OLD OR NOT SO OLD: THAT IS THE QUESTION FOR DELTAS AND FANS IN XANTHE TERRA, MARS.

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Introduction: Most aqueous activity on Mars (except the outflow channels) is thought to be older than ~3.8 Ga [1]. After a major and global environmental change [e.g., 2] of yet unknown reasons [3], the planet approached its current hyperarid climate. Despite this general agreement, many open questions remain: How abrupt was the climatic change at the Late Noachian/Early Hesperian boundary? Was the type of aqueous processes different before and after? How quickly disappeared the surface water? To address some of these questions, we revisited a part of Xanthe Terra where a number of fluvial valleys and channels and associated deltaic deposits can be observed [4]. Our main objective was to test the hypothesis that deltas (and, implicitly, lakes) on Mars formed mainly during the period of more intense fluvial activity more than ~3.8 Ga ago. We analyzed the morphology, determined absolute model ages and searched for the spectral signatures of alteration minerals that might have formed in response to fluvial and/or lacustrine processes. To test whether our results apply only regionally (to Xanthe Terra), or perhaps globally, we also investigated similar deltas in the eastern hemisphere (e.g., Aeolis region) which were proposed as indicators for an ancient ocean [5] and, therefore, expected to be old (> ~3.8 Ga).

Data and Methods: We used CTX images for crater counting, ideally suited because of their good contrast, high resolution (5-6 m/pixel), and wide coverage. For very small areas, HiRISE images (30 cm/px) were used. Topography was extracted from HRSC stereo data and MOLA laser shots. CRISM FRT cubes were analyzed for spectral information.

For age determination, representative surface areas were mapped on the basis of morphology (stratigraphy), and craters were counted utilizing the software ‘cratertools’ [6]. Absolute model ages were derived with the software tool ‘craterstats’ [7] by analysis of the crater-size frequency distributions applying the production function coefficients of [8] and the impact cratering chronology model coefficients of [9].

Morphology: As already reported earlier [4], the deltas are mostly situated in impact craters at the terminations of deep valleys with steep walls, abrupt (“amphitheater-like”) headwalls and few tributaries. These characteristics have often been interpreted as evidence for sapping, i.e. the retrogressive erosion of valleys induced by the seepage of groundwater. Whether sapping can indeed be a major landscape-forming process (this was questioned in the past, e.g. [10]) is currently investigated in another study [11] and will not further be addressed here. We note, however, that most deltas display morphologies that are consistent with short-lived processes (Fig. 1) [12,13]. We also note that most, but not all, deltas are superimposed on flat crater floors, which have been volcanically resurfaced after the main fluvial activity on Mars [14].

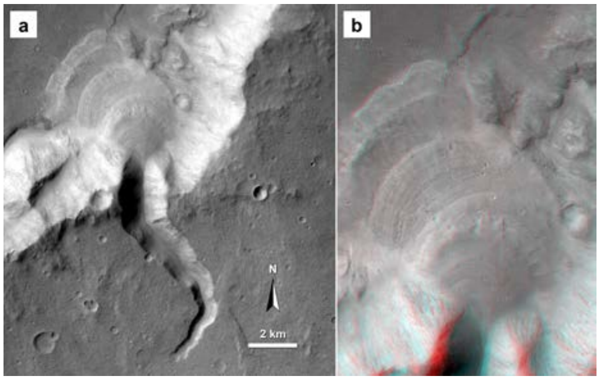

Figure 1 | “Stepped” delta in Dukhan crater in Xanthe Terra (7.59°S/321.03°E). (a) Context: Note the short and deep valley feeding the delta, and the flat floor of Dukhan Crater (upper left). Detail of CTX image G01_018544_1878). (b) Anaglyph image of delta. The morphology and the stair-stepped profile is very similar to a delta type observed on Mars and reproduced in the laboratory [12], (HiRISE images ESP_018544_1875 & ESP_017555_1875).

Spectral Analysis: Almost no alteration minerals have been detected on the investigated deltas so far. However, opaline silica has been detected on the distal part of a stepped fan delta (“Camichel“, #8 in Fig. 2), formed in the Amazonian. Opaline silica usually forms under arid/acid conditions on Earth, which suggests that it formed under a dry environment on Mars [15].

Ages: The results of our crater counting yield very diverse ages for the deltas (Fig. 2; Tab. 1). While some deltas may be as old as the Late Noachian/Early Hesperian transition, by far most deltas appear to have formed in the Hesperian and in the Amazonian. Although it was sometimes difficult to decide whether larger craters formed on top of the delta or were embayed by the deposits (and therefore older), we tried to be as conservative as possible in our age determination and, if in doubt, always went for the older ages. Therefore, we believe that the general trend of our findings is robust. Our mostly Hesperian-Amazonian absolute model ages are consistent with the stratigraphic relationships between the superposed deltas (younger) and the underlying flat crater floors (older), the latter typically having post-Noachian ages [14]. We conclude that the triggering mechanism that released the water over short timespans [13] operated over a long time even after the major climatic change on Mars in the Late Noachian/Early Hesperian. Although the past evolution of the atmospheric pressure is uncertain, the current low pressure is likely representative for most of the Hesperian and the Amazonian. Therefore, we can also conclude that this triggering mechanism operated in a climate which did not sustain strong precipitation. Thus, mobilization of ice in the cryosphere [16] by volcanism (operating throughout Martian history [17]) or impacts (ditto; e.g., [18]) appears as a likely trigger for water release. It can be qualitatively envisaged that such processes episodically occured over most of Mars` history, without implying a warmer and wetter climate. A formation of deltas by short and episodic events would also be consistent with the lack of associated alteration minerals – water was never present long enough for the required reaction times.

Implications: The observed type of deltas formed in short and local aqueous episodes in the Hesperian and Amazonian. In the very recent past, and even at present, other short-lived and spatially restricted aqueous processes have formed gullies [19] and recurrent slope lineae (RSL) [20]. Compared to the deltas, the amount of water forming the gullies was orders of magnitude *smaller* (even less for RSL). Outflow channels, overlapping in time with the deltas studied here, also represent short-lived aqueous activity, however with water volumes orders of magnitude *larger*.

In summary, episodic aqueous processes appear to have operated on Mars over the last billions of years, without the need for a warmer climate. Although the water came from both the subsurface/cryosphere (deltas, outflow channels) and the surface (gullies, RSL?), the required ultimate source to recharge the water reservoirs would have likely been snowfall [e.g., 21], the rate and amount of which depending on obliquity and orbital parameters and the associated climate [e.g., 22].

References: [1] Fassett C. I. and Head J. W. (2008) *Icarus, 195*, 61–89. [2] Bibring J.-P. et al. (2006) *Science*, *312*, 400–404. [3] Lammer H. et al. (2013) *Space Sci. Rev., 174*, 113–154. [4] Hauber E. et al. (2009) *Planet. Space Sci., 57*, 944–957. [5] Di Achille G. and Hynek B. M. (2010) *Nature Geosci., 3*, 459–463. [6] Kneissl T et al. (2011) *Planet. Space Sci., 59*, 1243–1254. [7] Michael G. and Neukum G. (2010) *EPSL, 294*, 223–229. [8] Ivanov B. A. (2001) *Space Sci. Rev.*, *96*, 87–104. [9] Hartmann W. K. and Neukum G (2001) *Space Sci. Rev., 96*, 165–194. [10] Lamb M. P. et al. (2008) *Science*, *320*, 1067–1070. [11] Marra, W. et al., *this conference*, abstract #1899. [12] Kraal E. et al. (2008) *Nature, 451*, 973–976. [13] Kleinhans M. et al. (2010) *EPSL, 294*, 378–392. [14] Goudge T. A. et al. (2012) *JGR, 117*, E00J21, doi: 10.1029/2012JE004115. [15] Tosca N. and Knoll A. (2009) *EPSL, 286*, 379–386. [16] Lasue J. et al. (2013) *Space Sci. Rev.*, *174*, 155–212. [17] Hauber E. et al. (2011) *GRL, 38*, L10201, doi: 10.1029/2011GL047310. [18] Mangold N. et al. (2012) *Icarus, 220*, 530–551. [19] Malin M. C. and Edgett, K. S. (2001) *Science, 288*, 2330–2335. [20] [McEwen A. S. et al. (2011) *Science*, *333*, 740–743. [21] Kite E. S. et al. (2013) *Icarus*, *in press*. [22] Wordsworth R. et al. (2013) *Icarus, 222*, 1–19.

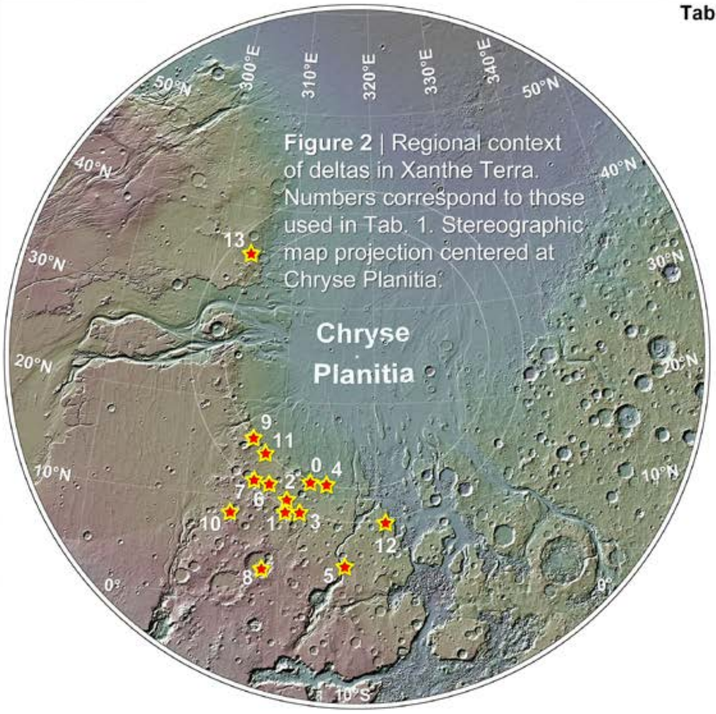

Figure 2 | Regional context of deltas in Xanthe Terra. Numbers correspond to those used in Tab. 1. Stereographic map projection centered at Chryse Planitia.

Table 1

#^{a}	Delta name^{b}	Lat [°N]	Lon [°E]	Age^{c}
	Xanthe Terra and circum-Chryse			
00	Sabrina	11.69	307.05	~3.4 Ga
01	Tyras	8.45	310.26	~3.4 to 3.6 Ga
02	Sibut	9.84	310.58	n/a
03	Nanedi	8.49	311.99	~3.6 Ga
04	Hypanis	11.3	314.57	~3.45 Ga
05	Shalbatana	3.05	316.75	~3.3 to 3.4 Ga^{d}
06	*unnamed*	11.38	308.72	~3.6 Ga
07	Subur	11.72	307.05	~1.4 Ga
08	Camichel	2.74	308.33	~571 Ma
09	Balvicar	16.04	306.78	~835 Ma
10	Cantoura	14.52	308.17	~1.95 Ga
11	Kolonga	8.17	304.89	~387 Ma
12	Dukhan	7.59	321.03	~294 Ma
13	Liberta	35.18	304.52	~844 Ma
	Eastern hemisphere (e.g., Aeolis) for comparison			
	unnamed	14.09	335.70	~924 Ma
	Nephentes^{e}	2.16	121.64	~1.8 Ga
	Aeolis 1	-5.62	140.49	~988 Ma
	Aeolis 2	-6.54	141.12	~3.5 Ga
	Aeolis 3	-6.49	141.69	~3.5 Ga

^{a}*Corresponds to delta numbers in Fig. 2.*

^{b}*Typically name of crater hosting the delta.*

^{c}*Ma: 10^6 years; Ga: 10^9 years.*

^{d}*measured by Di Achille et al. (2007) JGR, 112, E07007.*

^{e}*see, e.g., de Pablo and Pacifici (2008) Icarus, 196, 667-661.*