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Sedimentary deposits in Xanthe Terra: Implications for the ancient climate on Mars

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ABSTRACT

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 Stereo Camera (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 time scales. Our results point to episodes of a warmer and wetter climate on early Mars, followed by a long period of significantly reduced erosion rates.

1. Introduction

Fluvial and lacustrine deposits on Mars (e.g., Cabrol and Grin, 1999; Ori et al., 2000; Moore et al., 2003; Irwin et al., 2005a) contain a record of past hydrological conditions and are important targets of environmental and paleoclimatic studies (e.g., Newsom et al., 1996; Forsythe and Blackwelder, 1998). Ancient depositional landforms associated with fluvial channels are generally thought to indicate an active hydrosphere, involving precipitation, runoff, and significant erosion (Hynek and Phillips, 2001; Craddock and Howard, 2002). However, the exact nature of the flow processes and the time scales over which they occurred are under debate. End-member scenarios are represented by an early Mars that was either wet and warm (e.g., Craddock and Howard, 2002) or cold and dry (e.g., Gaidos and Marion, 2003). The analysis of sedimentary deposits can constrain paleohydrological models. For example, a warmer climate and persistent flow would have been required if they were formed in long-standing paleolakes. Alternatively, fans and deltas might have formed under subaerial conditions or in short-lived lakes. Therefore, the determination of the time when such deposits were formed in Mars' history, the duration of the fluvial activity, and the type of sedimentary environment is a critical component of paleoclimatic studies of Mars.

A detailed investigation of the formation of sedimentary deposits requires quantitative knowledge of their volume and the volume of the catchment area of the channel systems associated with them. However, the spatial resolution of imaging and topographic data of the Viking-era was typically not sufficient to determine their morphometric characteristics (e.g., Zimbelman, 1987). In particular, one major question is whether specific deposits were formed as subaerial alluvial fans (e.g., Moore and Howard, 2005; Di Achille et al., 2006a; Williams et al., 2006; Kraal et al., 2008a; see Harvey (1997) and Blair and McPherson (1994a) for reviews of terrestrial alluvial fans) or lacustrine deltas (e.g., Cabrol and Grin, 1999; Ori et al., 2000; Fassett and Head, 2005; Di Achille et al., 2006b; Weitz et al., 2006; Mangold and Ansan, 2006; Pondrelli et al., in press), a question that addresses the ability of Mars and its climate to host large bodies of standing surface water (e.g., Irwin et al., 2002; Wood, 2006). The interest in sedimentary deposits on Mars was further increased by findings of the imaging spectrometers, Observatoire pour la Minéralogie, l'Eau, les Glaces, et l'Activité (OMEGA) and Compact

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Reconnaissance Imaging Spectrometer for Mars (CRISM), which identified the spectral signatures of phyllosilicates in association with sedimentary deposits in Holden and Jezero craters (Milliken et al., 2007; Ehlmann et al., 2008). Recently, research was focused on a spectacular deposit in the Eberswalde Crater, which is characterized by well-preserved layering and sinuous, meandering channels (Malin and Edgett, 2003; Moore et al., 2003; Jerolmack et al., 2004; Bhattacharya et al., 2005; Wood, 2006; Lewis and Aharonson, 2006; Pondrelli et al., in press; Schieber, 2007), and on an alluvial fan in Holden Crater (e.g., Pondrelli et al., 2005; Grant et al., 2008; Irwin et al., 2008), both of which were considered as potential landing sites for the upcoming Mars Science Laboratory mission. However, there are many other sedimentary deposits which have not been examined in detail using the recent high-resolution data sets available from the Global Surveyor, Mars Express, Mars Odyssey, and Mars Reconnaissance Orbiter missions. Here we focus on a number of sedimentary deposits in the Xanthe Terra region, between the outflow channel systems of Maja Valles to the west and Shalbatana Vallis to the east.

The High-Resolution Stereo Camera (HRSC) (Neukum et al., 2004; Jaumann et al., 2007) on the Mars Express spacecraft obtains images which cover very large areas (up to $\sim 3 \times 10^5$ km^2) with a spatial resolution of typically 12–20 m/pixel. The instrument is a multiple line scanner, providing stereo images that allow derivation of both high-resolution digital elevation models (DEM) and orthoimages (Scholten et al., 2005; Gwinner et al., 2005). We used these and other images to investigate the paleohydrology of parts of Xanthe Terra near the equatorial region of Mars. In addition to HRSC image and topographic data, we use the Viking Orbiter Mosaicked Digital Image Model 2.1 (MDIM), images from the Mars Orbiter Camera (MOC; Malin et al., 1992; Malin and Edgett, 2001), Thermal Emission Imaging System (THEMIS; Christensen et al., 2004), Context Camera (CTX; Malin et al., 2007), and High-Resolution Imaging Science Experiment (HiRISE; McEwen et al., 2007), and Mars Orbiter Laser Altimeter (MOLA) elevation data (Zuber et al., 1992; Smith et al., 2001).

2. Geologic background

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 (Rotto and Tanaka, 1995). The study region is dissected by many small and shallow valleys, which are not associated with the deeply incised valleys or any sedimentary deposits. These small valleys were probably formed by fluvial processes, which 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 valley is younger and has a different morphologic appearance. It includes the valley systems of Nanedi, Hypanis, Sabrina, Ochus, Drilon, and Subur Valles. These valleys are deeply entrenched and show characteristics like amphitheater-shaped heads, few tributaries, low drainage density, and almost constant widths (see Laity and Malin (1985) for terrestrial analogues on the Colorado Plateau). They were interpreted to be indicative of an origin by groundwater sapping rather than by precipitation (Sharp and Malin, 1975; Harrison and Grimm, 2005), although other processes such as late-stage fluvial entrenchment, erosion through layered stratigraphy, and incision into a duricrust might also produce these morphological properties (Howard et al. (2005); see also Lamb et al. (2008), who describe a terrestrial amphitheater-headed canyon that was not eroded by sapping). The term (groundwater) sapping is used throughout this text to

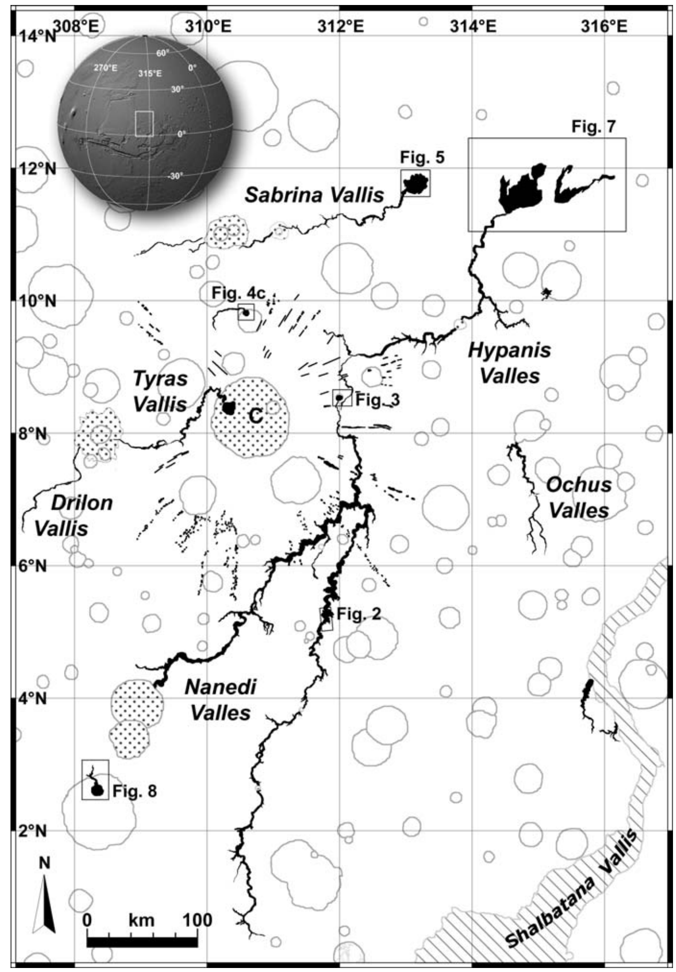

Fig. 1. Morphological sketch map of the study area, based on HRSC, THEMIS, Viking MDIM 2.1, and MOLA data (the Subur Vallis delta is located outside this base map at 11.72°N and 307.05°E). *Black:* valleys and deltas; *open circles:* impact craters; *dotted pattern:* superposed craters and their ejecta, which formed after the valleys onto which they are superposed; *dashed pattern:* outflow channel; *rows of black dots radiating outward from crater at C:* ejecta and secondary crater rows of large impact crater (C); *boxes:* locations of Figs. 2, 3, 4c, 5, 7, and 8. Inset on upper left shows location of study area in a global context.

refer to the process of sapping induced by seepage erosion, following Luo and Howard (2008). A contribution from overland flow to sapping valley formation seems to be likely from the analysis of terrestrial analogues in Utah and Arizona (Irwin et al., 2006). Very high-resolution images taken by the HiRISE camera (PSP_001508_1850, PSP_003341_1855) do not show unambiguous evidence for many small or shallow tributary channels indicative of overland flow connecting with the large entrenched valleys. However, at least one of the images (PSP_003341_1855) 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 (Fig. 2, see also MOC image AB1-08704 and Carr and Malin, 2000) and suggest sustained flow of water (Irwin et al., 2005b). Valley formation might have begun in the Noachian and continued into the Early Hesperian (Masursky et al., 1980; Rotto and Tanaka, 1995; Harrison and Grimm, 2005). Most deposits are situated where fluvial channels breach the rims of strongly degraded impact craters and debouch onto the crater floors. The entire region is moderately dust-covered (Ruff and Christensen, 2002), and consequently no spectral signatures of alteration