GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 24, 2292, doi:10.1029/2003GL019002, 2003

Martian Layered Fluvial Deposits: Implications for Noachian Climate Scenarios

Jeffrey M. Moore
NASA Ames Research Center, Moffett Field, California, USA

Alan D. Howard
University of Virginia, Charlottesville, Virginia, USA

William E. Dietrich
University of California, Berkeley, California, USA

Paul M. Schenk
Lunar and Planetary Institute, Houston, Texas, USA

Received 5 November 2003; revised 2 December 2003; accepted 8 December 2003; published 30 December 2003.

[1] Fluvial deposits in a basin north of Holden crater exhibiting a sinuous, anabranching pattern are of deltaic or fan origin. Channel width and meander wavelength indicate persistent flow magnitudes of about 700 m^3/s. If these flows were produced by quasi-periodic climate episodes involving typical terrestrial-style precipitation, the deposit required thousands to millions of years to accumulate. However, a scenario of deposition during a few short episodes of constant heavy precipitation resulting from large impacts cannot be excluded. *INDEX TERMS:* 1815 Hydrology: Erosion and sedimentation; 1824 Hydrology: Geomorphology (1625); 5407 Planetology: Solid Surface Planets: Atmospheres—evolution; 5415 Planetology: Solid Surface Planets: Erosion and weathering; 5470 Planetology: Solid Surface Planets: Surface materials and properties. **Citation:** Moore, J. M., A. D. Howard, W. E. Dietrich, and P. M. Schenk, Martian Layered Fluvial Deposits: Implications for Noachian Climate Scenarios, *Geophys. Res. Lett.*, *30*(24), 2292, doi:10.1029/2003GL019002, 2003.

1. Introduction

[2] *Malin and Edgett* [2003] recently reported the discovery of a compelling example of an exhumed and differentially eroded Martian layered fluvial delta or fan complex probably of late Noachian age created by fluvial flows of moderate magnitude derived from adjacent highlands. We analyze this layered deposit and its drainage basin, evaluate their implications for flow rates and durations, and preferably conclude that its features are consistent with a terrestrial-style sediment history persisting over thousands of years [e.g., *Squyres and Kasting*, 1994], but an alternative very rapid emplacement by precipitation during occasional catastrophes [e.g., *Carr 1989*; *Segura et al.*, 2002] cannot be ruled out. This study was initially executed without knowledge of the *Malin and Edgett* [2003] report, and thus it provides an independent assessment of this feature and its implication for Martian climate history.

0094-8276/03/2003GL019002

2. Geologic Setting and Outcrop Description

[3] The fan-shaped outcrop (24.1°S, 33.9°W) is roughly 10 by 12 km in plan view (Figure 1), covering an area ∼100 km^2, and is located at the west end of a ∼70 by 35 km elliptical, relatively flat-floored, depression (long axis oriented NW) centered at 24.4°S, 33.6°W (Figure 2). The elliptical depression is probably one or two very degraded impact craters that now form a continuous basin. It is situated just north of the Noachian-age 140 km-diameter Holden crater, whose proximal ejecta superposes the SW rim of the depression and underlies the fan-shaped outcrop. Data from the Mars Orbiter Laser Altimeter (MOLA) indicate that the floor of the elliptical depression lies between ∼−1200 m and ∼−1500 m, with the deepest part in the western center of the basin, just east of the fan-shaped outcrop.

[4] The fan-shaped outcrop lies at the mouth of a ∼20 km long flat-floored sinuous trunk valley whose upper reach connects to a valley system through deep incision to higher ground some 700 m above to the west. An anastomosing network of shallow valleys (labeled "V" in Figure 2) continues from the head of the trunk valley across flat ground (at ∼−500 m elevation) westward for ∼25 km until the ground steepens again into broad slopes incised by several valleys. This upland "drainage" basin of about ∼70 by 60 km (see dotted line in Figure 2) is probably a severely degraded impact crater whose rim was breached on its eastern side by the trunk valley.

[5] The fan-shaped outcrop itself appears nearly planar, with an abrupt drop-off of 100–200 m at a feathered or digitate periphery along the north and east (arrow in Figure 2). The outcrop lies between ∼−1200 and ∼−1400 m, with the bulk at the lower elevation. At much higher resolution (∼3–5 m/pixel) many low, flat-topped and often-sinuous ridges are visible, which converge toward the west (Figure 1a) at the apparent fan apex. Individual ridges are typically 100 to 200 m wide, with the widest approaching ∼1 km, while others are only a few-tens-of-meters across. Ridges are often stacked upon one another, exhibiting crosscutting and superposition (e.g., arrow in Figure 1a). The larger ridges display longitudinal lineations, which in some cases resolve to be even smaller flat-topped and very low ridges

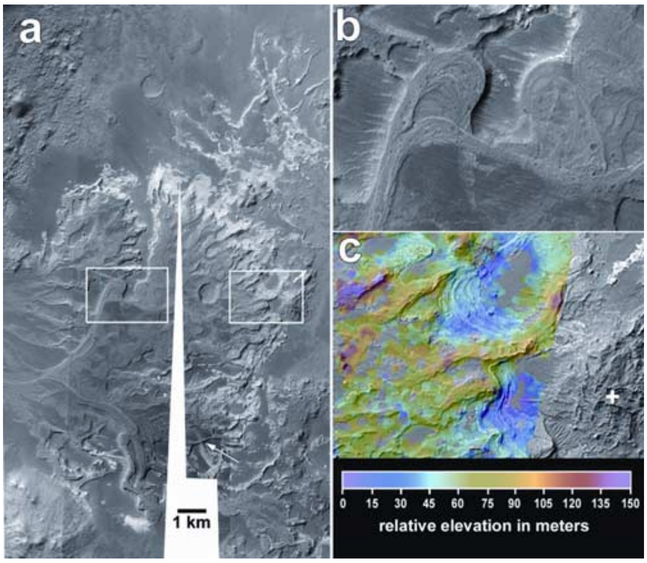

Figure 1. (a) Mosaic of visible light images acquired by the narrow angle Mars Orbiter Camera aboard *Mars Global Surveyor* (MGS), all with original resolutions of better than 5 m/pixel, showing details of a fan-shaped outcrop we interpret to be fluvial delta deposits exposed by deflation and differential erosion resulting in inverted relief. The mosaic is composed of images E17-01341, E18-00401, E21-01153, E23-00003. North is up. Illumination is from the left. The mosaic is centered on 24.1°S, 33.9°W. (b) Enlargement of left box in showing the form of a meander and cutoff (inset ~2.8 km across). (c) Enlargement of right box showing the periphery of the deposit, which exhibits step-like relief we interpret to be discrete sedimentary layers exposed by differential erosion (inset ~2.4 km across). Elevations were determined from stereo pairs (E14-01039 and E23-00003) using a scene autocorrelation algorithm described in *Schenk and Moore* [2000].

(Figure 1b). In Figure 1b, a well-defined loop with distinct, successive scroll-bar ridges records the progressive growth of the meander, and eventually its cutoff, identical to that seen on terrestrial floodplains. The lateral shifting was accompanied by aggradation, as suggested by the apparent rise in the exposed surface with outward migration of the bend, and by the crosscutting relationship where the channel cuts off the bend. Other ridges with lineations show similar, but less dramatic evidence for bend migration. The digitate periphery in detail is scarp-like, where individual ridge flanks and termini exhibit alternating steep slopes and ledges forming up to on order of a dozen steps, each ~10 m high (Figure 1c). These outcrop exposures are light-toned in the visible light images, and alternatively dark in daytime and bright in nighttime thermal infrared (IR) images acquired by the Thermal Emission Imaging System (THEMIS), indicating that this material has a relatively high thermal inertia (see details of THEMIS IR image interpretation in [*Christensen et al.*, 2003]). Taken together, the ability to support steep slopes and the relatively high thermal inertia, strongly imply that here are clean exposures of at least partially indurated, if not lithified, sediment.

[6] We concur with *Malin and Edgett* [2003] that this fan-shaped outcrop is an exhumed and differentially eroded fluvial delta or fluvial fan. The exhumation and differential erosion has exposed channel floor sediment that now forms the individual ridges. The resistance of this bed sediment to aeolian erosion indicates that it is either gravelly or partially lithified. Fine-grained floodplain sediment that overlay and/or laterally bounded the channel deposits has been differentially stripped, presumably by aeolian deflation. Most of these inter-channel depressions are now thinly mantled with aeolian sediment. The individual sedimentary layers exposed along the steeper delta margin (Figure 1c) may be inter-channel overbank deposits, or they may be distal delta facies (foreset or bottomset beds) or lake deposits buried by the advancing delta. Although definitive exposures are lacking, we infer from the increasing number and decreasing width of channels approaching the distal edge of the delta that transport occurred through a distributary branching pattern of channels. The overall digitate, or "bird's foot," pattern places this delta among terrestrial deltas whose shapes are *sediment* dominated (as opposed to *wave* or *tide* dominated) [*Orton and Reading*, 1993]. This is not surprising, as Mars has no significant tides and water bodies there may have often been ice covered [e.g., *Squyres and Kasting*, 1994].

3. Analysis

[7] A meandering channel pattern implies channel banks with a moderate degree of cohesion, because cohesionless banks result in a braided pattern because the resulting large channel width-to-depth ratio permits development of alternate bar instabilities that encourage flow branching [*Cant*, 1982]. Terrestrial meandering channels with strongly cohesive or well-vegetated banks, however, develop a highly sinuous meandering pattern not occurring in the Martian

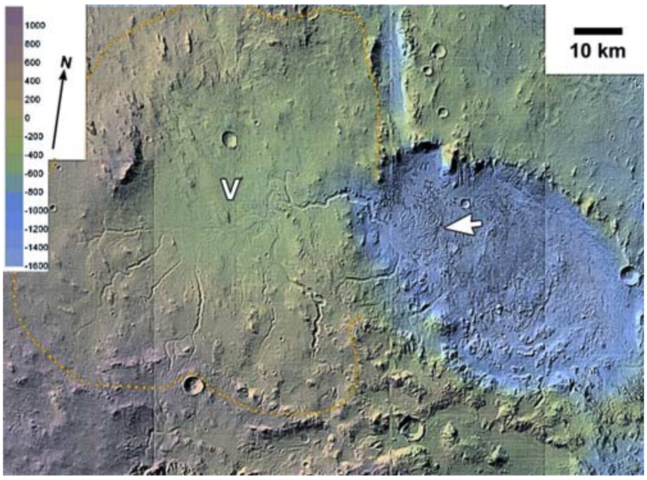

Figure 2. Mosaic of thermal infrared 100 m/pixel images taken during daytime by THEMIS aboard the *Mars Odyssey* orbiter showing the general geographic setting of the fan-shaped deposit (arrow), and its associated valley network. The dotted line shows the estimated area drained by the valley network. Part of the network is anastomosing, marked by "V." The mosaic is composed of images I01737002, I01762002, I02461003, I03185002, I03210002, and I04733002. Illumination is from the left. The mosaic is centered on ~24°S, 34°W. This mosaic has been "colorized" to show co-registered topographic elevations derived from MGS MOLA data. The topographic scale bar (left) gives values in meters.

case. Finally, the meander cutoff in Figure 1b occurred via a chute, rather than neck, cutoff, which is consistent with low, moderately cohesive banks. The source of the cohesion in the Martian case is uncertain. It could be due to a small percentage of silts and clays, or possibly due to frozen banks. The subsequent aeolian scour of the contemporaneously deposited bank and floodplain sediment also suggests moderate or temporary cohesion. The cutoff of the meander probably occurred during high flow conditions after the meander had stretched to a point that the flow exploited a more direct path across the meander loop.

[8] The excellent exposure of the meandering channel deposits permits a rough estimation of the magnitude of the corresponding fluvial flows. Measurements were concentrated in channels exposed near the apex of the delta complex, presumably above significant flow reduction through anabranching. Meander wavelength is the most unambiguous measurement of channel properties that can be made. At seven locations meander half-wavelength (apex to next apex with opposite curvature) was measured, giving estimated full wavelengths ranging from 1018–2866 m, averaging 1858 m. Although a meandering channel deposits a blanket of bed sediment, at a number of locations the exposed channel fills exhibited low curvature and reasonably parallel edges, suggesting that the full width of the original channel is represented. Five measurements yielded estimated widths from 112–162 m, averaging 128 m (this is greater than the 50 m estimated by *Malin and Edgett* [2003]). In freely-meandering terrestrial channels the ratio of wavelength to channel width averages about 12.3 [*Leopold and Wolman*, 1960; *Richards*, 1982] in reasonable agreement to the 14.5 from dividing the Martian average values. Theory for the initiation of meanders due to curvature-induced secondary flows suggests the initial meander wavelength should be $\lambda \sim 4.2\ D/C_f$, where C_f is a coefficient of friction given by the square of the ratio of shear velocity to mean velocity and D is average channel depth [*Ikeda et al.*, 1981; *Howard and Knutson*, 1984]. Unfortunately, these properties are impossible to measure from images acquired from orbit. A number of empirical studies on terrestrial channels, however, relate channel width and meander wavelength to their formative discharge. Straightforward use of such formulas results in biased estimates because Martian gravity is only about 0.4 of the terrestrial value. An analysis of empirical data on terrestrial gravel bed channels using dimensionless variables suggests that channel width should scale as about the −0.23 power of gravity [*G. Parker*, University of Minnesota, personal communication, 2003]. A similar analysis by Parker shows depth also varies with gravity in about the same ratio, so that the width-depth ratio in gravel streams is essentially unaltered by differences in gravity. It is uncertain whether the Martian channels are gravel- or sand-bed, but we assume similar gravity scaling for both bed types. Because empirical formulas estimate discharge from approximately the square of meander wavelength or channel width, this suggests that discharge estimates using terrestrial empirical relationships should be reduced by a factor of about 0.65 ($[0.4^{0.23}]^2$). This factor has been applied to the estimates quoted below. Empirical studies relating meander wavelength to some measure of river discharge, as summarized in [*Knighton*, 1988], suggest bankfull or mean annual flood discharge of about 650–975 m^3/s and a mean annual discharge of about 130 m^3/s based upon the average Martian meander wavelength. Empirical relationships also exist relating channel width to bankfull discharge, as summarized in *Knighton* [1987], which suggest discharges ranging from 300–1600 m^3/s, with the large terrestrial variability largely due to regional variations in channel width-depth ratio. An additional check is terrestrial relationships relating discharge to drainage area. The source drainage basin debauching onto the apex of the delta is estimated at 4800 km^2 (Figure 2) based upon interpretation of MOLA topography and the visible channel network. Data derived primarily from terrestrial humid temperate regions [*Knighton*, 1988] predict mean annual floods ranging from 300 to 800 m^3/s. In summary, these comparisons with terrestrial meandering channels suggest the formative discharge for the Martian delta was about 700 m^3/s.

[9] Through estimation of the delta volume and the size of the drainage basin contributing sediment, a rough assessment can be made of the headwater erosion required to build the delta. The delta is estimated to be 11 km by 8 km in size and 150 m thick (based on MOLA profiles), for a volume of 13.2 km^3 (*Malin and Edgett* [2003] estimate a smaller volume of 6 km^3). Thus a maximum of 3 m of average erosion within the contributing basin is needed to form the visible delta, although the actual erosion would have been somewhat greater if the volume of bottomset beds and post-depositional erosion of the delta could be accounted for. Much of this headwater erosion, however, could have been derived from the several deeply incised channels, including the ~21 km long canyon just upstream from the delta and 7 valleys on the south and west sides of the basin, each about 20 km long (including the channel entering the delta from the south). Estimating, from MOLA profiles, an average width and depth for the canyon of 1200 m and 60 m, respectively, and 500 m and 40 m for the 7 valleys, the total valley volume is about 4.3 km^3, about one-third of the estimated delta volume. The deep incision, low drainage density and poorly branched character of these entrenched channels suggest erosion by (precipitation charged) groundwater sapping.

[10] The delta basin and its upland contributing basin appear to be strongly degraded, presumably in part by mantling from Holden Crater ejecta, but probably also by earlier fluvial activity indicated by the degraded crater rims. Deposits and channels from this earlier erosional epoch are not recognizable due to the Holden Crater ejecta blanket. Subsequent to the delta deposition, massive friable deposits were emplaced within the delta basin (e.g., hill labeled "+" in Figure 1c). Because these deposits appear to unconformably overlie the delta sediments in some locations and are present on the basin floor just beyond the scarp at the delta front, we infer that the delta deposits were scoured prior to the deposition of the massive unit (which is presumably very friable airfall materials). This airfall mantling may have helped preserve the delta deposits, which have been relatively recently reexposed (explaining the paucity of superimposed impact craters).

4. Implications for Early Martian Climate

[11] The length of time over which the delta was formed is uncertain, but we evaluate two scenarios. The consistent width of the exposed channels, the moderate discharges we calculate, the meandering rather than braided pattern, and

the gradual enlargement of meander bends to the point of cutoff suggest that the delta was formed either by repeated runoff events of moderate intensity or by relatively steady discharges as opposed to catastrophic floods. On Earth, meander evolution to the formation of a cutoff typically takes place on multi-decadal to 1000-year time scales depending upon the bank erodibility and river size [*Fisk*, 1944]. Sediment yields in terrestrial drainage basins typically range from about 4 to 2000 metric tons $\mathrm{km}^{-2}\,\mathrm{yr}^{-1}$ (see summary in [*Summerfield*, 1991]), although yields can be much lower in hyperarid and non-glaciated polar deserts and considerably higher from unvegetated fine-grained sediments. Assuming an arbitrary but reasonable bulk sediment specific gravity of 1.5, the duration would range from about 2,000 to 10^6 years for the above range of terrestrial sediment yields. Such long durations are consistent with terrestrial climates, in which most sediment delivery and channel-forming processes to deltas occur only for a few days per year ($\leq$1%/yr) of high discharges. This is true both in temperate climates dominated by storms and in arctic climates dominated by snowmelt [*Clark*, 1988]. If runoff occurred only during favorable climatic conditions associated with extremes of Martian quasi-cyclical climate changes [*Toon et al.*, 1980] the total duration could have been much longer.

[12] *Segura et al.* [2002] suggest that the early Martian climate may have been cold and dry with the exception of brief episodes of warm wet conditions following major impact events, as was similarly suggested by *Carr* [1989]. According to this scenario, rainfall from typical large late-Noachian impact events would have been very strong and unceasing, but gradually declining over ~10 years depending upon the size of the impact. If continuous flows of 1000 m^3/s with 5% volume of solids are assumed, about 3.0 km^3 of sediment could be delivered per Martian year. Thus even with considerably smaller assumed sediment loads, the entire delta could be built within a few years. Issues that must be faced, however, by such scenarios include the frequency of large impacts, the reasonableness of their estimates of the magnitude and constancy of precipitation, and the likelihood that sediment yields would rapidly decline as rainfall and runoff erosion in the headwaters gradually concentrated larger rock fragments (e.g., impact breccias) on the surface to form a coarse armor (desert pavement). In terrestrial climates this tendency is to some degree counteracted by long-term weathering and inter-storm mixing of the regolith surface layers by biotic and abiotic processes, such as freeze-thaw.

[13] The sediment layering exposed in the steep distal slope of the delta (Figure 1c) indicates temporal variation in the composition or grain size of the supplied sediment. Both the depositional environment of the layering (overbank deltaic deposits, delta foreset or bottomset beds, or lacustrine deposits) and the timescales represented by individual layers are uncertain. Individual layers may represent the effects of switching of the locus of coarse sediment deposition as avulsions on the delta shift the location of the active delta lobe. The deltaic layers might also reflect the pronounced quasi-periodic climatic variations on Mars [*Toon et al.*, 1980] with variations in obliquity, precession and eccentricity over timescales of 10^5 to 10^7 years. Finally, the layers could represent deposition events associated with individual impacts according to a *Segura et al.* [2002] model, but only if runoff is very heavy and continuous over at least a decade-scale period. The qualitative visual appearance of layers of similar thickness seems more consistent with quasi-cyclical climatic forcing as opposed to runoff events of random intensity and duration associated with impacts or with lobe-switching events.

[14] The large volumes of the delta deposits, and the even larger volumes of discharge required to erode and transport sediment from the source basin to the delta front, require precipitation of some form during the period of delta formation. This is true whether the runoff was due to short-term impact-induced climatic optima or longer-term runoff or groundwater discharge [*Craddock and Howard*, 2002] in a Noachian climate permitting occasional rainfall or snowfall followed by snowmelt.

[15] **Acknowledgments.** We thank Jon Pelletier and especially Brian Hynek for their careful reviews, and Gary Parker for providing us with his pre-publication analysis of gravity-scaling in gravel channels. This research was performed under grants from NASA's Mars Data Analysis and Planetary Geology and Geophysics Programs.

References

Cant, D. J., Fluvial Facies Models and Their Application, in *Sandstone Depositional Environments Mem. 31*, edited by P. A. Scholle and D. Spearing, pp. 115–137, Am. Assoc. Petrol. Geol., Tulsa, Oklahoma, 1982.

Carr, M. H., Recharge of the early atmosphere of Mars by impact-induced release of $\mathrm{CO_2}$, *Icarus*, *79*, 311–327, 1989.

Christensen, P. R., et al., Morphology and composition of the surface of Mars: Mars Odyssey THEMIS results, *Science*, *300*, 2056–2061, 2003.

Clark, M. J., Periglacial Hydrology, in *Advances in Periglacial Geomorphology*, edited by M. J. Clark, pp. 415–462, Wiley, Chichester, 1988.

Craddock, R. A., and A. D. Howard, The case for rainfall on a warm, wet early Mars, *J. Geophys. Res.*, *107*(E11), 5111, doi:10.1029/2001JE001505, 2002.

Fisk, H. N., *Geological Investigation of the Alluvial Valley of the Lower Mississippi River*, Mississippi River Commission, Vicksburg, 1944.

Howard, A. D., and T. R. Knutson, Sufficient conditions for river meandering; A simulation approach, *Water Resour. Res.*, *20*(11), 1659–1667, 1984.

Ikeda, S., G. Parker, and K. Sawai, Bend theory of river meanders, Part 1, Linear development, *J. Fluid Mech.*, *112*, 363–377, 1981.

Knighton, A. D., *Fluvial Forms and Processes: A New Perspective*, Arnold, London, 1988.

Knighton, A. D., River channel adjustment, The downstream dimension, in *River Channels*, edited by K. S. Richards, pp. 95–128, Basil Blackwell, Oxford, 1987.

Leopold, L. B., and M. G. Wolman, River meanders, *Geol. Soc. Am. Bull.*, *71*(6), 769–793, 1960.

Malin, M. C., and K. S. Edgett, Evidence for persistent flow and aqueous sedimentation on early Mars, *Science*, in press, 2003.

Orton, G. L., and H. G. Reading, Variability of deltaic processes in terms of sediment supply, with particular emphasis on grain size, *Sedimentology*, *40*, 475–512, 1993.

Richards, K. S., *Rivers: Form and Process in Alluvial Channels*, Methuen, London, 1982.

Schenk, P. M., and J. M. Moore, Stereo topography of the south polar region of Mars: Volatile inventory and Mars Polar Lander landing site, *J. Geophys. Res.*, *105*(E10), 24,529–24,546, 2000.

Segura, T., O. B. Toon, A. Colaprete, and K. Zahnle, Environmental effects of large impacts on Mars, *Science*, *298*, 1977–1980, 2002.

Squyres, S. W., and J. F. Kasting, Early Mars — How warm and how wet?, *Science*, *265*, 744, 1994.

Summerfield, M. A., *Global Geomorphology*, John Wiley & Sons, New York, 1991.

Toon, O. B. J., B. Pollack, W. Ward, J. A. Burns, and K. Bilski, The astronomical theory of climatic change on Mars, *Icarus*, *44*, 552–607, 1980.

W. E. Dietrich, University of California, Berkeley, CA, USA.

A. D. Howard, University of Virginia, Charlottesville, VA, USA.

J. M. Moore, NASA Ames Research Center, Moffett Field, CA, USA. (jeff.moore@nasa.gov)

P. M. Schenk, Lunar and Planetary Institute, Houston, TX, USA.