Moore and Howard*, 2005; *Pondrelli et al.*, 2005; *Grant et al.*, 2008] (Figure 3a). Individual fans are headed by scalloped alcoves that cut up to the summit of the Holden rim without strong evidence of significant fan head erosion or valley infill (Figure 3b). *Moore and Howard* [2005] argued that the physiography of the Holden fan alcoves suggests an input from atmospheric precipitation and not groundwater.

[14] Topographic profiles, obtained from Mars Orbiter Laser Altimeter (MOLA) data (Figures 3c and 3d), reveal a similar slope between the fans and their related catchments. The Holden crater fan slopes are ~2° with a fan head that is roughly half way up the now degraded crater rim. Given the low gradient of the Holden fans, our model would suggest that fan formation timescales are long or require significant precipitation as represented by the solid lines in Figure 2. Below, we explore the development of the Holden fans assuming a semiarid terrestrial precipitation rate of 0.2 myr^{-1} or an arid precipitation rate of 0.05 myr^{-1} and using $\kappa = 10^{-2}\ \mathrm{m}^2\mathrm{yr}^{-1}$. Geometrically, assuming the pristine Holden crater had an interior slope of 20° and a depth of *ca.* 4 km [*Garvin et al.*, 2003], and that the fan apex is fixed half way up the crater rim, a 2-D fan of 2° slope would require an area of erodible landscape within the 2-D model of the order of 40 km^2. Therefore, for Holden, we model an initial condition of a catchment length of 40 km to allow for sufficient material to erode and subsequently deposit in the crater.

[15] Generally, the measured topographic profiles of the Holden catchment-fan systems match the model outcomes within an order of magnitude of the modeled duration of catchment-fan development and the time that is suggested by the actual morphology of the Holden features. Under semiarid conditions, it takes between approximately 1 and 3 Myr to generate the Holden fans and between 0.25 and 1 Myr to erode the crater rim down to the observed slopes of the Holden catchment alcoves (Figure 3c). Up to 20 or 60 Myr is required to generate the Holden fans under arid conditions and 10 to 20 Myr to generate the catchment slopes (Figure 3d). The model predicts a shorter duration for catchment erosion relative to fan construction and therefore does not, perhaps unsurprisingly, directly reproduce catchment-fan topography. This inability to reproduce topography is likely due to the simplifying assumptions that allow us to reduce the system to a function of only two variables, precipitation and gravitational erodibility (with rim height fixed). Yet the intention of the idealized system presented is not to directly predict Martian topography, but show the order of magnitude time scales and precipitation rates required to erode sufficient material to build the scale of fans observed on Mars.

5. Conclusions

[16] An idealised 2-D numerical model for erosion and fan deposition generally suggests that under terrestrial arid to temperate precipitation rates, low-gradient (<6°) alluvial fans on Mars formed over million year timescales, regardless of the erodibility of the catchment or position of the catchment-fan boundary. From our results, we suggest two end-member scenarios for low-gradient fan development under specific Martian climate regimes, which are both at the upper range of previous estimates: (1) A temperate to semiarid climate phase, or "humid pulse", of ~10^6 yr duration. (2) A relatively long-lived arid climate, an "Earth-like desert", extending for 10^7 to 10^8 yr.

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References

Armitage, J. J., R. A. Duller, A. C. Whittaker, and P. A. Allen (2011), Transformation of tectonic and climatic signals from source to sedimentary archive, *Nat. Geosci.*, *4*, 231–235, doi:10.1038/ngeo1087.

Bull, W. B. (1964), *Geomorphology of Segmented Alluvial Fans in Western Fresno County, California*, U.S. Gov. Print. Off., Washington, D. C.

Carr, M. (1996), *Water on Mars*, 229 pp., Oxford Univ. Press, New York.

Clevis, Q., P. de Boer, and M. Wachter (2003), Numerical modelling of drainage basin evolution and three-dimensional alluvial fan stratigraphy, *Sediment. Geol.*, *163*, 85–110, doi:10.1016/S0037-0738(03)00174-X.

Craddock, R. A., and T. A. Maxwell (1990), Resurfacing of the Martian highlands in the Amenthes and Tyrrhena region, *J. Geophys. Res.*, *95*(B9), 14,265–14,278, doi:10.1029/JB095iB09p14265.

Densmore, A. L., P. A. Allen, and G. Simpson (2007), Development and response of a coupled catchment fan system under changing tectonic and climatic forcing, *J. Geophys. Res.*, *112*, F01002, doi:10.1029/2006JF000474.

Fassett, C. I., and J. W. Head (2008a), Valley network-fed, open-basin lakes on Mars: Distribution and implications for Noachian surface and subsurface hydrology, *Icarus*, *198*(1), 37–56, doi:10.1016/j.icarus.2008.06.016.

Fassett, C. I., and J. W. Head (2008b), The timing of Martian valley network activity: Constraints from buffered crater counting, *Icarus*, *195*(1), 61–89, doi:10.1016/j.icarus.2007.12.009.

Garvin, J. N., S. E. H. Sakimoto, and J. J. Frawley (2003), Craters on Mars: Global geometric properties from gridded MOLA topography, Abstract 3277 presented at Sixth International Conference on Mars, Lunar. Planet. Inst., Pasadena, Calif., 20–25 July.

Golombek, M. P., et al. (2006), Erosion rates at the Mars Exploration Rover landing sites and long-term climate change on Mars, *J. Geophys. Res.*, *111*, E12S10, doi:10.1029/2006JE002754.

Grant, J. A., and S. A. Wilson (2011), Late alluvial fan formation in southern Margaritifer Terra, Mars, *Geophys. Res. Lett.*, *38*, L08201, doi:10.1029/2011GL046844.

Grant, J. A., R. P. Irwin, J. P. Grotzinger, R. E. Milliken, L. L. Tornabene, A. S. McEwen, C. M. Weitz, S. W. Squyres, T. D. Glotch, and B. J. Thomson (2008), HiRISE imaging of impact megabreccia and sub-meter aqueous strata in Holden Crater, Mars, *Geology*, *36*(3), 195–198, doi:10.1130/G24340A.1.

Grant, J. A., R. P. Irwin, S. A. Wilson, D. Buczkowski, and K. Siebach (2011), A lake in Uzboi Vallis and implications for Late Noachian-Early Hesperian climate on Mars, *Icarus*, *212*(1), 110–122, doi:10.1016/j.icarus.2010.11.024.

Hartmann, W. K., and G. Neukum (2001), Cratering chronology and the evolution of Mars, *Space Science Reviews*, *96*, 165–194, doi:10.1023/A:1011945222010.

Howard, A. D. (2007), Simulating the development of Martian highland landscapes through the interaction of impact cratering, fluvial erosion, and variable hydrologic forcing, *Geomorphology*, *91*(3–4), 332–363, doi:10.1016/j.geomorph.2007.04.017.

Howard, A. D., and J. M. Moore (2011), Late Hesperian to early Amazonian midlatitude Martian valleys: Evidence from Newton and Gorgonum basins, *J. Geophys. Res.*, *116*, E05003, doi:10.1029/2010JE003782.

Howard, A. D., J. M. Moore, and R. P. Irwin (2005), An intense terminal epoch of widespread fluvial activity on early Mars: 1. Valley network incision and associated deposits, *J. Geophys. Res.*, *110*, E12S14, doi:10.1029/2005JE002459.

Hynek, B. M., and R. J. Phillips (2003), New data reveal mature, integrated drainage systems on Mars indicative of past precipitation, *Geology*, *31*(9), 757–760, doi:10.1130/G19607.1.

Irwin, R. P., A. D. Howard, R. A. Craddock, and J. M. Moore (2005), An intense terminal epoch of widespread fluvial activity on early Mars: 2. Increased runoff and paleolake development, *J. Geophys. Res.*, *110*, E12S15, doi:10.1029/2005JE002460.

Jerolmack, D. J., D. Mohrig, M. T. Zuber, and S. Byrne (2004), A minimum time for the formation of Holden Northeast fan, Mars, *Geophys. Res. Lett.*, *31*, L21701, doi:10.1029/2004GL021326.

Kraal, E. R., E. Asphaug, J. M. Moore, A. Howard, and A. Bredt (2008), Catalogue of large alluvial fans in Martian impact craters, *Icarus*, *194*(1), 101–110, doi:10.1016/j.icarus.2007.09.028.

Malin, M. C., and K. S. Edgett (2003), Evidence for persistent flow and aqueous sedimentation on early Mars, *Science*, *302*(5652), 1931–1934, doi:10.1126/science.1090544.

Moore, J. M., and A. D. Howard (2005), Large alluvial fans on Mars, *J. Geophys. Res.*, *110*, E04005, doi:10.1029/2004JE002352.

Paola, C., P. Heller, and C. Angevine (1992), The large-scale dynamics of grainsize variation in alluvial basins: 1. Theory, *Basin Res.*, *4*, 73–90, doi:10.1111/j.1365-2117.1992.tb00145.x.

Pondrelli, M., A. Baliva, S. Di Lorenzo, L. Marinangeli, and A. P. Rossi (2005), Complex evolution of paleolacustrine systems on Mars: An example from the Holden crater, *J. Geophys. Res.*, *110*, E04016, doi:10.1029/2004JE002335.

Rech, J. A., J. Quade, and J. L. Betancourt (2002), Late Quaternary paleohydrology of the central Atacama Desert (lat 22°–24°S), Chile, *Geol. Soc. Am. Bull.*, *114*(3), 334–348, doi:10.1130/0016-7606(2002)114<0334:LQPOTC>2.0.CO;2.

Simpson, G., and F. Schlunegger (2003), Topographic evolution and morphology of surfaces evolving in response to coupled fluvial and hillslope sediment transport, *J. Geophys. Res.*, *108*(B6), 2300, doi:10.1029/2002JB002162.

Smith, T. R., and F. Bretherton (1972), Stability and conservation of mass in drainage basin evolution, *Water Resour. Res.*, *8*, 1506–1529, doi:10.1029/WR008i006p01506.

Talling, P. J., and M. J. Sowter (1998), Erosion, deposition and basin-wide variations in stream power and bed shear stress, *Basin Res.*, *10*, 87–108, doi:10.1046/j.1365-2117.1998.00088.x.

Warner, N., S. Gupta, S.-Y. Lin, J.-R. Kim, J.-P. Muller, and J. Morley (2010), Late Noachian to Hesperian climate change on Mars: Evidence of episodic warming from transient crater lakes near Ares Vallis, *J. Geophys. Res.*, *115*, E06013, doi:10.1029/2009JE003522.

Wood, L. J. (2006), Quantitative geomorphology of the Mars Eberswalde delta, *Geol. Soc. Am. Bull.*, *118*(5–6), 557–566, doi:10.1130/B25822.1.

Zienkiewicz, O. C., and R. L. Taylor (2000), *The Finite Element Method*, vol. 1, Butterworth-Heinemann, Oxford, U. K.

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