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A minimum time for the formation of Holden Northeast fan, Mars

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[1] The recently discovered deposits of a channelized fan located northeast of Holden Crater preserve a history of vertical and lateral accretion and avulsion of many channels, indicating water flowed freely across the surface of the fan during its construction. These sedimentary deposits, however, do not unambiguously discriminate between a deltaic or purely riverine origin for the feature. By using a numerical model describing fan construction solely by river channels, we estimate a minimum formation time of several decades to centuries. A minimum value for the total volume of transporting fluid required to construct the fan is modest, 900 km^3, and may not have required precipitation. *INDEX TERMS:* 1860 Hydrology: Runoff and streamflow; 1824 Hydrology: Geomorphology (1625); 5415 Planetology: Solid Surface Planets: Erosion and weathering. **Citation:** 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.

1. Introduction

[2] With few exceptions, putative fluvial features identified on Mars have been erosional in nature [e.g., *Mars Channel Working Group*, 1983; *Aharonson et al.*, 2002, and references therein]. The recent discovery of a large, partially eroded fan deposit in a crater northeast of Holden Crater (hereafter called Holden NE Crater [*Malin and Edgett*, 2003]; also assigned the provisional IAU name Eberswalde) has, therefore, significant implications for both the history of flowing water in the region, and the persistence of liquid water on Mars during Noachian (~3.7 Ga) time [*Moore et al.*, 2003]. *Moore et al.* [2003] interpreted the Holden NE fan as a delta, i.e., building out into a standing body of water. Herein we argue that the fan may have been constructed without a standing body of water present at its distal end, but acknowledge that remote imaging of the sedimentary deposits is not sufficient to unambiguously distinguish between these depositional origins. We quantitatively assess the evidence for water recorded by the sedimentary deposits at Holden NE Crater, using data from Mars Orbiter Laser Altimeter (MOLA), Thermal Emission Imaging System (Themis) and Mars Orbiter Camera (MOC). In particular, we use a numerical model of riverine fan construction [*Parker et al.*, 1998] to invert topographic and volumetric data from MOLA, producing an estimate of the time required to build the fan out of channel and overbank deposits. This analysis provides a minimum estimate of formation time, as there is no way to assess how long or how frequently the fan was active, and construction of the fan as a delta would require more time due to the reduced transport efficiency in lacustrine versus riverine environments [see, e.g., *Paola*, 2000]. This minimum time is relevant to considerations of whether fan formation required climatic conditions drastically different from the present day.

2. Observed Features

[3] Holden NE Crater is a severely degraded elliptical depression, with major and minor axes of ~70 km and ~50 km, respectively, and a maximum depth of 1.2 km (Figure 1a). To the west of the crater lies a tributary network of erosional channels (Figure 1a) connecting to two ~0.7 km wide channels on the western rim of Holden NE Crater that define the apex of the depositional fan (Figures 1b and 2 and Table 1). The average longitudinal slope, *S*, of the bed for the longer of the two erosional channels entering the crater is 0.06. This slope drops to a characteristic value of 0.006 upon entering the crater (in agreement with *Malin and Edgett* [2003]), associated with the approximately radial eastward expansion of the fan. The distal end of the fan is defined by an abrupt increase in surface slope (Figure 3). The deposits most likely represent an ancient delta or riverine fan, depending on interpretation of the amount of post-depositional erosion associated with generation of this terminal surface.

[4] The fan surface is covered by a series of superposed, cross-cutting ridges [*Malin and Edgett*, 2003; *Moore et al.*, 2003] that we interpret as more resistant, possibly coarser-grained deposits filling paleochannels (Figures 1b, 2a, and 2b). These channel-filling deposits are exposed in plan form on the top of the fan, and in cross section along its terminal surface; they possess relatively low sinuosities (Table 1) and their branching, radial arrangement is consistent with development either by a distributary network, or via amalgamation of successive deposits from an avulsing channel [*Rannie*, 1990]. Erosion at the distal end of the fan has produced cliffs revealing stratigraphic layers that appear discontinuous over distances of a few hundred meters (Figure 2a), which we interpret as representing nearly vertical cuts through numerous channel-filling deposits distributed throughout the entire fan package.

3. Analysis

[5] The observed superposition of discrete channel-filling deposits with varying flow directions is consistent with stratigraphy produced by a small number of active channels

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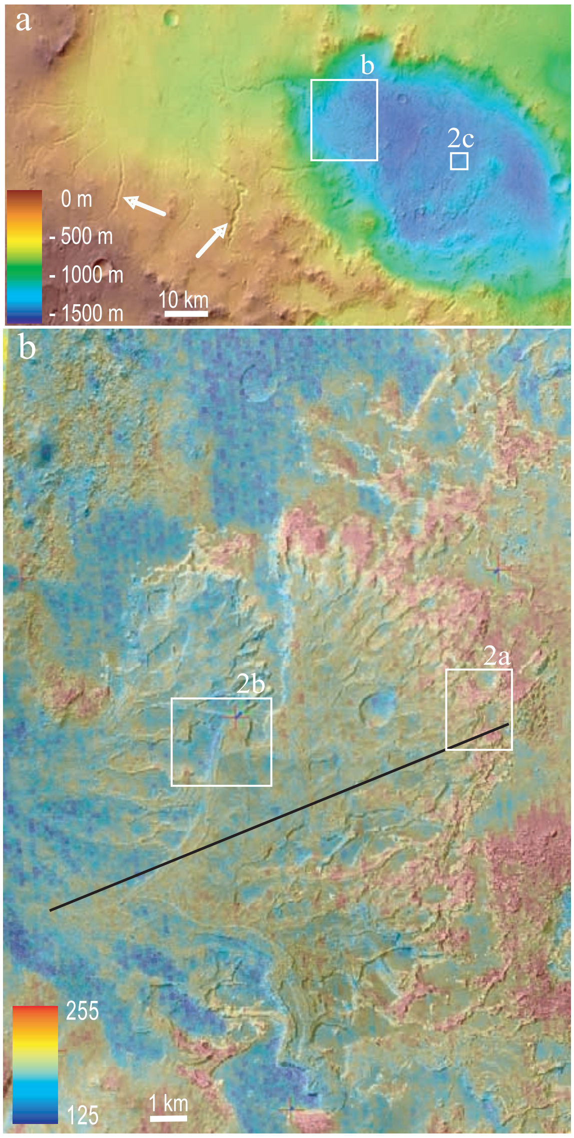

Figure 1. (a) Interpolated 500 m resolution MOLA topography draped on Themis daytime image mosaic (100 m/pixel, images I01737002, I01762002, I02461003, I03185002, I03210002, I03572002, I03597002, I04733002 and I04758002). White boxes indicate locations of other figures. Arrows point to large erosional channels. The mosaic is centered on 26°S, 34°W. (b) Themis night-time infrared image (100 m/pixel, image I04327002) superposed on MOC image mosaic (<5 m/pixel, images M18-00020, E14-01039, E17-01341, E18-00401, E21-01153, E21-00454, E22-01159, E23-00003, R06-00726, R08-01104 and R09-01067). Night-time temperature (indicated in legend) is strongly correlated to exposure of outcrop. Black line indicates location of profile shown in Figure 3. North is up for all figures.

occupying different sites on the fan via relatively abrupt lateral shifts, or avulsions [*Mohrig et al.*, 2000; *Rannie*, 1990; *Slingerland and Smith*, 2004]. A previously identified meander 'cutoff' [*Malin and Edgett*, 2003; *Moore et al.*, 2003] is more likely an avulsed channel that reoccupied a former channel course (Figure 2b), as is frequently seen in terrestrial outcrops where old channels may persist as topographic lows [*Mohrig et al.*, 2000]. Margins of the 'cutoff' show the channel is superposed on the previous deposit (Figure 2b), and stereo anaglyphs (not shown) show meander scroll-bars progressively increase in elevation

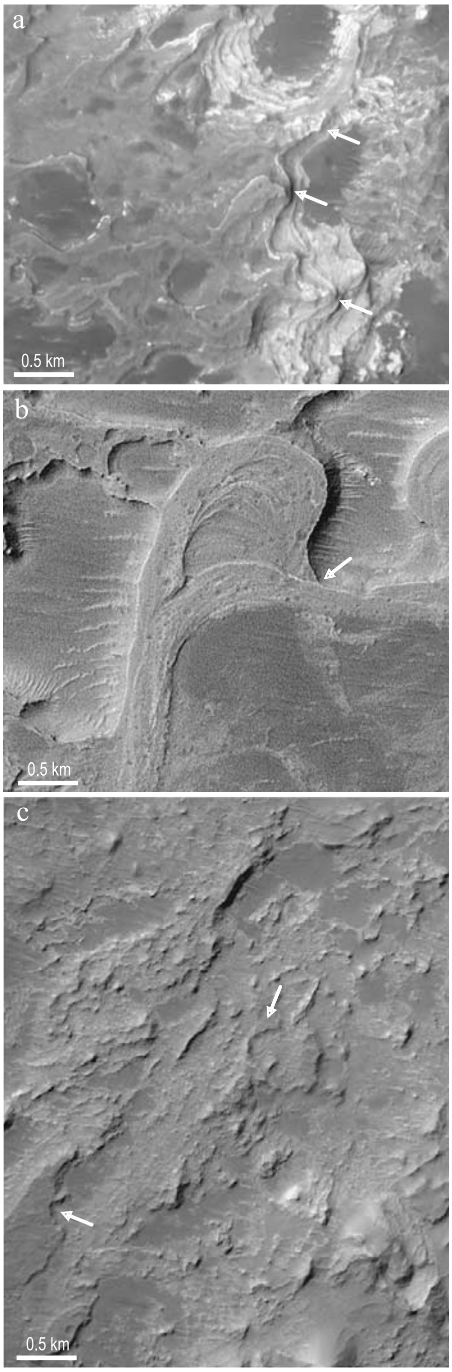

Figure 2. MOC sub-images of (a), distal end of the fan with resistant channel ridges corresponding to steep slopes, indicated by arrows (image E14-01039); (b), aggrading, migrating meander bend and a superposed avulsed channel denoted by arrow (image E18-00401); and (c), remnant sedimentary deposits (indicated by arrows) found in the middle of Holden NE crater (image E20-01420) – see Figure 1 for locations of all images.

Table 1. Characteristics of Present and Proposed Pre-erosion Holden NE Fan[a]

Fan	L [km]	$R_{\max}$ [km]	θ [°]	A [km^2]	V [km^3]	S [km/km]	K_{ave} [km/km]
Present	12.6	0.15	81	90	6	0.006	1.19
Proposed	45	~0.15	81	1400	30	~0.006	~1.19

[a] $R_{\max}$, A, and K_{ave} are maximum relief, fan area and average channel sinuosity (for channels longer than 1 km) – all other parameters defined in text. S is reported for top fan surface.

(as noted by *Moore et al.* [2003]), implying aggradation-driven channel migration.

[6] The fan considered here is an erosional remnant of a larger depositional feature. MOC images show that all channels terminating at the distal end correspond to steep slopes at the fan edge, while less resistant material between channels grades into the crater bottom at shallow slopes (Figure 2a). Also, remnant 'stringer' channels, sinuous ridges similar in morphology to those on the fan, extend across the floor of Holden NE Crater, beyond the fan (Figure 2c). Taken together, these observations suggest that the original fan was more extensive, and point to the abrupt termination of the fan being an erosional artifact, most likely produced by wind. We propose that the entire fan may have been constructed from river-like channels traversing its entire length.

[7] Themis night-time infrared data show a correlation between temperature and degree of rock exposure (Figure 1b), resulting in exhumed features having higher thermal inertia than surrounding terrain [*Christensen et al.*, 2003], which is mantled with loose sediment. MOC data from the fan record no evidence of talus (rubble piles) or scree at the base of steep slopes, suggesting that material eroded off of the fan deposit by wind abrasion is also transported away by wind, and implying the channel deposits are composed of weakly lithified sand or finer-grained material.

[8] We explore the conditions required to construct the observed deposit by a purely riverine system. Our goal is to provide a reasonable minimum bound on the time that freely flowing water persisted in Holden NE Crater, as this is the only constraint we can deduce from the current data. To do this we use the numerical model *Acronym6*, based on the theory of *Parker et al.* [1998], for the equilibrium shape of channelized alluvial fans (code freely available at http://www.safl.umn.edu/publications/software/srmsgf.shtml). This semi-analytical formulation computes bed slope and elevation of a fan experiencing frequent avulsions, which act to distribute water and sediment across the fan surface. A significant advantage of this sediment transport formulation is that model equations are dimensionless. Martian gravity (g = 3.7 m/s^2) is then directly accounted for in determining the dimensional, system-wide values.

[9] The model takes advantage of the following simplified conditions. Dimensionless formative shear stress, τ_a^*, is treated as constant for the length of the fan, as observed in terrestrial environments [*Parker et al.*, 1998; *Paola et al.*, 1999]. Steady and uniform flow is assumed, and the relationship between shear stress, τ, and sediment discharge, Q_s, follows $Q_s \sim \tau^n$, where n is 1.5 for gravel and 2.5 for sand. The result of this formulation is an equation relating fan slope along the profile to sediment and fluid discharge (equation (29) of *Parker et al.* [1998]):

$$S = \left[R^{-1/2}\alpha_s^{-1}\alpha_b^{(3+2p)/2}\alpha_r\left(\frac{\alpha_b}{R}-\tau_c^*\right)^{-n}\frac{Q_s(1-\hat{r}^2)}{Q_w}\right]^{1/(1+p)}, \tag{1}$$

where R, τ_c^*, $\hat{r}$ and Q_w are submerged specific density of grains, critical dimensionless Shields stress, dimensionless down-fan distance (ranging from 0 to 1) and fluid discharge, respectively. The coefficients α_s, α_b and α_r, and the exponent p are dependent on the form of the sediment transport and flow resistance relationships. The numerical model solves equation (1) to obtain the slope along the profile for a given sediment/water discharge ratio; all other parameters are treated as constant, though values of some constants are different for sand and gravel. Elevation along the profile is found by integrating equation (1) subject to the proper boundary conditions [see *Parker et al.*, 1998]. As grain size is an unconstrained parameter, all computations are performed for both medium sand (D = 0.3 mm) and gravel (D = 20 mm), with values for all constants as reported in table 1 of *Parker et al.* [1998] for simplicity.

[10] The top surface of the present day fan is taken to represent the equilibrium profile. While some erosion has occurred, the fact that large channels may be traced over the entire fan top implies differential eolian weathering on this surface is less than one channel-depth in magnitude, and so the present surface slope is taken as a reasonable approximation of the original fan gradient. The ratio Q_s/Q_w in the model is varied in an iterative manner to find the theoretical fan profile that best matches the observed slope and elevation (Figure 3). This surface fit implies that the fan was significantly more extensive than now (Table 1), having a total length, L = 45 km. We assume one active channel with a measured width, B = 100 m. To estimate channel depth, H, we use the observed relationship for terrestrial alluvial rivers, $3 < BS^{0.2}/H < 10$ [*Fukuoka*, 1989].

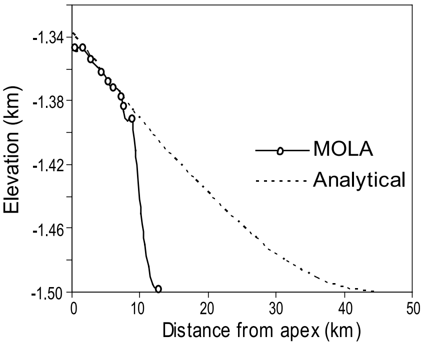

Figure 3. Interpolated MOLA longitudinal profile across Holden NE fan - circles are actual MOLA shots. Dotted line is the numerical solution of *Parker et al.* [1998] fit to the profile of the top fan surface. Location is shown in Figure 1b.

Table 2. Minimum, Maximum and Preferred Discharges (Units [m^3/s]), and the Corresponding Formation Times (Units [year]), Associated With Construction of Holden NE Fan[a]

Parameter	Min. Q_w	Max. Q_w	Pref.
Q_w-sand	280	950	**410**
Q_s − sand	8.5	28	**12**
t_{eq} − sand	70	20	**50**
Q_w-gravel	240	790	340
Q_s-gravel	1.3	4.3	1.8
t_{eq}-gravel	480	140	340

[a] Values of Q_w correspond to: Min. − $BS^{0.2}/H = 3$; Max − $BS^{0.2}/H = 10$; Pref. − $BS^{0.2}/H = 7$.

Finally, Q_w can be obtained by calculating mean fluid velocity, u, using a Chezy flow resistance relation:

$$u = \left(\tau_a^* R g D \alpha_r^2\right)^{1/2}. \tag{2}$$

A similarity closure based on the Froude number yields a velocity estimate similar to that of equation (2). Fluid discharge is computed as $Q_w = uBH$, using combinations of parameter values specified above to obtain a minimum, maximum, and 'preferred' value, where the preferred value uses $BS^{0.2}/H = 7$, the middle range of terrestrial values. The time scale of formation, t_{eq}, can be estimated directly from fan volume (corrected for assumed porosity, $\lambda = 0.35$) and sediment discharge as $t_{eq} = (1 - \lambda)V/Q_s$, assuming that all sediment input at the apex is captured by the fan. A reconstructed volume for the fan, $V = 30$ km^3, was calculated by fitting the analytical profile with parabolic cross sections assuming a radially symmetric fan of $L = 45$ km and opening angle $\theta = 81°$.

4. Implications and Conclusions

[11] Frequently avulsing terrestrial channels on alluvial fans produce deposits consistent with those seen in the Martian fan deposit. Abundant stratigraphic evidence for vertical accretion and channel avulsion clearly demonstrates that the top of the fan was a free surface, not confined by an overlying rigid boundary such as a glacier. We cannot determine, however, whether channels formed in a completely riverine environment or on top of a delta draining into a (possibly ice-covered) crater lake. On Earth, rivers often build alluvial fans at abrupt transitions in slope [*Rannie*, 1990]. Ancient avulsing channels and their associated alluvial fans have been found as inverted sandstone ridges in Oman [*Maizels*, 1990] and Spain [*Mohrig et al.*, 2000], with gradients and channel sinuosities similar to the Holden NE fan [*Maizels*, 1990].

[12] The preferred water discharge for a sandy fan, $Q_w = 410$ m^3/s (Table 2), is close to the value of 700 m^3/s proposed by *Moore et al.* [2003], who used empirical terrestrial relations between discharge and meander wavelength, channel width and drainage area. Our approach, however, takes advantage of the time-integrated deposit and thus allows estimation of time scales and sediment yields associated with construction of Holden NE fan. Unconstrained variables having the greatest influence on calculated discharges and fan formation time are grain size and channel depth. Calculations have been performed for reasonable ranges of these values (Table 2). The analysis shows that Holden NE fan could have been constructed in decades to centuries, with a preferred minimum formation time of 50 years for medium sand. Calculated times, reported in terrestrial years, assume continuous flow at calculated discharge values, consistent with the minimum time formulation. If flow had a typical terrestrial intermittency value of 0.05 [*Parker et al.*, 1998], which means channel-forming flow conditions were present 5% of the time, fan formation times reported in Table 2 would increase by a factor of 20.

[13] If the deposit in Holden NE Crater is in fact an alluvial fan, the original structure must have occupied a large portion of the crater floor (Figure 3). While there is no definitive evidence for a fan of such extent, there are indeed sedimentary deposits of similar morphology extending across the floor of Holden NE Crater (Figure 2c). Inspection of the crater rim does not reveal any outlet through which water flowed, so inflowing water was either contained within the crater or infiltrated into the ground, as observed in some terrestrial desert environments [*McCarthy et al.*, 1988]. Estimates of water discharge and duration vary depending on choice of channel depth (Table 2), but the total volume of water necessary to build the fan is only affected by grain size, which changes sediment discharge (equation (1)) and hence fan formation time. We estimate this water volume to be 900 km^3 for sand, and 5000 km^3 for gravel. The absence of talus on exposed steep slopes suggests that the fan material is weakly lithified sand.

[14] We present an internally consistent, quantitative method [*Parker et al.*, 1998] showing that the observed fan could have been built in a rapidly aggrading riverine environment in less than 100 years. The modest estimated quantity of water necessary for alluvial fan construction does not require precipitation [e.g., *Moore et al.*, 2003] if a local source of water was present. If the Martian soil contained significant water ice, groundwater could have been delivered to the surface by heat generated from the impact formation [*Jach et al.*, 1999] of nearby Holden Crater to the south. We are currently evaluating the adequacy of shock heating to deliver the fluid and sediment discharges required for fan formation.

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