FLUVIAL VALLEYS AND SEDIMENTARY DEPOSITS IN XANTHE TERRA: IMPLICATIONS FOR THE ANCIENT CLIMATE ON MARS.

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Summary: A variety of sedimentary deposits is observed in Xanthe Terra, Mars, including Gilbert-type deltas, fan deltas dominated by resedimentation processes, and alluvial fans. Sediments were provided through deeply incised valleys, which were probably incised by both runoff and groundwater sapping. Mass balances based on high-resolution HRSC digital terrain models show that up to ~30% of the material that was eroded in the valleys is present as deltas or alluvial fan deposits. Stratigraphic relationships and crater counts indicate an age of ~4.0 to ~3.8 Ga for the fluvial activity. Hydrologic modeling indicates that the deposits were probably formed in geologically very short timescales. Our results indicate episodes of a warmer and wetter climate on early Mars, followed by a long period of significantly reduced erosion rates.

Introduction: Two major questions in studies of Martian valley networks concern the nature of the fluvial activity (surface runoff versus groundwater seepage) and the depositional environment (subaerial alluvial fans versus lacustrine deltas), a question that addresses the ability of Mars and its climate to host large bodies of standing surface water [e.g., 1,2]. The interest in sedimentary deposits on Mars was recently increased by findings of the imaging spectrometers, OMEGA and CRISM, which identified the spectral signatures of phyllosilicates in association with sedimentary deposits in Holden and Jezero craters [3]. Research activities currently focus on a spectacular deposit in the Eberswalde Crater, which is characterized by well-preserved layering and sinuous, meandering channels [e.g., 4-6], and on deposits in Holden Crater [e.g., 7,8], both of which are considered as potential landing sites for the upcoming MSL mission. However, there are many other sedimentary deposits which have not been examined in detail using the new high-resolution datasets from recent Mars missions. Here we focus on sedimentary deposits in Xanthe Terra, between the outflow channels Maja Valles to the west and Shalbatana Vallis to the east (Fig. 1).

Geologic context: The study area is located in Xanthe Terra between Maja and Shalbatana Valles (Fig. 1). It is characterized by a high density of craters with >10 km diameter and resurfacing in the late Noachian [9]. The study region is dissected by two types of valleys. Valleys of the first type are narrow (few km) and shallow (meters to tens of meters). They were probably formed by fluvial processes that were not very intense and did not lead to the development of mature drainage patterns with high-order tributaries and high drainage densities. A second type of valleys is younger and and includes Nanedi, Hypanis, Sabrina, Ochus, Drilon, and Subur Valles. Valleys of this type are deeply entrenched and show characteristics like

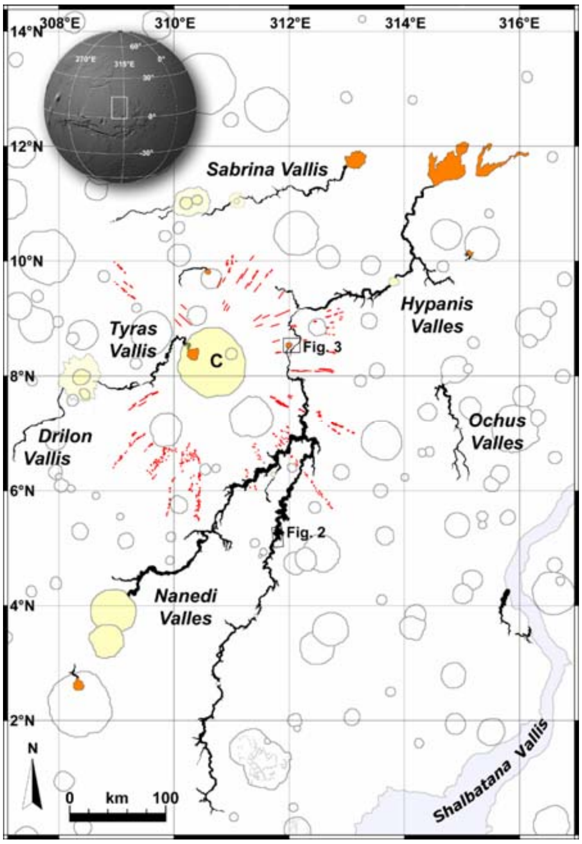

Figure 1. Sketch map of the study area (the Subur Vallis delta is located outside this base map at 11.72°N and 307.05°E). *Black:* valleys; *orange:* sedimentary deposits; *open circles:* impact craters; *yellow:* superposed craters and their ejecta, which formed after the valleys onto which they are superposed; *blue:* outflow channel; *rows of red dots:* ejecta and secondary crater chains radiating outward from large impact crater (C); *boxes:* locations of Fig. 2 and 3.

amphitheater-shaped heads, few tributaries, low drainage density, and almost constant widths (see [10] for terrestrial analogues on the Colorado Plateau). They were interpreted to be indicative of an origin by groundwater sapping rather than by precipitation [11,12], although other processes such as late-stage fluvial entrenchment, erosion through layered stratigraphy, and incision into a duricrust might also produce these morphological properties ([13]; see also [14], who describe a terrestrial amphitheater-headed canyon that was not eroded by sapping). A contribution from overland flow to sapping valley formation on Earth seems to be likely from the analysis of terrestrial analogues in Utah and Arizona [15]. The few very high-resolution images taken by HiRISE do not show unambiguous evidence for many small or shallow tributary channels indicative of overland flow connecting with the large entrenched valleys. But at least one of the images displays a faint pattern of very shallow and small valleys (Fig. 2), which might have hosted fluvial channels. Erosion and blanketing of the surface with wide-spread eolian dunes may have obscured the traces of others. Small interior channels are incised into some valley floors [16] and suggest sustained flow of water [17]. Valley formation might have begun in the Noachian and continued into the Early Hesperian [18; 9; 12]. Most deposits are situated where fluvial channels breach the rims of strongly degraded impact craters and debouch onto the crater floors. The region is moderately dust-covered [19], and consequently no spectral signatures of alteration minerals could be identified [20,21; Poulet, pers. comm].

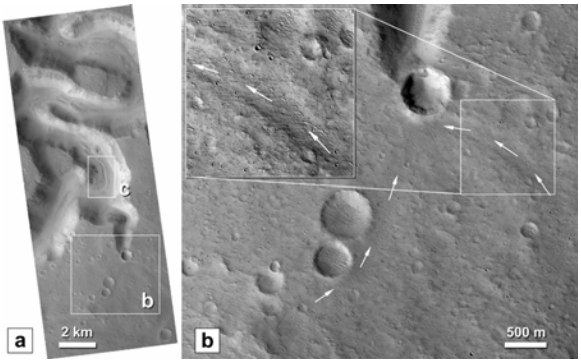

Figure 2. Morphologic evidence for surface runoff in Xanthe Terra. (a) Portion of the Nanedi Valles system (HiRISE PSP_003341_1855; see Fig. 1 for location), white boxes mark locations of panels b and c (not shown). (b) Faintly visible shallow valleys might have been fluvial channels localizing surficial runoff due to precipitation. Similarly, shallow contributing streams have been found on the Colorado plateau above theatre-headed valleys [15]. Inset shows details, contrast was enhanced for better visualization of valley topography. The co-existence of both deeply incised valleys and shallow upslope tributaries makes sapping as a sole cause for the creation of the theatre-headed valleys unlikely (compare to Figs. 2b and 2c of [17]).

Observations of deposits: Two of the deposits identified in Xanthe Terra are described in detail here, the others are covered elsewhere [22] (Fig. 1).

Nanedi delta. The smallest of the deposits is located near 8.5°N, 312°E at the end of the Nanedi Valles (hereafter referred to as Nanedi Deposit). It is located inside a degraded impact crater with 6.5 km diameter (Fig. 3) and covers almost the entire crater floor. The surface of the deposit covers an area of ~23 km^2 and is dissected by a pattern of radially distributing channels. Where the deposit does not onlap the inner crater wall, its distal parts are marked by a steep front, along which fine layers are exposed. The layers have thicknesses of only a few meters, and there are no boulders or blocks that could be identified at the scale of the HiRISE image (25 cm/pixel). The layers can be traced for a few hundred meters and do not display evidence for faulting or unconformal contacts. It must be noted, however, that the entire area is heavily covered with wind-blown dunes and ripples which obscure much of the underlying bedrock. The height of the distal margin is about 50 m, according to the HRSC DEM (Fig. 4a). Assuming a constant thickness of 50 m over the entire area of the deposit, we obtain a volume of about 1.15 km^3. Since the thickness is probably larger at the crater center, we consider this value to be a lower limit of the total volume. The surface of the deposit has an average topographic gradient of ~0.014, as measured in the HRSC DEM. The crater has a small outlet channel at its eastern part. Outlet channels from craters are strong indicators for open-lake basins [23], and the morphology of the outlet channel, including a small streamlined island, is suggestive of liquid flow. This and the small slope would be in agreement with ponding of water in the crater, formation of the deposit in a lake, and drainage of lake water into the outlet channel. However, the available data do not permit a definitive interpretation, and a formation as alluvial fan, as suggested by [12] can not be ruled out.

Subur delta: An interesting sedimentary deposit can be observed in an unnamed 41 km-diameter impact crater centered at 11.97°N and 307.28°E (outside area shown in Fig. 1). Where Subur Vallis breaches the southeastern crater wall, a deposit (hereafter Subur Deposit) extends for several kilometers onto the crater floor (Fig. 4). This deposit is the most complex example described in this paper because, even from the plan view images, it shows two distinct depositional subsystems. The upper part of the deposit consists of a flat

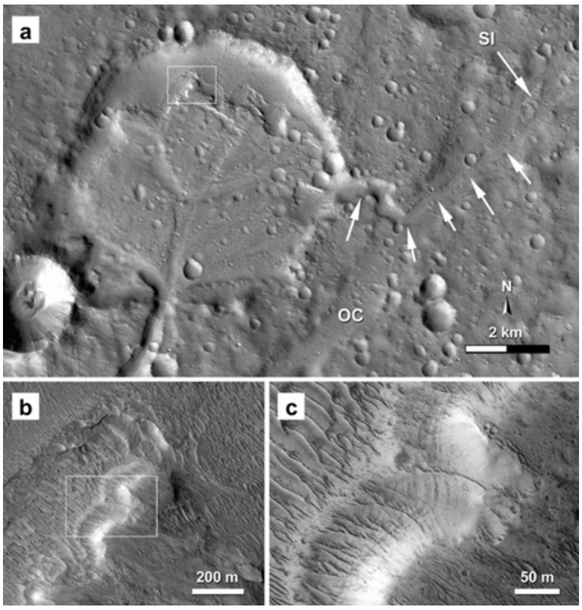

Figure 3. Small delta in an unnamed 5 km-diameter impact crater at the terminus of Nanedi Valles (see Fig. 1 for location). (a) The downstream part of Nanedi Valles cuts the southern crater wall, and a little outlet emanates from the eastern crater wall (white arrows). The small and relatively pristine appearing outlet curves into the course of an abandoned, old and degraded channel (OC), and a small streamlined island (SI) attests to the flow of a liquid medium (detail of CTX P06_003407_1872; crater center at 8.62°N, 48.0°E; North is up; white box shows location of panel b). (b) Distal portion of the deposit, showing the ubiquitous presence of eolian ripples and dunes (detail of HiRISE image PSP_006954_1885; white box shows location of panel c). (c) Blow-up of topographic scarp marking the distal margin of the deposit. Layers with apparent thicknesses of a few meters or less can be traced for hundreds of meters without evidence for unconformal contacts.

plain with a steep front, like it is observed in Gilbert-type deltas with flat topsets and steep foresets [24]. The lack of significant fluvial dissection of the deposit suggests that fluvial activity sharply declined after deposition, as already noted by [25]. According to MOLA data, the proximal part slopes very gently with an angle of ~1.1°, while the steep front displays slopes of up to 10°. Since small-scale topography is smoothed in MOLA data, this steep slope value is probably even an underestimation. At the distal part of this deposit and in a topographically deeper position there are low, concentric terraces. These could be erosional scarps from wave action. On the other hand, they might constitute strata which are not directly linked to a delta front because they appear to be subhorizontal. On Earth, a number of fan deltas show large resedimentation processes that form complex deep-sea deposits, and in some cases almost all of the delta is resedimented [26]. In most cases, the proximal part of the delta complex is preserved and consists of a large Gilbert-type fan delta with foresets reaching the basin floor and merging into a deep-sea resedimented system [e.g., 27]. For example, some fan deltas in the Gulf of Corinth (Greece) display a delta front-slope-fan apron architecture, which strongly resembles the morphology of the Subur Delta (compare Fig. 2a of [27] to Fig. 4). Therefore, our tentative interpretation is that the Subur Deposit might be composed of a proximal Gilbert-delta merging into deep-water resedimented facies.

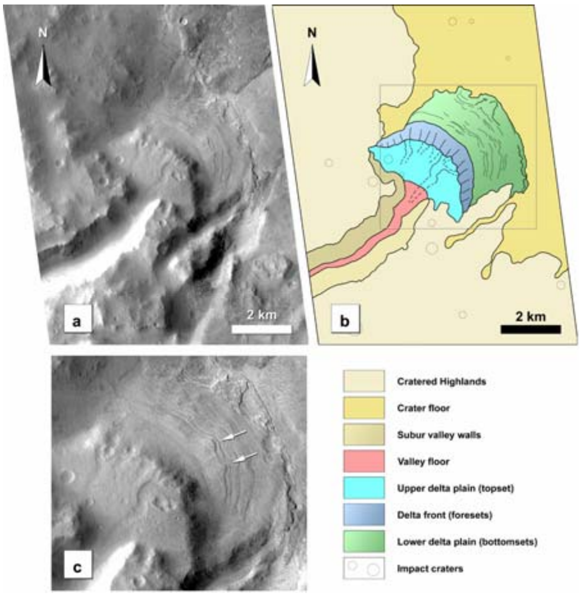

Figure 4. Gilbert-type delta in unnamed crater at the termination of Subur Vallis (at 11.72°N and 307.05°E). (a) High-resolution view of the downstream part of Subur Vallis and the delta (mosaic of MOC images; white scale bar is 2 km, illumination from the left). (b) morphological sketch map of the delta. Note the well expressed features that are typical for Gilbert-type deltas (flat topset and steep foresets) and the possibly resedimented distal layers (black scale bar is 2 km). (c) enlarged detail, marked by white box in panel a. Arrows point to possible depositional lobes, although it can not be excluded that they represent an erosional signature. Indentations of the delta front might have been left by mass wasting processes.

Time scales of sedimentation: Flow discharge and sediment transport computations (see [28,22] for details) indicate minimum time scales for fluvial activity in the order of ~10^1 to ~10^4 years (Tab. 1). Such a formation time is consistent with the study of [29] and [30], who both give very short time-scales for deposit formation. The lack of late-stage incision into sedimentary deposits indicates a relatively abrupt termination of the fluvial activity, in agreement with similar observations by [25] and [30].