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Light-toned strata and inverted channels adjacent to Juventae and Ganges chasmata, Mars

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Received 11 July 2008; revised 20 August 2008; accepted 22 August 2008; published 8 October 2008.

[1] Light-toned layered deposits on the plains adjacent to Juventae and Ganges Chasmata have been identified and analyzed with several instruments onboard the Mars Reconnaissance Orbiter, including HiRISE, CTX, and CRISM. Beds exhibit variations in brightness, color, polygonal fracturing, and erosional properties that are not seen in light-toned layered deposits within the chasmata. At both Juventae and Ganges, the light-toned layered deposits along the plains have associated features we interpret as fluvial, including sinuous ridges (inverted channels) that exhibit light-toned layering and an extensive valley system for the Ganges deposit. The strong correlation between the inverted channels and light-toned layered deposits suggests an association with fluvial-lacustrine processes, although pyroclastic and eolian activity may also be involved in their emplacement. The identification of potential fluvial-lacustrine layered deposits and associated valley networks suggests surface water flow in the Valles Marineris region that occurred for sustained periods during the Hesperian (3.7–3.0 Gyr). **Citation:** Weitz, C. M., R. E. Milliken, J. A. Grant, A. S. McEwen, R. M. E. Williams, and J. L. Bishop (2008), Light-toned strata and inverted channels adjacent to Juventae and Ganges chasmata, Mars, *Geophys. Res. Lett.*, *35*, L19202, doi:10.1029/2008GL035317.

1. Introduction

[2] Light-toned layered deposits (LLDs) have been identified and targeted by the Mars Reconnaissance Orbiter (MRO) in several locations along the Hesperian-aged plains adjacent to Valles Marineris, including (1) southwest of Melas Chasma, (2) south of Ius Chasma, (3) south of West Candor Chasma, (4) west of Ganges Chasma, and (5) west of Juventae Chasma [*Weitz et al.*, 2007]. The LLDs on the plains are only seen in locations where there has been erosion of an unconformably overlying meters-thick dark-toned unit or along exposed crater and trough walls. At both Juventae and Ganges (Figure 1), the LLDs along the plains incorporate features interpreted as fluvial, such as former channels that are now topographically above the surrounding plains (inverted channels) [*Malin and Edgett*, 2003; *Williams et al.*, 2005; *Mangold et al.*, 2008], suggesting a possible fluvial-lacustrine origin or modification of these two deposits.

[3] Here we report on recent MRO observations of LLDs on the plains at these two locations using the High Resolution Imaging Science Experiment (HiRISE) camera [*McEwen et al.*, 2007], Context Camera (CTX) [*Malin et al.*, 2007], and Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) [*Murchie et al.*, 2007]. The ability to identify and analyze the LLDs has been greatly aided by HiRISE, including: the high resolution (~26 cm/pixel) which can reveal small exposures of light-toned beds beneath the dark-toned mantle unit; color images which show apparently variable compositions not previously observable by monochromatic cameras; and stereo image pairs which provide valuable stratigraphic relationships within the deposits and to adjacent units. CRISM visible-near infrared spectra have been used to identify compositions within the LLDs that provide insight into possible origins [*Milliken et al.*, 2008]. Finally, the CTX images at spatial scales of 6 m/pixel permit a regional view of the LLDs and neighboring terrain, thereby providing context and helping to identify or infer the presence of LLDs and other geologic units where no HiRISE images yet exist. Together these three datasets provide valuable information needed to interpret the plains LLDs that was unobtainable prior to the MRO mission.

2. Juventae Deposits

[4] The Juventae plains LLD is divided into three components, with most of the deposit concentrated around the northern and southern portions of an isolated 17 km wide, 1.7 km deep pit that is about 20 km west of Juventae Chasma (Figure 1b). Smaller exposures of light-toned strata occur beneath preserved crater ejecta and inverted channels (ICs). The LLD is stratigraphically above units mapped and interpreted to be Hesperian-age lava plains [*Scott and Tanaka*, 1986]. The plains LLD does not extend to the chasma edge but instead has been eroded back tens of meters by the wind, likely due to its friable nature. An estimate for the current area of the LLD is 820 km^2. The ICs that also consist of light-toned layered material cover an area of 760 km^2, noting that a large fraction of this value represents the underlying plains between individual ICs. MOLA profiles across the LLD indicate it is ~50 m thick, although the thickness varies spatially depending upon the extent of erosion.

[5] The most striking characteristics of the strata in the LLDs are the brightness, color, erosional style, and polygonal fractures that are either lacking or distinct from those in the Interior Layered Deposits (ILDs) within the chasmata (Figures 2a–2d). Although most beds are light-toned in

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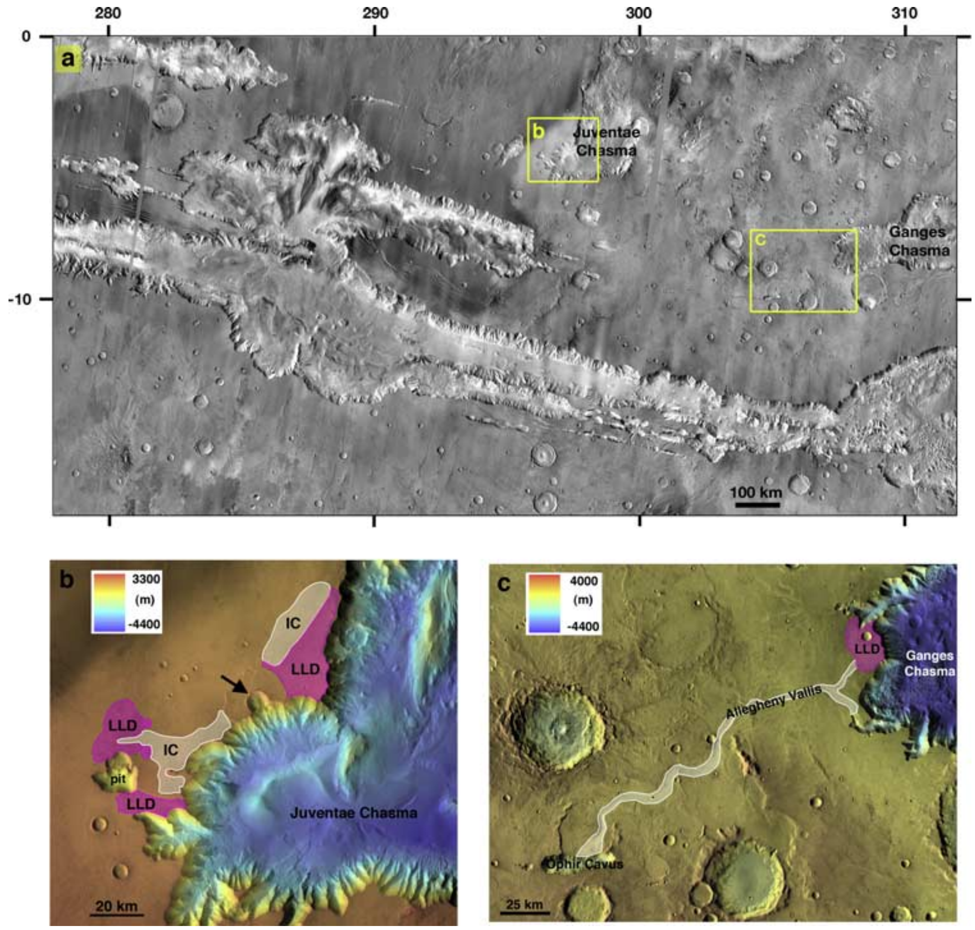

Figure 1. (a) THEMIS (Thermal Emission Imaging System) daytime infrared mosaic of Valles Marineris region. Yellow boxes outline locations of Figures 1b and 1c. (b) MOLA (Mars Orbiter Laser Altimeter) elevation data (color) superimposed on THEMIS daytime infrared mosaic of Juventae Chasma study area. The LLD on the plains is mapped in pink and inverted channels (IC) are mapped in white. Bold arrow identifies a crater that appears superimposed on the LLD and ICs but partially destroyed by Juventae Chasma. (c) MOLA elevation data (color) superimposed on THEMIS daytime infrared mosaic of Ganges Chasma study area. The LLD on the plains is mapped in pink and major valley system branches are mapped in white.

nature relative to the darker plains, there are also beds of darker-toned material within the LLD. Dark-toned beds can result from a surficial cover of relatively dark eolian debris in some instances, but where the layer brightness is homogeneous across topographic and spatial distances and the layer has a sharp rather than diffuse edge then the dark-tone can be attributed to properties of the layer rather than surficial debris. In contrast, ILDs within Juventae and Ganges Chasmata appear uniform in color, and where beds can be distinguished, each bed appears similar in morphology to all the others within the sequence (Figures 2c and 2d), suggesting minimal variations in the depositional environment and physical properties of these materials over time. Thicknesses of individual beds in the LLD are variable but all appear to be several meters or less at the resolution of HiRISE images. Where exposures allow us to trace individual beds over several kilometers, there is no apparent change in their thickness. We have not yet seen any evidence of cross-bedding, but it may not be exposed or could occur at scales below the resolution of HiRISE images.

[6] Polygonal fractures are commonly found on the surfaces of individual light-toned beds (Figure 2e) and can vary in size and shape between and within beds, but typically have diameters ranging from 1–10 meters. The polygons could have formed by thermal contraction or through desiccation of hydrated materials and are commonly seen on other LLDs elsewhere on Mars (e.g., Mawrth Vallis [*Wray et al.*, 2008]). The polygonal fractures are a diagnostic characteristic of the LLDs that we have used when mapping their areal distribution at both sites, particularly in small exposures where only a few light-toned layers are visible. We have noticed that beds with the same style of polygonal fractures can be found at several heights throughout an exposed sequence, perhaps suggesting a cyclic process for deposition or the emplacement of similar nature beds at different times within the strata.

[7] Broad exposures of the Juventae plains LLD display a stair-step pattern with some layers producing flat terraces along their topmost surfaces while others erode at a faster rate resulting in steeper faces. The steeper faces can vary in thickness depending upon the number of layers contained within them, and flatter terraces can be spaced apart at variable distances in height to produce an irregular spacing within the stair-step pattern (Figure 2a). The observation

Figure 2. (a) Portion of HiRISE color image PSP_3579_1755 of the Juventae plains LLD. (b) LLD on the plains west of Ganges (portion of HiRISE color image PSP_5161_1720). (c) Portion of an ILD on the floor of Juventae Chasma (portion of HiRISE color image PSP_4291_1755). (d) Layering seen in an ILD on the floor of Ganges Chasma (portion of HiRISE color image PSP_6519_1730). (e) Enlargement of a portion of HiRISE red mosaic PSP_3579_1755 showing different sizes of polygonal fractures on the surfaces of light-toned beds. (f) Portion of HiRISE color image PSP_4990_1755 of a LLD on the floor of the pit west of Juventae Chasma. The beds appear similar in lithology for the LLD on the plains (a,b) and in the pit (f), but the ILDs inside Juventae (c) and Ganges (d) lack the heterogeneities in brightness, color, and erosional style. The light-dark ''zebra'' pattern in the ILD of Ganges Chasma is a result of dark-toned surficial debris resting on bed surfaces and is not a physical property of individual beds.

that some layers have broad flat upper surfaces whereas others erode more easily and produce steep vertical exposures, as well as the color variations and distinct style of polygonal fractures seen on different layers, likely results from differences in the material properties and/or particle sizes that compose the layers. Either the properties of the materials changed over time to explain the heterogeneities between the layers or there were spatial variations in post-depositional alteration and induration that caused some beds to become more or less friable relative to others.

[8] A LLD inside a pit on the west side of Juventae (Figure 1b) is located on the central floor of the depression. The layering in the pit's wallrock (Figure 2f) appears morphologically similar to the lava plains whereas layers in the LLD resemble the plains LLD rather than the ILD seen within Juventae Chasma. Although the contacts between the LLD and wallrock are commonly obscured by debris, the LLD appears to underlie the wallrock based upon HiRISE images of this geologic contact. If the LLD underlies the wallrock, then it would be older and represent a distinct episode of deposition from the plains LLD.

[9] Inverted channels are clustered in two locations along the plains adjacent to Juventae Chasma (Figure 1b). *Williams et al.* [2005] identified four discreet third- and fourth-order stream networks that have drainage densities among the highest observed on Mars (0.9–2.3 km^{-1}). There are no recognizable ICs within the larger exposures of LLD, perhaps because there hasn't been enough erosion of the deposit to expose them. HiRISE images of the ICs show that they contain light-toned beds (Figure 3) that appear to be the same as those within the LLD, sharing the same color and brightness variations between layers, polygonal fractures, and erosional properties. The ICs indicate a former water flow consistent with the 0.2° regional slope downwards to the northeast [*Mangold et al.*, 2008]. MOLA profiles across a few ICs show they are ~20 m thick. The orientation and organization of the ICs favor fluvial deposition within channels followed by eolian deflation of surrounding less resistant material to expose the layered sediment that was once deposited in the channels [*Williams et al.*, 2005; *Pain et al.*, 2007; *Mangold et al.*, 2008]. The sediment within the former channels could be more resistant due to coarser grain sizes and/or cementation by late fluid circulation.

3. Ganges Deposits

[10] The Ganges plains LLD is smaller in areal extent relative to the Juventae deposit and covers ~300 km^2 (Figure 1). The deposit has a blanket of dark-toned mantling debris with fewer exposures of strata than seen at Juventae. The LLD has been eroded by the wind and partially destroyed by the continued expansion of Ganges Chasma. In addition, a 5.5-km diameter crater and its ejecta are superimposed on the LLD, causing the deposit to be partially disrupted and destroyed. MOLA profiles across the LLD suggest a current thickness of 20–50 m. Exposures along the chasma walls indicate that lava plains likely underlie the LLD. Where exposures are large enough to examine multiple layers of the LLD, the morphology is comparable to the Juventae plains LLD, with a diversity of

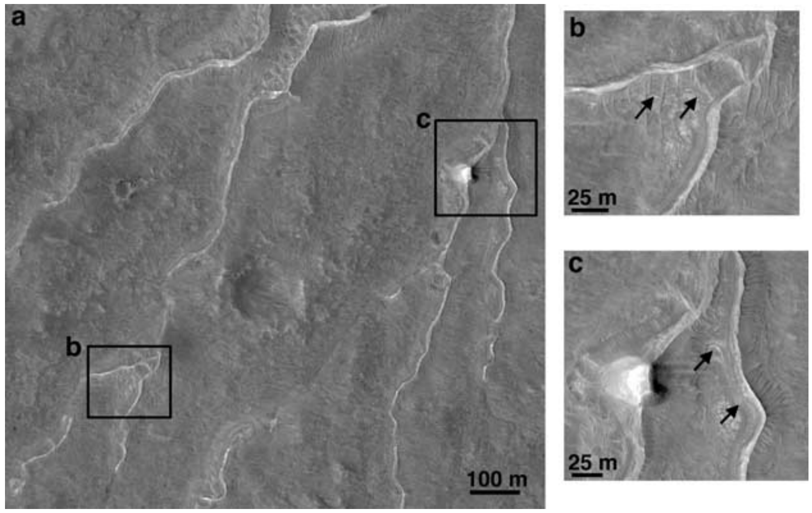

Figure 3. (a) Portion of HiRISE image PSP_3223_1755 showing inverted channels along the plains west of Juventae Chasma. (b and c) Examples of locations where light-toned beds are exposed within and between the inverted channels (bold arrows).

brightness, color, polygonal fracturing, and erosional properties for individual layers within the strata (Figure 2b).

[11] The LLD next to Ganges is located at the terminus of one branch of the 155-km long Allegheny Vallis system (Figure 1c). About a dozen inverted channels are associated with this LLD. The largest IC extends 4 km outside the LLD and into a branch of Allegheny Vallis (Figures 4a and 4b). This IC can also be traced into the LLD ~11 km. Lineations branch out from this IC in the north-south directions at high angles (up to 90° in the downstream direction) (Figure 4c). Similar lineations with high branch angles were found in association with postulated sublacustrine deposition fans in Melas Chasma (J. M. Metz, personal communication, 2008), although the fans in Melas also exhibit lobe-shaped terminations and occur within a closed basin interpreted as the site of a former paleolake [*Quantin et al.*, 2005], neither of which are observed in the Ganges plains LLD. Consequently, the branching lineations here could result from erosion by the wind or ejecta disruption by the crater rather than represent depositional structures like those seen in the Melas fans. The other ICs occur as sinuous ridges to the south of the

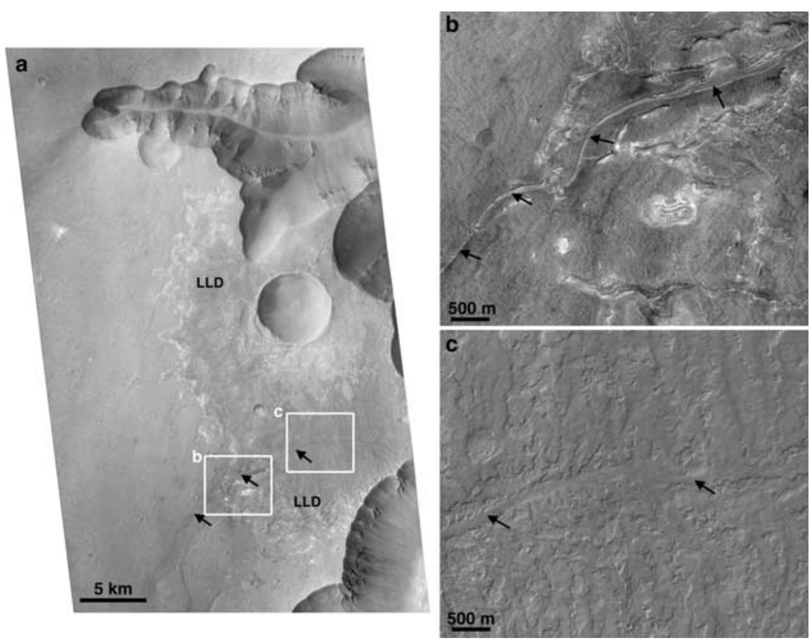

Figure 4. (a) Portion of CTX image P11_5161_1715 that covers the LLD west of Ganges Chasma. White boxes identify locations of Figures 4b and 4c. Bold arrows point to the prominent inverted channel that extends both into Allegheny Vallis and the LLD. (b) HiRISE image (portion of PSP_5161_1720) of the prominent inverted channel (bold arrows) and light-toned beds in the LLD. (c) Portion of HiRISE image PSP_8154_1720 showing branching lineations extending out from the prominent inverted channel (bold arrows).

LLD and appear to be remnant deposits where the neighboring material has been completely removed by the wind.

4. Discussion

[12] Possible origins for the LLDs along the plains include eolian, fluvio-lacustrine, and pyroclastic volcanism. The observation that the five LLDs with these particular characteristics are only seen on the plains adjacent to Valles Marineris but not at other locations along the plains suggests that their origin or exposure must be somehow tied to the formation or distribution of the troughs. An eolian origin is plausible given that the light-toned layered deposits at Meridiani Planum where the Opportunity Rover has been exploring are thought to be sulfate-rich eolian and interdune facies derived from reworked evaporites originally formed in a playa environment [*Squyres et al.*, 2004; *Grotzinger et al.*, 2005]. However, there is no explanation for why eolian deposits would be concentrated in these particular locations adjacent to Valles Marineris given the current topography and regional setting.

[13] CRISM spectra of the Juventae plains LLD are closely matched to opaline silica and Fe-sulfates [*Milliken et al.*, 2008; *Bishop et al.*, 2008]. This mineralogy represents aqueous alteration, possibly resulting from the chemical weathering of lava flows, volcanic ash, hydrothermal springs, and/or impact glass [*Milliken et al.*, 2008]. A pyroclastic origin for the LLDs is possible based upon their compositional similarities to altered pyroclastic deposits on Earth, their association with the Hesperian-aged lava plains and their layered nature. However, the Ganges LLD is associated with a valley and both LLDs locations have inverted channels that would favor a fluvial origin. Nevertheless, we cannot rule out that the plains LLDs are the result of pyroclastic activity that was subsequently altered or transported by water, perhaps associated with the volcanic eruptions, and this water deposited the light-toned sediments found in the inverted channels.

[14] The concentration of inverted channels and associated layered sediments along the plains at Juventae and Ganges may be due to former precipitation resulting from local climatic effects, and/or to regional heatflow that triggered snowmelt in specific regions [*Mangold et al.*, 2008]. This activity may have lasted on the order of 10,000 years to produce the drainage densities and network development observed at Juventae [*Mangold et al.*, 2004, 2008]. The occurrence of LLDs with valleys and inverted channels would seem to favor a fluvio-lacustrine origin for the LLDs, but there are unresolved issues for this formation. For example, the deposits stand above the lava plains with no evidence for a basin that would favor concentration of layered fluvial sediments in these locations. Additionally, while the Ganges LLD could have resulted from deposition of sediments carried through Allegheny Vallis, in the case of Juventae most of the plains LLD must have resulted from material deposited at the source of the channels but not from the channels.

[15] Although not discussed in this paper, other LLDs analyzed on the plains adjacent to Valles Marineris (i.e., southwest of Melas Chasma, south of Ius Chasma, and south of West Candor Chasma) appear similar in morphology to these two sites [*Weitz et al.*, 2007] and we have also identified valleys associated with the Melas and Candor plains LLDs, providing further evidence in support of a fluvial origin for the deposits. The identification of valley networks and inverted channels at multiple locations on the plains adjacent to Valles Marineris in association with LLDs suggests surface water flow that occurred for sustained periods during the Hesperian (3.7–3.0 Gyr). Additionally, a similar but potentially older LLD on the floor of a pit next to Juventae Chasma could indicate that these deposits may have formed along the plains of Valles Marineris at several times in the Martian geologic history.

[16] **Acknowledgments.** We thank F. Chuang for assistance with the MOLA PEDR data. Nathalie Cabrol and an anonymous reviewer provided valuable comments that improved the quality of the paper. We are very grateful to the members of the HiRISE science team as well as the MRO project for all their efforts to acquire such wonderful data from Mars.

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