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Fluvial sedimentary deposits on Mars: Ancient deltas in a crater lake in the Nili Fossae region

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[1] New spacecraft observations in the Nili Fossae region of Mars reveal two valley networks (~80 and ~200 km long) that each formed distributary fans as they entered an ancient 40-km diameter impact crater. An outlet channel on the eastern crater rim, lying at an elevation above the fans, suggests these fans formed as subaqueous deltas in a crater lake. Water flowing in the valley networks entered the crater and deposited the fans, and ponded to a maximum depth of about 450 m. The lake then overtopped and breached the crater rim, incising it and dropping the lake level by ~100 m. Geological evidence, combined with the volume of water necessary to fill the crater, suggests the duration of flow through this system was prolonged. The existence of the deposits described here implies that the early Martian environment supported overland flow and ponding of water for an extended period of time. **Citation:** Fassett, C. I., and J. W. Head III (2005), Fluvial sedimentary deposits on Mars: Ancient deltas in a crater lake in the Nili Fossae region, *Geophys. Res. Lett.*, *32*, L14201, doi:10.1029/2005GL023456.

1. Introduction

[2] Despite substantial evidence for ancient fluvial erosion on the Martian surface, primarily manifested in the form of valley networks [*Carr*, 1996], there have been relatively few observations of unambiguous fluvial sedimentary deposits. Although *Cabrol and Grin* [1999] interpreted many deposits on the interior of craters as of fluvial origin using Viking data, more recent examination of these deposits suggests that the origin of many of these are uncertain [*Malin and Edgett*, 2003]. In addition, much of the floor of Gusev Crater was interpreted to be of lacustrine origin [*Cabrol et al.*, 1996], but instead of sediments at the MER Spirit's initial landing site, the rover found a broad plain of apparently unweathered basaltic rock [*Squyres et al.*, 2004]. Recent work has also reinterpreted deposits in a crater in western Memnonia, thought to be lacustrine in origin, as basaltic lava flows [*Leverington and Maxwell*, 2004]. These apparent contradictions and new findings, as well as general uncertainty as to the nature of climate and fluvial process in the Late Noachian [e.g., *Carr*, 1996] provide motivation for studying new examples of candidate fluvial sedimentary deposits on Mars. Specifically, clear evidence for the character of sedimentary deposits associated with valley network systems would help to clarify the nature of fluvial processes on early Mars. Recent documentation of a large, inverted fan deposit in a basin northeast of Holden crater is the strongest evidence yet observed from orbit of fluvial sedimentation, but it is unclear whether that example is an alluvial fan or formed in a standing body of water [*Malin and Edgett*, 2003; *Moore et al.*, 2003].

[3] We present new observations of two distributary fan deposits in a 40-km unnamed crater (centered at 77°40′E and 18°25′N; Figure 1) that occur within the context of an integrated fluvial system, and thus provide important new information about the dynamics of fluvial processes on early Mars. Two valleys entered the crater from the west and north, depositing sediment at their mouths. Influx of water from these valleys filled the crater until the eastern rim was overtopped and breached. Water then flowed through a sizable exit valley into the adjacent lowlands. Given the geometry of the fan deposits, and their position below the elevation of the outlet channel, it seems highly likely that they were deposited as deltas in a standing body of water. We have compiled MOC narrow angle, THEMIS, HRSC, and MOLA data for the region in order to document the nature of this fluvial system.

2. Observations

[4] The 40-km diameter crater is well illustrated in a THEMIS IR daytime mosaic combined with a false color rendering of MOLA gridded topography (Figure 1). Here we describe the major components of the fluvial system.

2.1. Input Valleys

[5] The two input valleys that transported sediment to the fan deposits are long, sinuous valleys which appear to be typical examples of valley networks [*Carr*, 1996]. The valley associated with the western fan extends ~200 km westward, and the valley associated with the northern fan extends at least 80 km to the north and west. The valley system appears to have been active during the Noachian (>3.7 Gya, [*Hartmann and Neukum*, 2001]), based on regional mapping [*Greeley and Guest*, 1987] and superposition relationships with the Nili Fossae graben. This is consistent with the age of most other valley networks [*Carr*, 1996].

[6] Both valleys have well-developed meanders, which evolved over time, as evidenced by an older, cutoff meander segment in the western valley. The combined drainage area of both input valleys is ~15000 km^2, significantly larger than that of Holden NE crater (~4000 km^2 *Malin and Edgett* [2003]). The drainage density of this watershed is in the range 2.6×10^{-2}–4.4×10^{-2} km^{-1} (depending on the acceptance criteria for mapping of small tributaries), consistent with other Noachian regions of Mars based on recent data [e.g., *Hynek and Phillips*, 2003].

2.2. Morphology of the Fan Deposits

[7] Both fans have a broadly triangular shape (Figure 1); the western fan is better preserved and has a more classic

0094-8276/05/2005GL023456

"birdfoot" geometry than the northern fan. The present combined areal extent of the fan deposits is ~56 km^2, and we estimate that the volume of sediment of the present fan deposits is approximately 5 km^3.

[8] At MOC scale, the western fan surface is composed of layered ridges of sediment that cross-cut each other (Figure 2). This is similar to what is observed at Holden NE crater [*Malin and Edgett*, 2003]. We interpret these ridges as relatively coarse channel bed material that was deposited due to the drop in stream power as the valley entered the crater. These deposits are now expressed as positive topography because of the removal of intervening fine particles by wind. The sharp margin of the fan surface itself suggests that the total area and volume has been reduced by aeolian erosion.

[9] The northern fan is less well preserved and individual channel deposits are not evident, though high resolution images (MOC and HRSC) reveal layered outcrops consistent with a sedimentary interpretation as well as with the layered appearance of the western fan.

2.3. Output Channel and the Crater Lake

[10] A channel is cut into the eastern rim of the crater (Figure 1) and forms a short, sinuous valley that incised the rim at least 100 meters, to an elevation of ~−2395 m. This elevation is above most of the central crater (Figure 1b), and the fan deposits have a median elevation ~50 meters below this contour. We believe that the most reasonable interpretation of this geometry is that water entering the crater through the input channels ponded into a substantial lake. The eastern rim was then breached, resulting in the formation of the notch and outlet channel, partial drainage of the crater lake, and downcutting of the exit channel.

[11] The area delineated by the −2395 m contour (Figure 1) is a minimum extent for the proposed lake when the breach valley was actively draining the lake. A variety of evidence suggests that the initial stand was higher. There has been significant incision of the eastern rim (~80–100 m), which implies that the initial eastern rim elevation was greater than −2320 m. The western input valley also appears deeply entrenched where it enters the crater, which suggests lowering of the local base level over time. We tentatively interpret textural evidence in high-resolution images, as well a local decrease in MOLA point-to-point slope at an elevation of approximately −2260 m, as a terrace or shoreline associated with an upper stand. A firm upper limit for the size of the crater lake is the next lowest

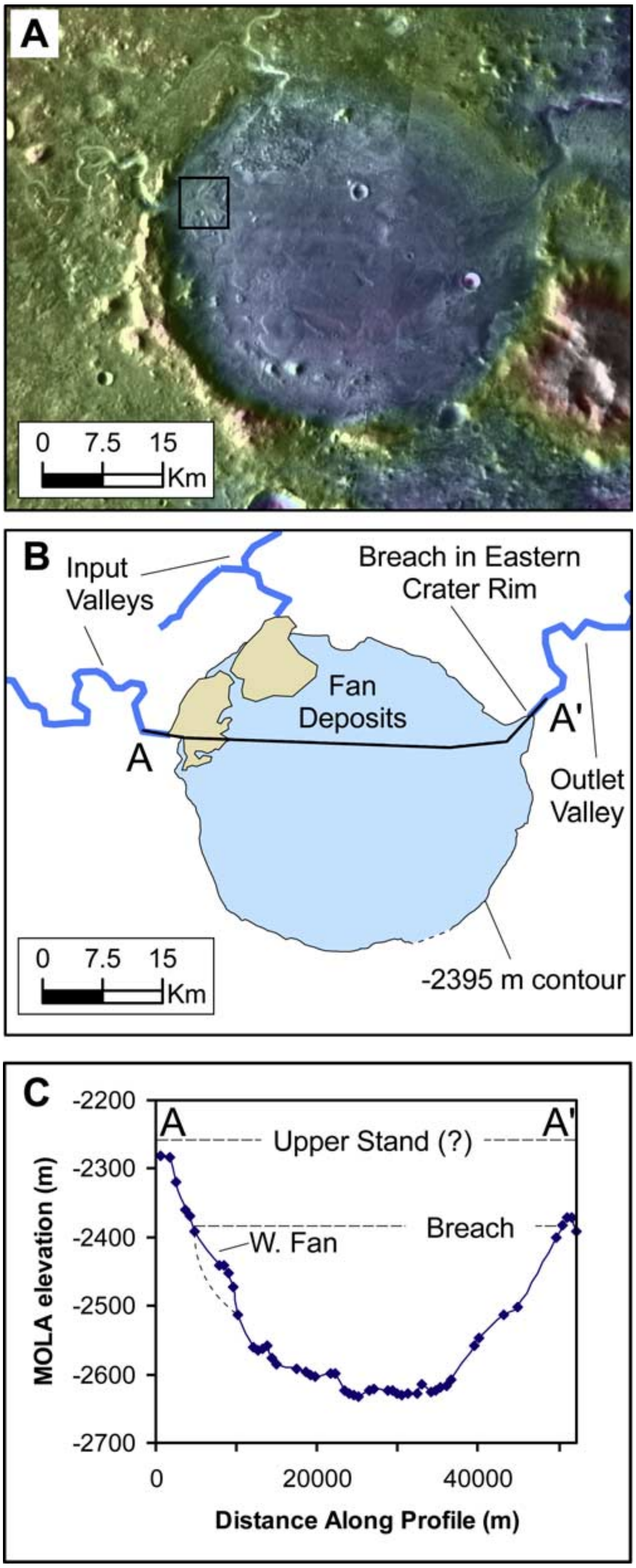

Figure 1. (a) THEMIS IR daytime mosaic of the Nili Fossae crater fan deposits (with false color MOLA topography). The black box outlines Figure 2. (b) Sketch map of crater and fan. The −2395 m contour outlines the crater interior, and represents the minimum extent of ponding based on the outlet valley breach elevation, omitting a section of the southeastern rim (dotted) that was cratered subsequent to the period of fluvial activity. (c) Profile A-A′, shown in Figure 1b, illustrating the relative elevations of the western fan, crater interior, and breach point. Given that the elevation of the breach is above most of the crater floor and both fans, ponding is required for the outlet valley to form. The highstand was likely well above the present elevation of the outlet, with a possible upper stand shown (see text). The slight slope of the crater floor eastward is consistent with the regional slope, which is evidence that the crater has not been tilted after formation. The data for the profile are derived from MOLA gridded data only in regions well-constrained by MOLA shots.

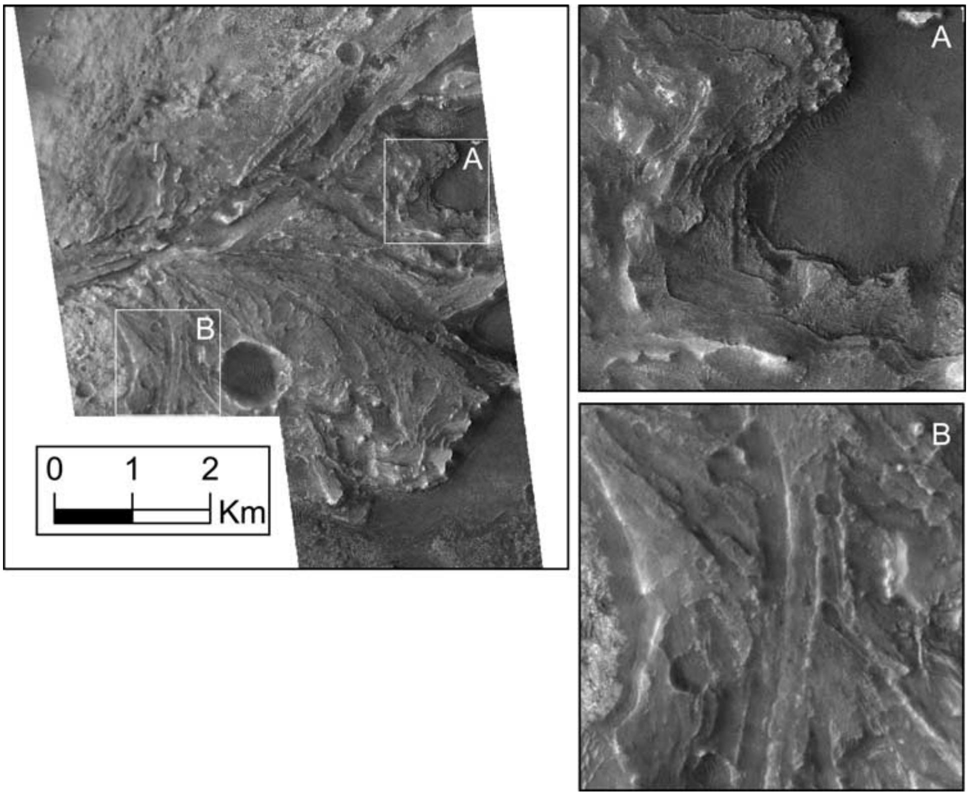

Figure 2. (left) View of the western fan in portions of MOC narrow angle images R23-00833 (left) and S04-00725 (right) (M. C. Malin et al., Images R23–00833 and S04–00725, 2005, Public request images, http://www.msss.com/mars_images/moc/publicresults/). Pervasive layering (inset A) is apparent, suggesting that the fan was episodically active at a given location. The crosscutting ridges on the fan surface are indicative of channel switching (see inset B).

point at which a spillway would have developed, or ∼−2170 m.

3. Discussion and Implications

[12] On the basis of the observations presented above, we interpret the fan deposits as having been emplaced as deltas in a lacustrine environment. Using the morphology of the present fan deposits and observations of the valley networks, we can assess the conditions of flow that produced these features. This information provides some constraints for climatic conditions at the time the valleys were active and the fan deposits were formed.

[13] In order to understand the nature of the early Martian climate, it is important to constrain the magnitude, duration, and episodicity of aqueous flow that formed the valley networks. Thus there has been substantial discussion of how long it took to form the Holden NE deposits [*Jerolmack et al.*, 2004; *Moore et al.*, 2003; *Malin and Edgett*, 2003]. *Moore et al.* [2003] argue that if flow was quasiperiodic, it likely took thousands to millions of years to form the deposits in Holden NE crater. However, as *Moore et al.* [2003] and *Jerolmack et al.* [2004] note, if peak flow conditions were continuously maintained, it would be possible to build the present Holden NE fans in tens of Earth years or less.

[14] The geological situation in the Nili Fossae crater discussed here has advantages for estimating the length of time that the fluvial system must have been active, because we can develop a confident estimate of the minimum volume of water that must have flowed through the system to overtop the eastern rim and form the observed exit breach. At Holden NE crater, a minimum flow estimate has to be inferred indirectly, because the fate of the water subsequent to forming the fan and hence whether the fan formed subaerially or subaqueously is unknown. The present volume of the Nili Fossae crater is ∼250 km^3, measured to the −2395 m contour (the minimum stand, see Figure 1). However, the minimum amount of water needed to fill and overtop the crater was likely at least ∼350 km^3 (the volume to the −2320 m contour), given the amount of incision of the eastern crater rim.

[15] Estimates of discharge on Mars are subject to large uncertainties, both because of difficulty in observationally constraining the relevant parameters and theoretical uncertainty related to channel formation in Martian conditions. Nonetheless, *Irwin et al.* [2005] present an empirical method for estimating discharge in alluvial channels on Mars, based on scaling arguments that imply that channel-forming discharge (Q) can be related to inferred channel width (W) using

$$Q = 1.44\ W^{1.22}. \tag{1}$$

For this system, we estimate $W \approx 50-100$ m based on measurement on the fan surface and in the input valleys. Using equation (1), these widths would imply a channel forming discharge of 170–400 m^3/s. *Irwin et al.* [2005] argue that the uncertainty on this estimate is approximately an order of magnitude. We obtain somewhat larger estimates of ~500–900 m^3/s using Manning's equation scaled for Mars, assuming a flow depth of a few meters and a roughness coefficient of $n = 0.0545$ [*Wilson et al.*, 2004].

[16] A discharge of 700 m^3/s would fill the crater to the present breach level in ~11 Earth years or to the nominal upper stand in ~18 years. This length of time is consistent with minimum values for the formation time of the Holden NE crater deposits on the basis of similar calculations (*Jerolmack et al.* [2004] give a minimum of ~20 years). However, such a discharge would require runoff production of ~0.5 cm/day over the entire watershed over the entire period.

[17] These minimal times assume that channel-forming flow conditions occurred continuously, and no water was lost to the environment (to the atmosphere and/or groundwater). This seems possible only in scenarios that invoke an essentially continuous source of supply for liquid water, such as impact-driven precipitation [*Segura et al.*, 2002] or an impact-driven groundwater system (as suggested by *Jerolmack et al.* [2004] for the Holden NE crater). Given the length of the valley networks that fed the Nili Fossae fan deposits and the large distances that separate their headwaters, it seems hard to conceive of an impact-driven groundwater scenario that could explain these deposits. Moreover, the drainage density we infer is within an order of magnitude of terrestrial values mapped at similar resolutions [*Carr and Chuang*, 1997], which is evidence for precipitation having occurred [*Hynek and Phillips*, 2003; *Mangold et al.*, 2004].

[18] Channel-forming flow conditions occur rarely on Earth because of the variability inherent in climatic phenomena [e.g., *Wolman and Miller*, 1960]. There is no reason to think this would be different for the valley networks we observe on Mars. *Jerolmack et al.* [2004] suggest that if the discharges that formed the Holden NE fan were intermittent, formation times might be increased by a factor of 20, which is appropriate for humid or subhumid climates on Earth [*Parker et al.*, 1998]. If conditions on early Mars were analogous to arid or hyperarid terrestrial environments, the frequency of the events that do the most geomorphic work is less than that of humid regions, and an increase in the formation time by a factor of at least 100 would be reasonable [*Wolman and Miller*, 1960; *Osterkamp and Friedman*, 2000]. This would imply that the interval of activity in the system described here was on the order of thousands of years.

[19] Along with inferences from the paleohydrology, there are qualitative geological indicators that suggest that a prolonged period of variable fluvial activity occurred. Layering is apparent on much of the fan margin to the limits of MOC resolution, with up to ten discrete layers visible (Figure 2, inset A). A plausible explanation for this layering is deposition of layers in individual high discharge events when sediment transport was much enhanced. This is consistent with intermittent periods of peak flow.

[20] Another qualitative indicator that activity in this system persisted for a relatively long amount of time is the apparent adjustment of disparate parts of the fluvial-lacustrine system as it evolved. The present fan surfaces are below the minimum breach elevation, and neither of the fans were stranded above this −2395 m level. There is also evidence for a morphological and textural transition at this minimum lake level (somewhat similar to what is seen at ~−2260 m), which may represent a terrace or shoreline. The fact that we observe these transitions in morphology suggests the lake experienced stands at these levels that were prolonged enough to have geomorphic effects.

[21] Finally, an independent indicator that water must have been available in this region for a geochemically-significant amount of time comes from recent results of the OMEGA instrument. OMEGA finds abundant evidence of hydrated minerals, which are consistent with smectite clays, within the watershed of the valley systems described here [*Bibring et al.*, 2005; *Mustard et al.*, 2005; *Poulet et al.*, 2005].

[22] In summary, several lines of evidence suggest that the duration of flow which produced the valley system, filled and breached the crater, and formed the fan deposits as deltas was substantial. Constraining the actual necessary duration of fluvial activity is sensitive to the recurrence rate of channel-forming flow conditions, which is difficult to infer in the absence of more detailed knowledge of the climate. The minimum formation times that we infer (even with intermittent flow) are short, however, compared to the timescale for climate excursions that might be expected to be driven by Mars' orbital parameters, but are long compared to what could be accomplished under conditions that closely resembled those of the present-day. Our observations and interpretations imply that climatic conditions in the Noachian in the Nili Fossae region supported the flow and ponding of liquid water across the surface for an extended period of time.

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